NSI at Neutrino Factories:

CP violation & correlation effects

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NuFact10

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Based on a collaboration with:

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and
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Very Brief Motivation

• Neutrino masses and mixing → evidence of Physics Beyond the SM

• NSI: a phenomenological way of parameterizing the whole possible New Physics effects in neutrino oscillations.

• We