NSI at Neutrino Factories: correlations & degeneracies

Pilar Coloma

Instituto de Física Teórica
UAM/CSIC
Madrid, Spain

NOW2010
September 10th
Conca Specchiulla, Italy

Based on a work in collaboration with:
A. Donini, J. López-Pavón and H. Minakata

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum c_i O_i^{p,d,f}$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum c_i O_i^{p,d,f}$$

NSI@production

$$O^p : \epsilon_{e\alpha}^{p} (\bar{\mu}\gamma_L^{\mu}\nu_{\mu})(\bar{\nu}_{\alpha}\gamma_{\mu L} e)$$

$$\mu^- \rightarrow e^- \nu_{\mu} \bar{\nu}_{\alpha}$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum c_i O_i^{p,d,f}$$

NSI@production

$$O^p : \epsilon^p_{e\alpha} (\bar{\mu}\gamma^{\mu}_L \nu_{\mu})(\bar{\nu}_{\alpha}\gamma_{\mu L} e)$$

$$\mu^- \to e^- \nu_{\mu} \bar{\nu}_{\alpha}$$

NSI@detection

$$O^d : \epsilon^d_{\mu\alpha} (\bar{\nu}_{\alpha}\gamma^{\mu}_L \mu)(\bar{d}\gamma_{\mu L} u)$$

$$\nu_{\alpha} N \to \mu^- N'$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum c_i O_i^{p,d,f}$$

NSI@production

$$O^p : \epsilon^p_{e\alpha} (\bar{\mu}\gamma^\mu_L \nu_\mu)(\bar{\nu}_\alpha \gamma_{\mu L} e)$$

$$\mu^- \to e^- \nu_\mu \bar{\nu}_\alpha$$

NSI@detection

$$O^d : \epsilon^d_{\mu\alpha} (\bar{\nu}_\alpha \gamma^\mu_L \mu)(\bar{d}\gamma_{\mu L} u)$$

$$\nu_\alpha N \to \mu^- N'$$

NSI@propagation

$$O^f : \epsilon^f_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu_L \nu_\beta)(\bar{f}\gamma_\mu f)$$

$$\nu_\alpha f \to \nu_\beta f$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}^{mass} + \sum c_i O_i^{p,d,f}$$

Too Many parameters!!

NSI@producti

O^p : ... $\nu_\mu \bar{\nu}_\alpha$

NSI@detec

O^d : ... $\mu^- N'$

NSI@propagation

$O^f : \epsilon^f_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu_L \nu_\beta)(\bar{f}\gamma_\mu f)$

$\nu_\alpha f \to \nu_\beta f$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum c_i O_i^{p,d,f}$$

Near Detectors:
S. Antusch *et al*,
arXiv:1005.0756 [hep-ph]
MINSIS workshop report,
arXiv:1009.0476 [hep-ph]

NSI@production

$$\mu^- \to e^- \nu_\mu \bar{\nu}_\alpha$$

NSI@detection

$$\nu_\alpha N \to \mu^- N'$$

NSI@propagation

$$\nu_\alpha f \to \nu_\beta f$$

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum c_i O_i^{p,d,f}$$

NSI@production

$$\mu^- \to e^- \nu_\mu \bar{\nu}_\alpha$$

NSI@detection

$$\nu_\alpha N \to \mu^- N'$$

NSI@propagation

$$\nu_\alpha f \to \nu_\beta f$$

Effective matter potential:
Far detectors

NSI: what is that?

$$A^{NSI} = A \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

T. Kikuchi, H. Minakata, S. Uchinami
arXiv:0809.3312v2 [hep-ph]

NSI: what is that?

$$A^{NSI} = A \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

δA

T. Kikuchi, H. Minakata, S. Uchinami
arXiv:0809.3312v2 [hep-ph]

NSI: what is that?

$$A^{NSI} = A \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

Brief review to analytical dependences:

Diagonal sector

$$P_{\alpha\beta}(\epsilon_{ee} - \epsilon_{\tau\tau}) \sim \mathcal{O}(\varepsilon^3)!!$$

$$P_{\alpha\beta}(\epsilon_{\mu\mu} - \epsilon_{\tau\tau}) \sim \mathcal{O}(\varepsilon^2)$$

T. Kikuchi, H. Minakata, S. Uchinami
arXiv:0809.3312v2 [hep-ph]

NSI: what is that?

$$A^{NSI} = A \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

Brief review to analytical dependences:

Diagonal sector

$$P_{\alpha\beta}(\epsilon_{ee} - \epsilon_{\tau\tau}) \sim \mathcal{O}(\varepsilon^3)!!$$

$$P_{\alpha\beta}(\epsilon_{\mu\mu} - \epsilon_{\tau\tau}) \sim \mathcal{O}(\varepsilon^2)$$

Off-diagonal sector

$$P_{e\mu,e\tau} = P^{std}_{e\mu,e\tau} + \mathcal{O}(\varepsilon^2) \qquad (\epsilon_{e\mu},\ \epsilon_{e\tau},\ \cancel{\epsilon_{\mu\tau}})$$

$$P_{\mu\mu,\mu\tau} = P^{std}_{\mu\mu,\mu\tau} + \mathcal{O}(\epsilon_{\mu\tau}) + \mathcal{O}(\varepsilon^2)$$

T. Kikuchi, H. Minakata, S. Uchinami
arXiv:0809.3312v2 [hep-ph]

NSI: what is that?

- Pure phenomenological approach, model independent.

NSI: what is that?

- Pure phenomenological approach, model independent.
- WARNINGS!
  - Suppression with scale of New Physics
  - Many parameters to be introduced at once

NSI: what is that?

- Pure phenomenological approach, model independent.
- WARNINGS!
  - Suppression with scale of New Physics
  - Many parameters to be introduced at once
- Up to now, no correlations studied in literature
  - MonteCUBES allows to introduce all parameters at once (M.Blennow, E. Fernández-Martínez; arXiv:0903.3985 [hep-ph])

Why Neutrino Factories?

- Astonishing sensitivities to standard oscillation parameters

Why Neutrino Factories?

- Astonishing sensitivities to standard oscillation parameters
- Long baseline
- High energies
- Multi-channel facility

Large matter effects!

Why Neutrino Factories?

- Astonishing sensitivities to standard oscillation parameters
- Long baseline
- High energies

→ **Large matter effects!**

- Multi-channel facility
- But...what if θ_{13} is measured soon?

Why Neutrino Factories?

- Astonishing sensitivities to standard oscillation parameters
- Long baseline
- High energies

}⇒ **Large matter effects!**

- Multi-channel facility
- But...what if θ_{13} is measured soon?
  - Open possibility: re-optimization of NF to search for New Physics?

Setups

- IDS25:
  - 25 GeV muons;
  - Two 50 kton MIND detectors (arXiv:1004.0358 [hep-ex]):
    - @4000 km: good for CP
    - @7500 km: good for θ_{13} and hierarchy (MB)
  - 5×10^{20} useful muon decays/year/baseline/polarity

Setups

- IDS25:
  - 25 GeV muons;
  - Two 50 kton MIND detectors (arXiv:1004.0358 [hep-ex]):
    - @4000 km: good for CP
    - @7500 km: good for θ_{13} and hierarchy (MB)
  - 5×10^{20} useful muon decays/year/baseline/polarity

- IDS50: 50 GeV upgrade of the IDS25

Setups

But the NF is multi-channel!

So we will study a 3rd setup:

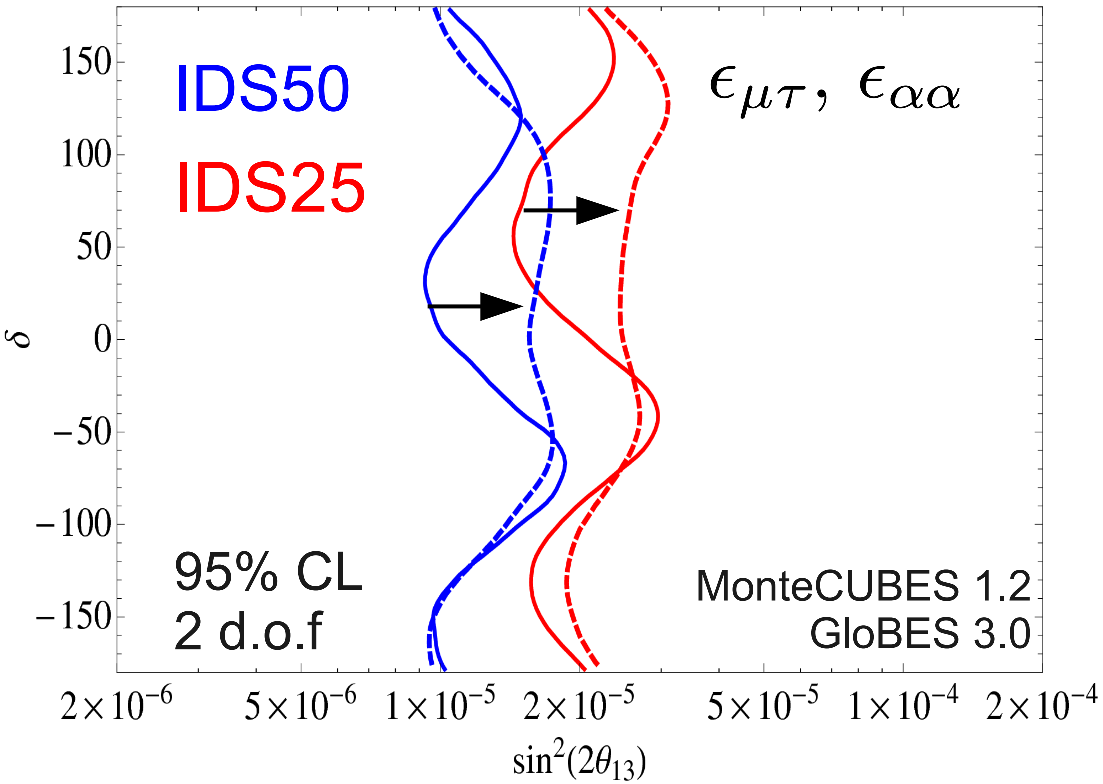
- 1B50:
  - 50 GeV muons:
  - A composite detector @ 4000 km:
    - 50 kton MIND to detect muons;
    - 4 kton MECC to detect taus (arXiv:hep-ph/0305185).
  - Double flux: 10^{21} useful muon decays/year/polarity

1st question:
Does the sensitivity to θ_{13}
change in presence of NSI?

1st question:
Does the sensitivity to θ_{13} change in presence of NSI?

YES

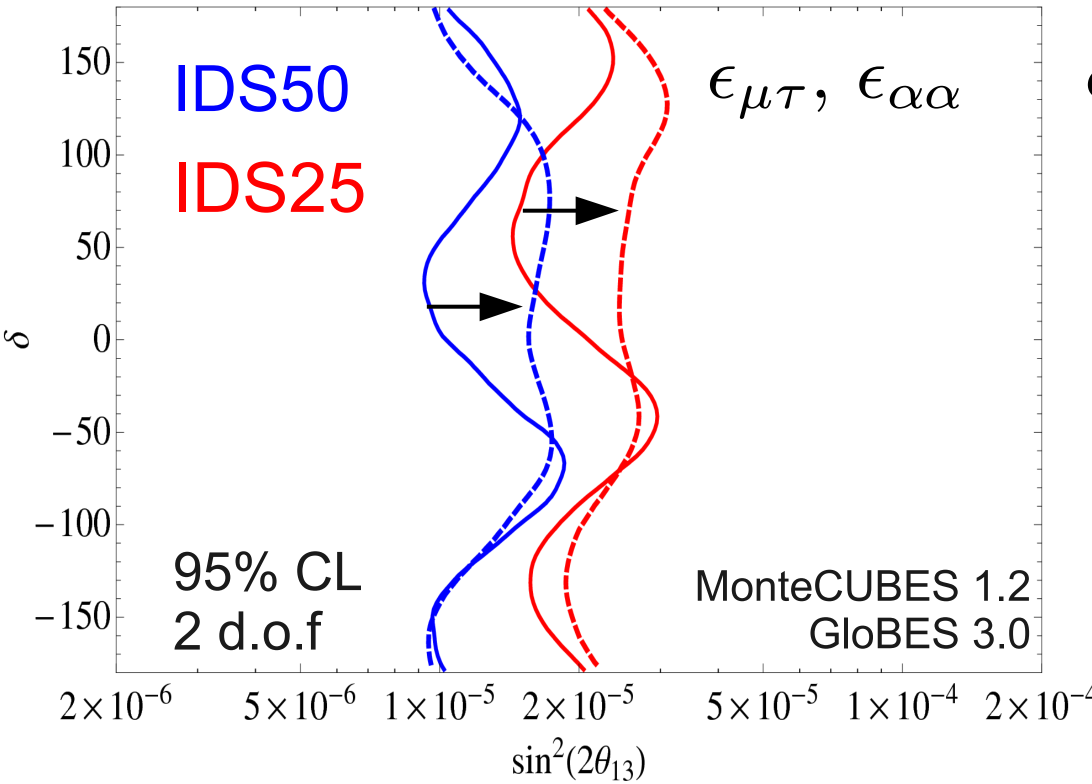
Sensitivity to θ_{13} in *presence* of NSI

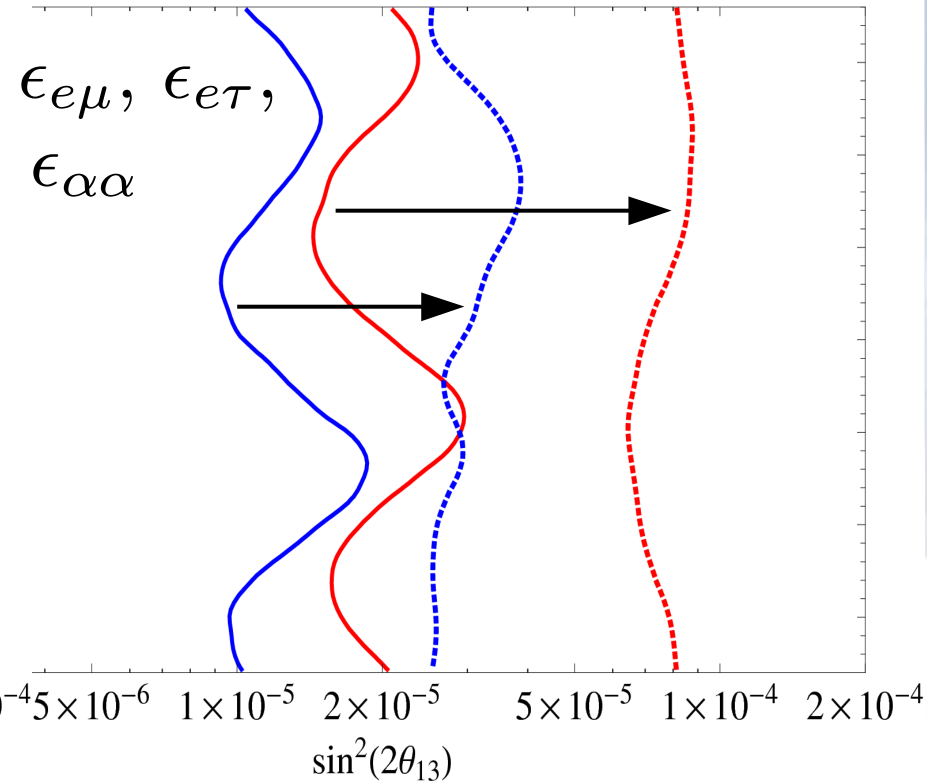


No correlation at all with $\epsilon_{\mu\tau}$
Worsening exclusively
due to $\epsilon_{\alpha\alpha}$

(Marginalization performed over all standard parameters)

Sensitivity to θ_{13} in *presence* of NSI



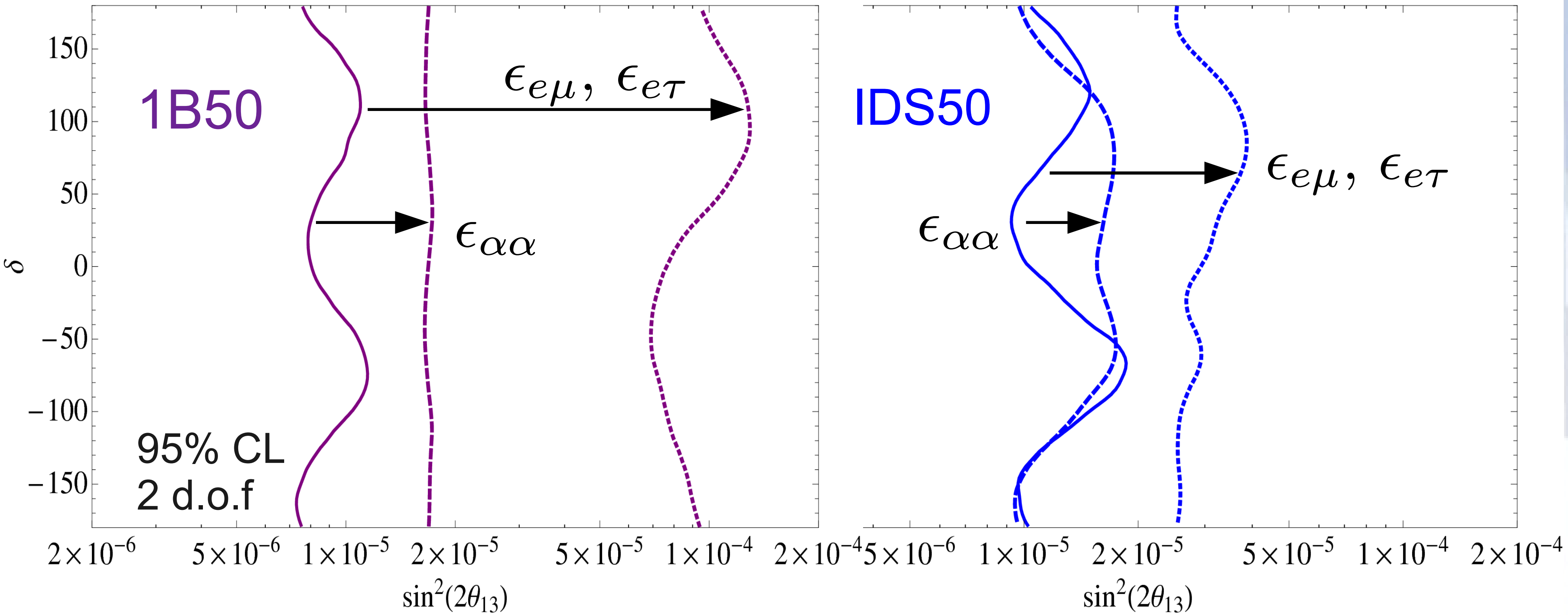


No correlation at all with $\epsilon_{\mu\tau}$
Worsening exclusively due to $\epsilon_{\alpha\alpha}$

Strong correlation due to simultaneous appearance in golden channel

(Marginalization performed over all standard parameters)

Sensitivity to θ_{13} in *presence* of NSI



Magic Baseline performs better in solving degeneracies

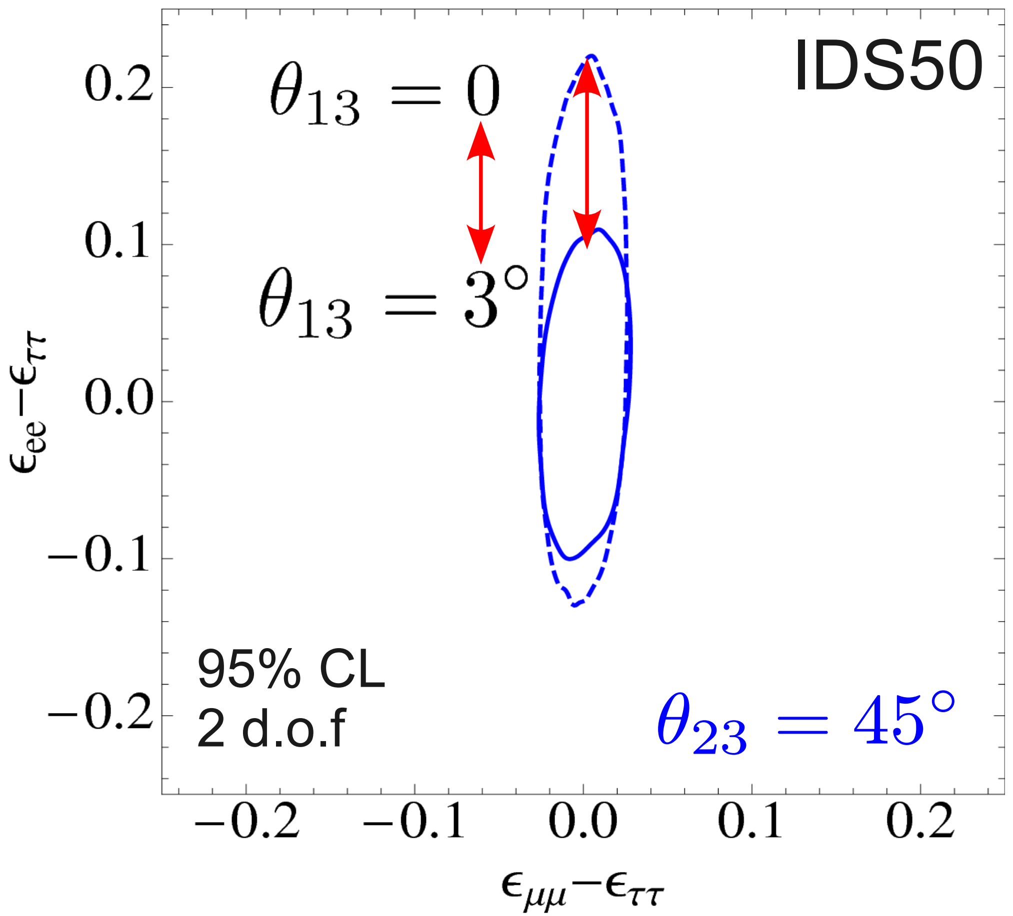
(Marginalization performed over all standard parameters)

2nd question:
Will we actually be able to see NSI?

Blennow, Meloni, Ohlsson, Terranova, Westerberg, arXiv:0804.2744 [hep-ph]

Kopp, Ota, Winter, arXiv:0804.2261 [hep-ph]

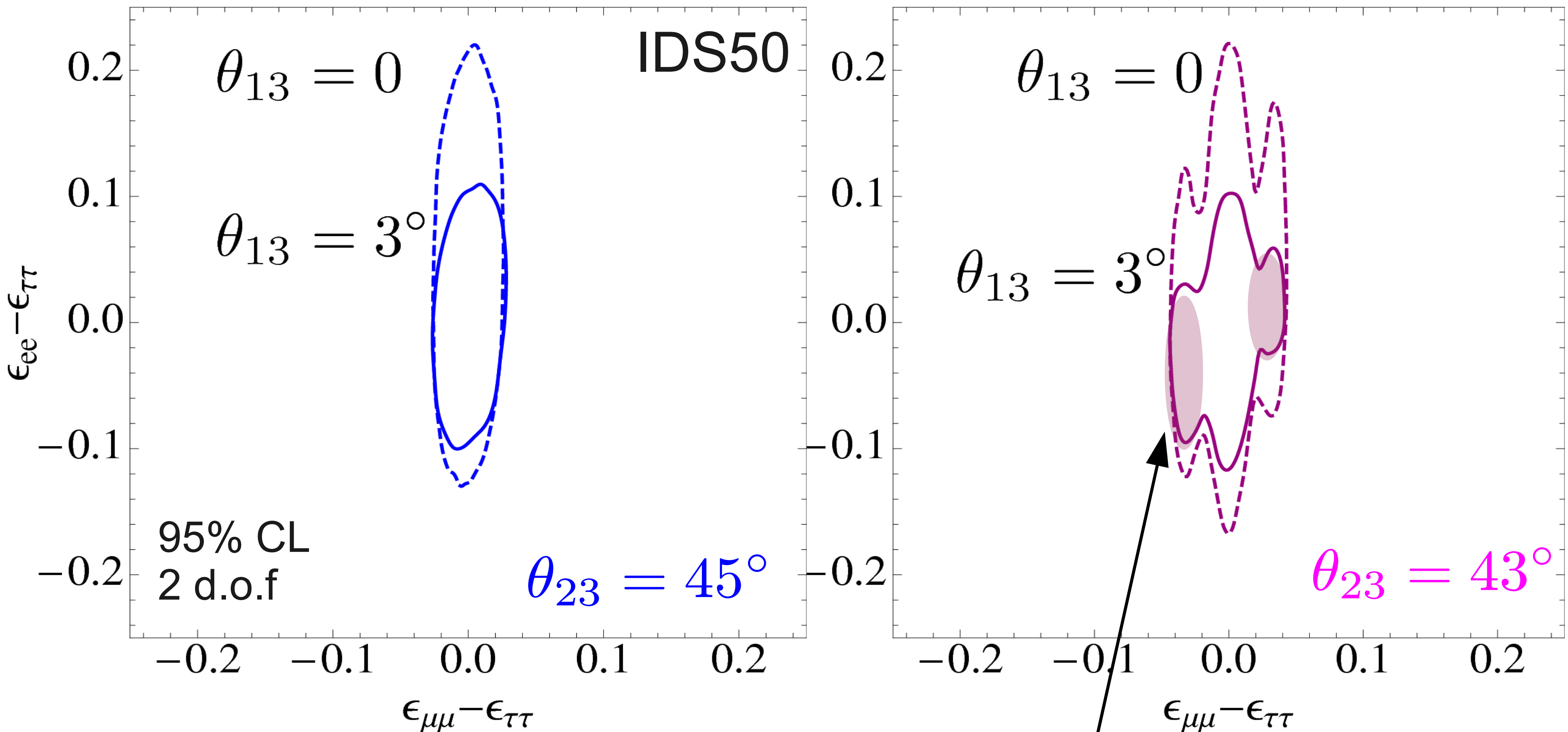
Sensitivity to $\epsilon_{\alpha\alpha}$



Sizable effect due to nonzero θ_{13}

(Marginalization performed over all standard parameters)

Sensitivity to $\epsilon_{\alpha\alpha}$



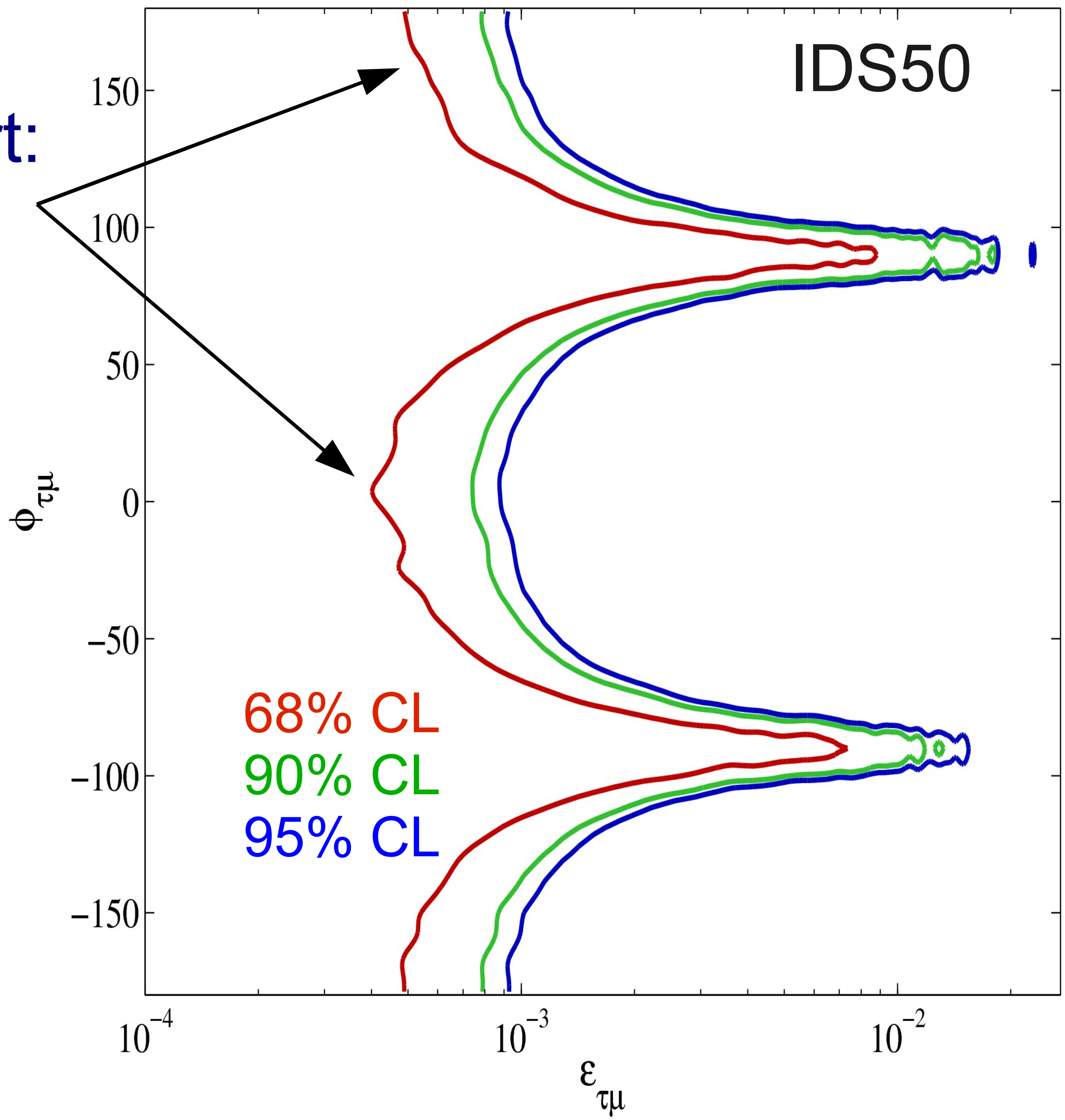
Effect due to $\delta\theta_{23}$

(Marginalization performed over all standard parameters)

Sensitivity to $\epsilon_{\mu\tau}$

- Linear dependence only on the real part:

$$P_{\mu\mu}^{NSI}(\varepsilon) \propto \mathrm{Re}(\epsilon_{\mu\tau})$$



(Marginalization performed over all standard parameters)

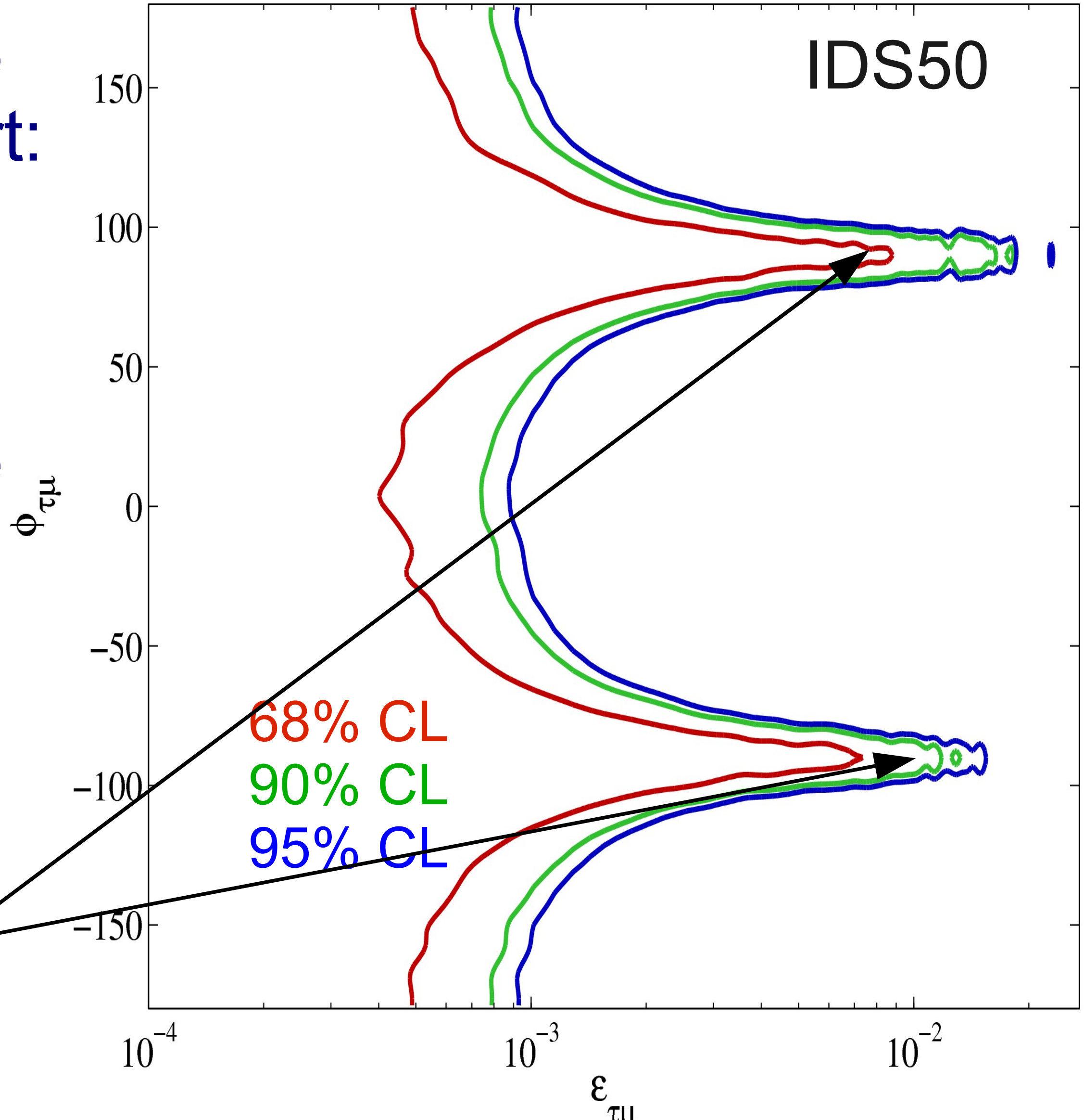
Sensitivity to $\epsilon_{\mu\tau}$

- Linear dependence only on the real part:

$$P_{\mu\mu}^{NSI}(\varepsilon) \propto \mathrm{Re}(\epsilon_{\mu\tau})$$

- Still some dependence on the imaginary part through 2[rd] order terms:

$$P_{\mu\mu}^{NSI} = P_{\mu\mu}^{NSI}(\varepsilon) + (\mathrm{Im}(\epsilon_{\mu\tau}))^2 + \ldots$$



(Marginalization performed over all standard parameters)

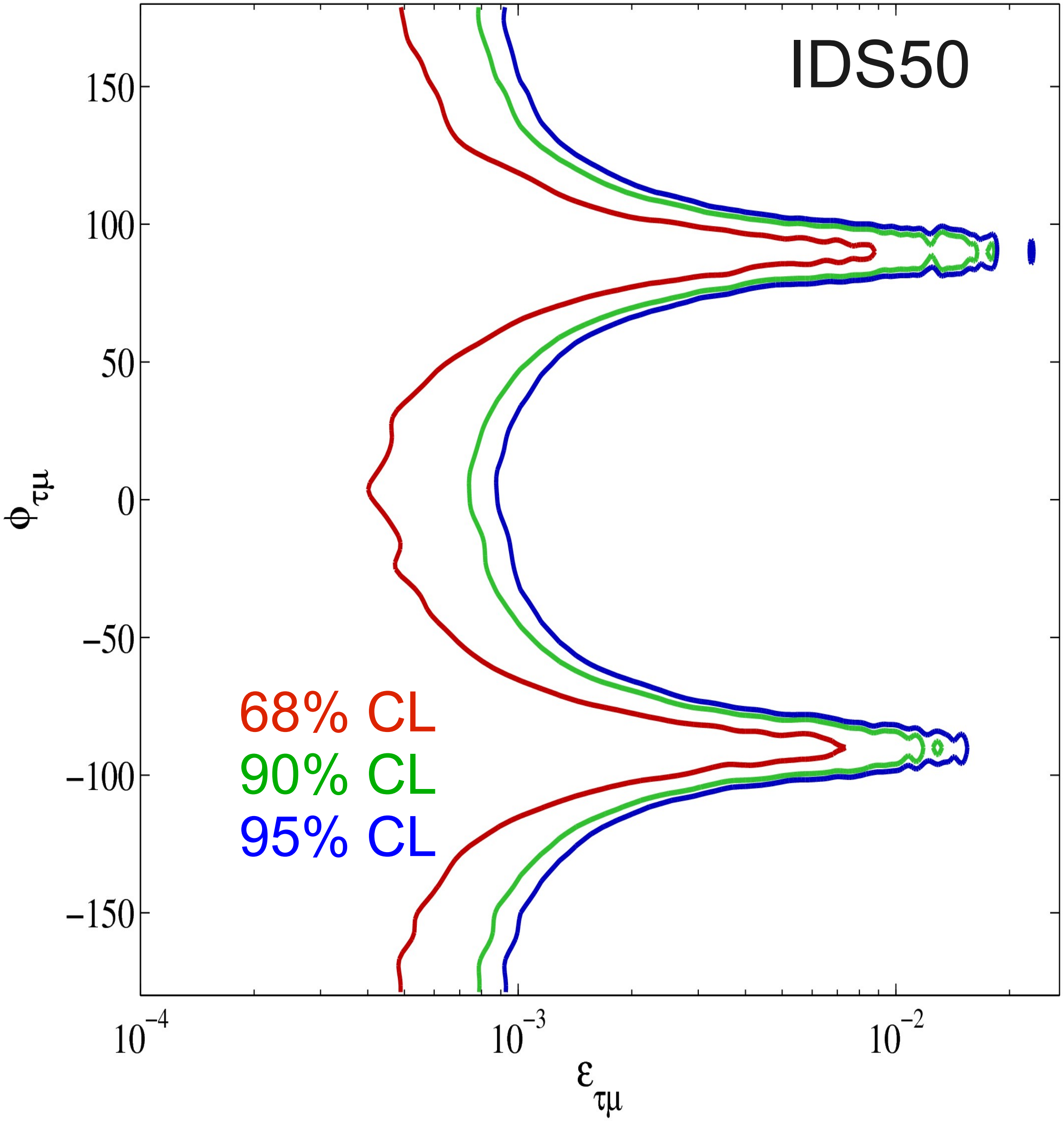
Sensitivity to $\epsilon_{\mu\tau}$

- Good news:

  No correlation with $\theta_{13}, \epsilon_{\alpha\beta}$

  Mild correlation with $\epsilon_{\alpha\alpha}$

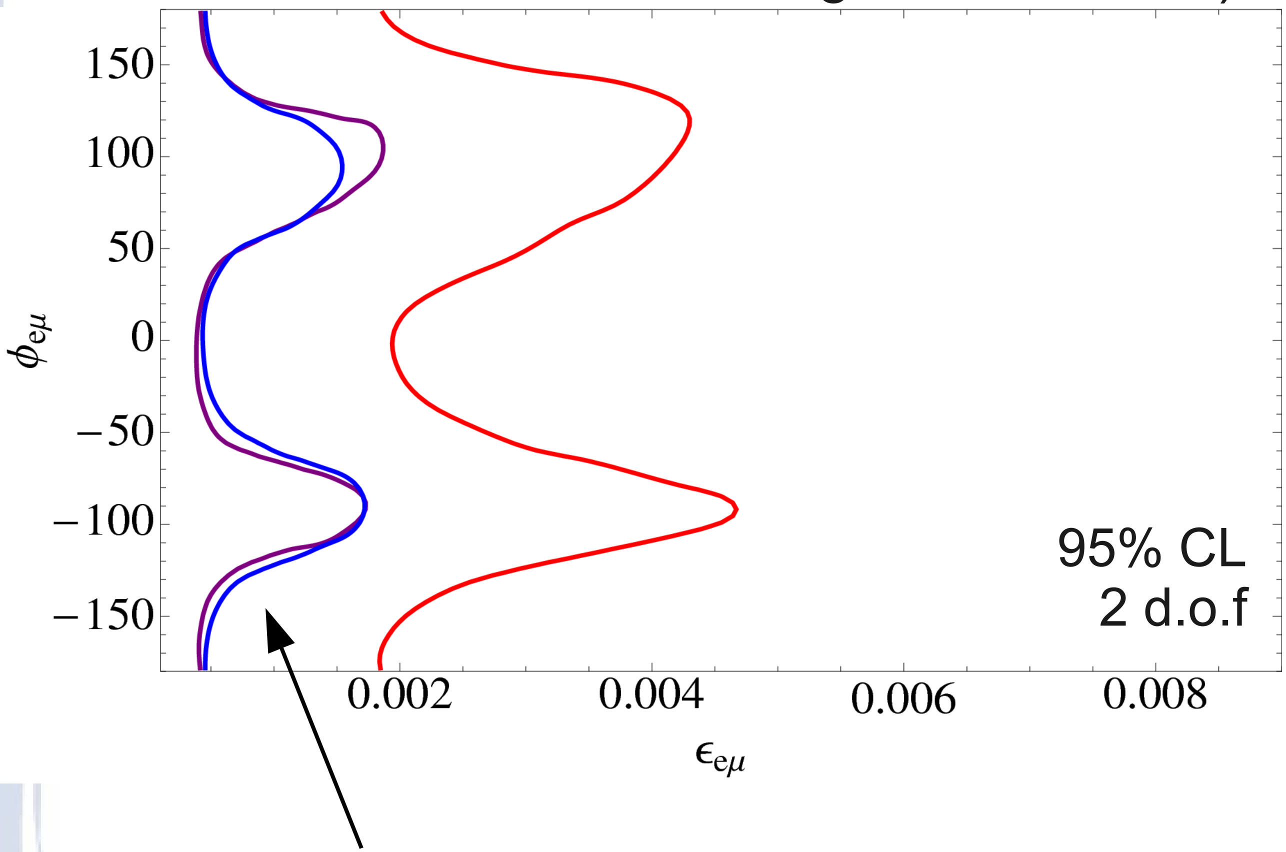
- Same result for all setups under study.



(Marginalization performed over all standard parameters)

Sensitivity to $\epsilon_{e\mu}, \epsilon_{e\tau}$

(Achieved mainly through golden channel)

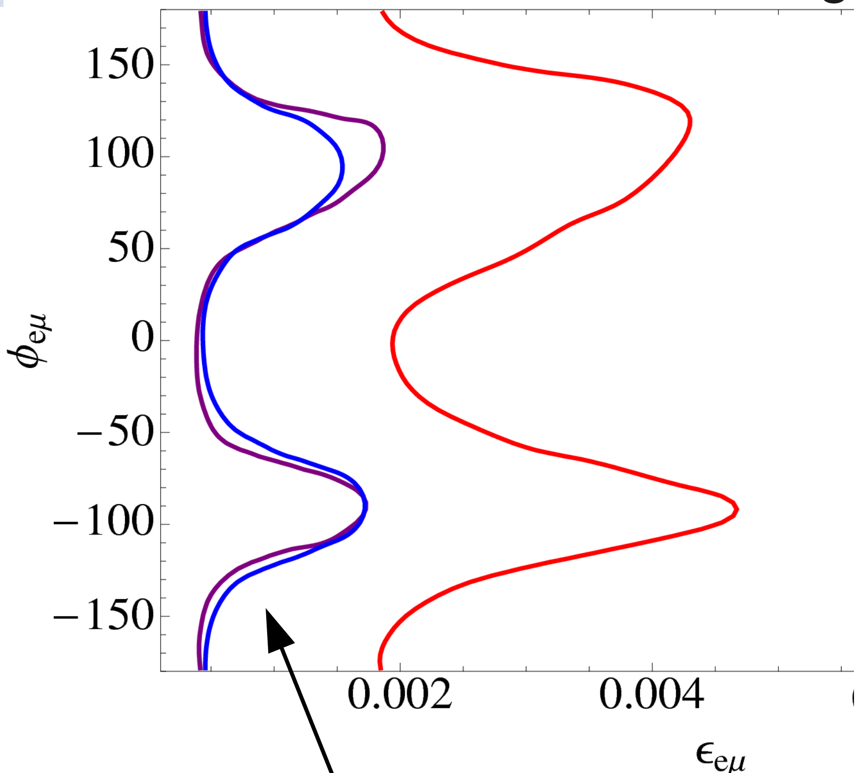


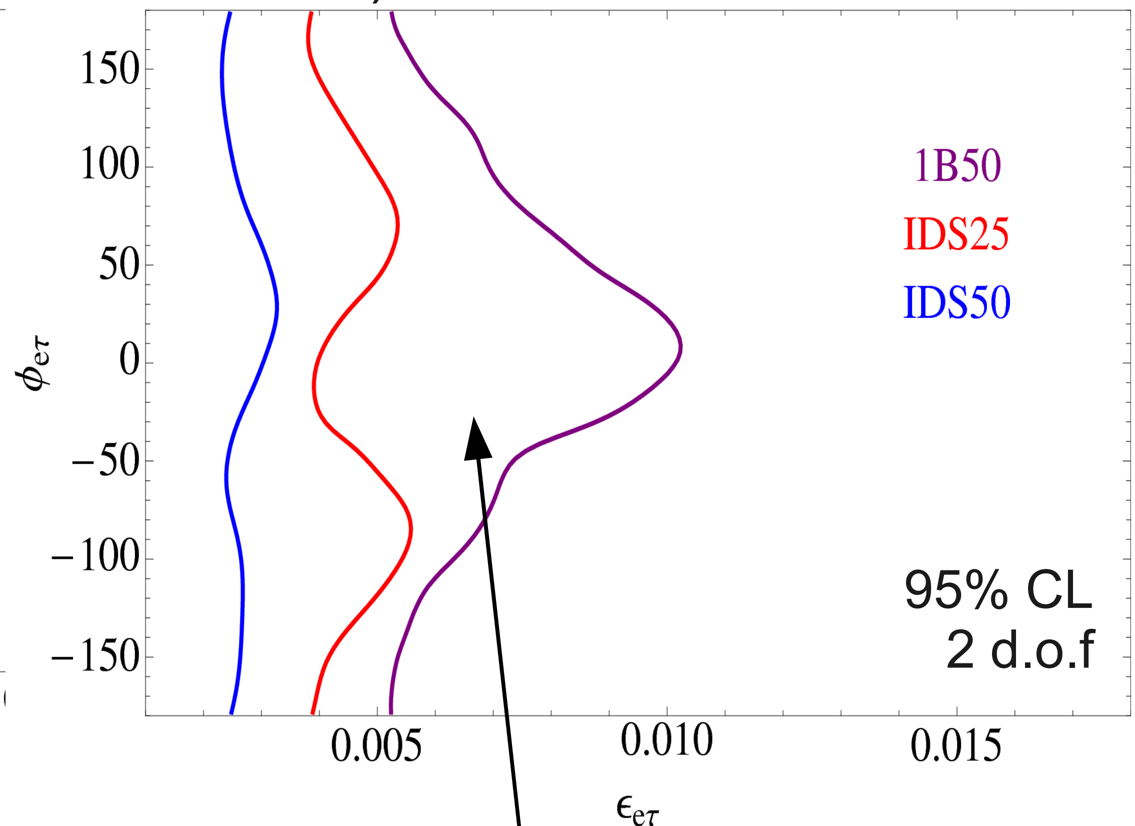
Key factor: energy (either with 1 or 2 baselines)

(Marginalization performed over all standard parameters)

Sensitivity to $\epsilon_{e\mu}$, $\epsilon_{e\tau}$

(Achieved mainly through golden channel)





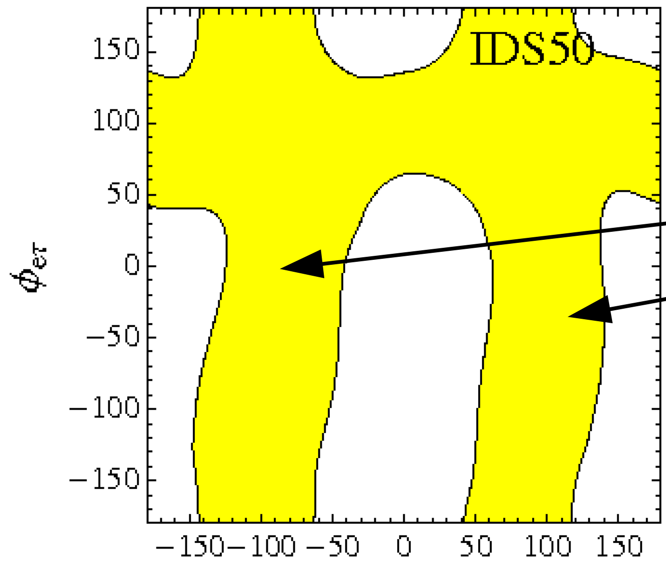
Key factor: energy (either with 1 or 2 baselines)

Key factor: combination of baselines

(Marginalization performed over all standard parameters)

3rd question: What about CP violation?

CP violation due to NSI



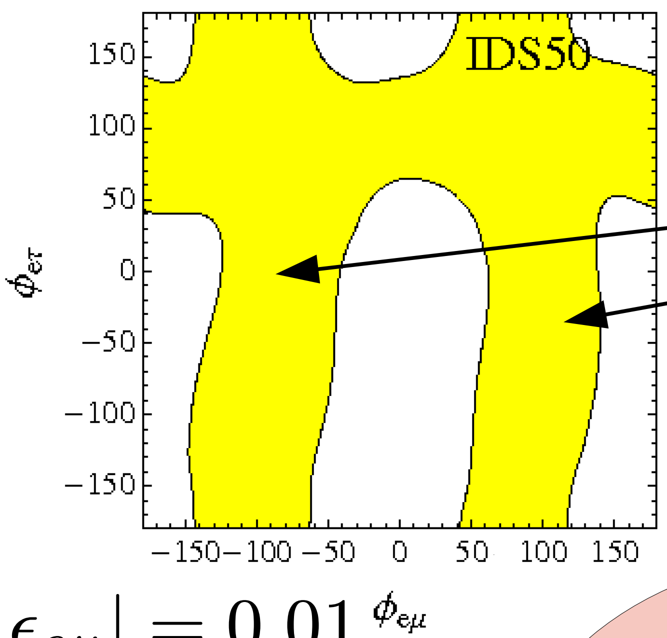
$|\epsilon_{e\mu}| = 0.01$

$|\epsilon_{e\tau}| = 0.01$

Vertical bands due to golden channel: situation dominated by $\epsilon_{e\mu}$

99 % CL 2 d.o.f. (No marginalization performed, but over θ_{13}, δ)

CP violation due to NSI



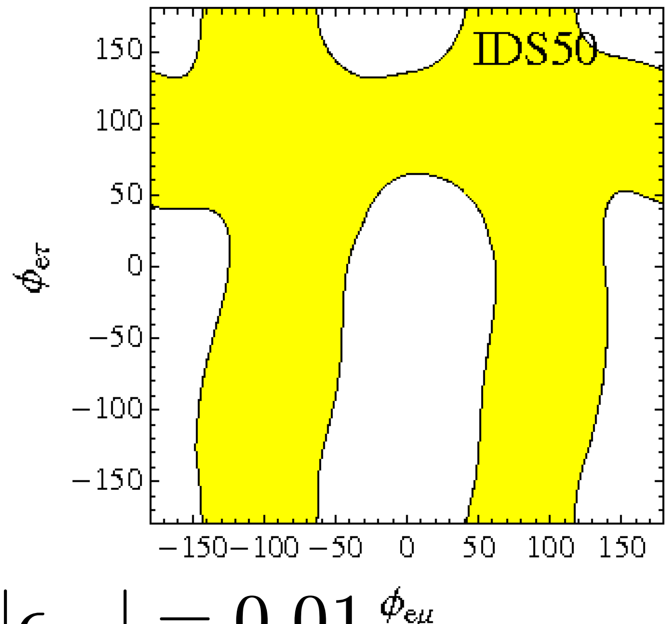
$$|\epsilon_{e\mu}| = 0.01$$
$$|\epsilon_{e\tau}| = 0.01$$

Vertical bands due to golden channel: situation dominated by $\epsilon_{e\mu}$

CP violation can be discovered even for vanishing θ_{13}

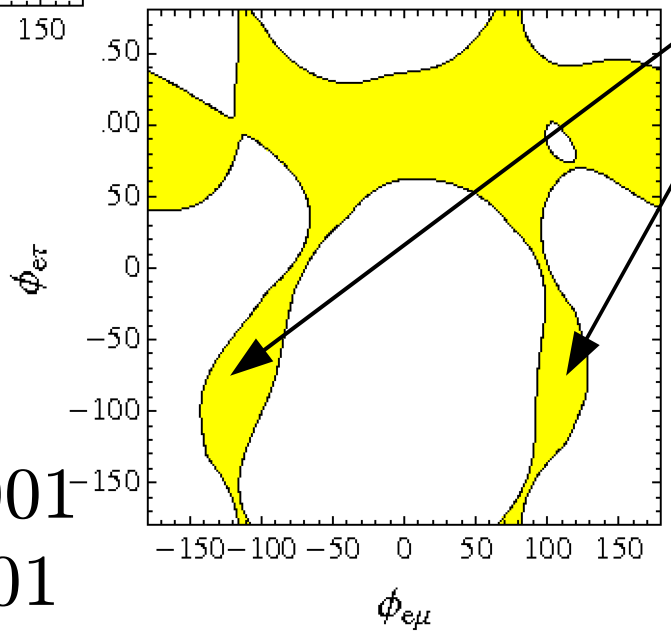
99 % CL 2 d.o.f. (No marginalization performed, but over $\theta_{13}, \ \delta$)

CP violation due to NSI



$|\epsilon_{e\mu}| = 0.01$

$|\epsilon_{e\tau}| = 0.01$



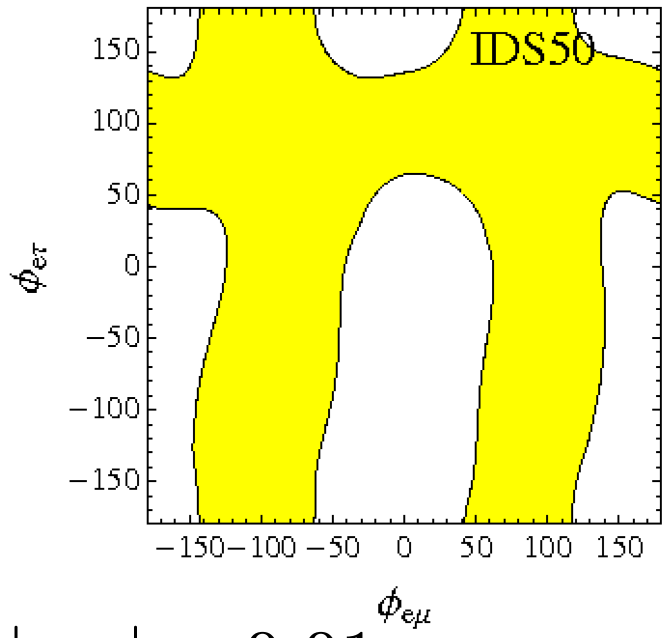
$|\epsilon_{e\mu}| = 0.001$

$|\epsilon_{e\tau}| = 0.01$

Vertical bands start to disappear for $|\epsilon_{e\mu}|$ one order of magnitude smaller

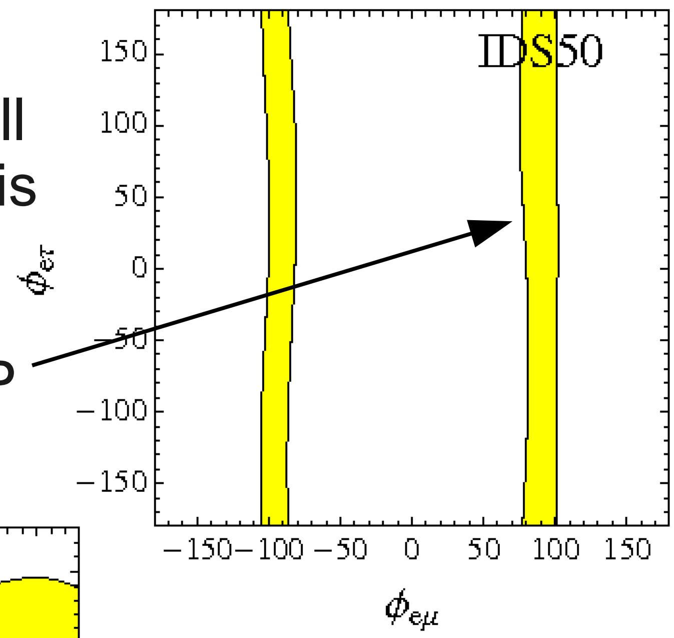
99 % CL 2 d.o.f. (No marginalization performed, but over θ_{13}, δ)

CP violation due to NSI

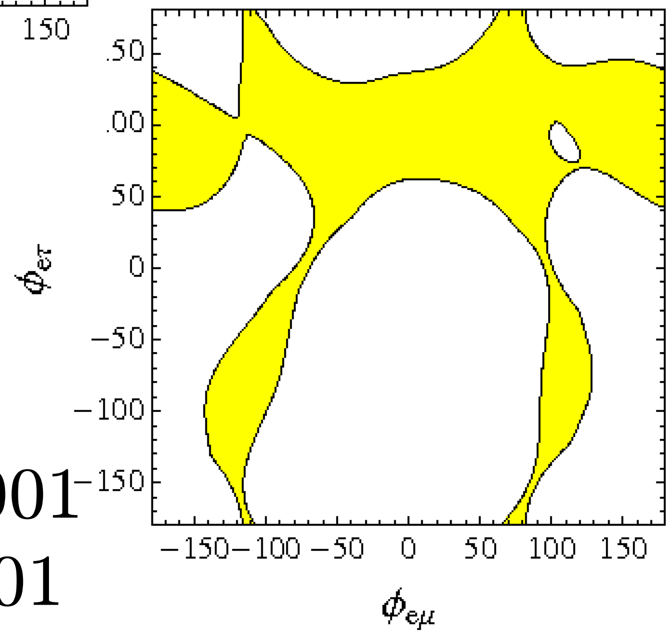


$$|\epsilon_{e\mu}| = 0.01$$
$$|\epsilon_{e\tau}| = 0.01$$

Even for small values, there is still a small chance of observing CP violation



$$|\epsilon_{e\mu}| = 0.001$$
$$|\epsilon_{e\tau}| = 0.001$$



$$|\epsilon_{e\mu}| = 0.001$$
$$|\epsilon_{e\tau}| = 0.01$$

99 % CL 2 d.o.f.
(No marginalization performed, but over $\theta_{13}, \ \delta$)

Conclusions

- Generically, we conclude that higher energy setups are better to study NSI;
- How do NSI affect θ_{13} sensitivity?
  - No correlations with $\epsilon_{\mu\tau}$ are observed;
  - Mild correlations with $\epsilon_{\alpha\alpha}$;
  - Strong correlations with $\epsilon_{e\mu}$, $\epsilon_{e\tau}$.
- Diagonal NSI parameters:
  - Sizable effects due to $\theta_{13} \neq 0$; $\delta\theta_{23} \neq 0$,
  - Sensitivity $\mathcal{O}(10^{-1})$ for $(\epsilon_{ee} - \epsilon_{\tau\tau})$;
    $\mathcal{O}(10^{-2})$ for $(\epsilon_{\mu\mu} - \epsilon_{\tau\tau})$.

Conclusions

- Off-diagonal parameters:
  - $\epsilon_{e\mu}$: higher energies are the key
  - $\epsilon_{e\tau}$: the MB is the key factor

  } Sensitivities of $\mathcal{O}(10^{-3})$ are achievable

  - $\epsilon_{\mu\tau}$: independent of setup. Linear dependence on real part gives rise to sensitivities ranging from $10^{-3} - 10^{-2}$
- CP violation:
  - CP violation exclusively due to NSI could be measured for vanishing θ_{13} in a 35% of the phase space for $|\epsilon_{e\mu}| = 0.001; |\epsilon_{e\tau}| = 0.01.$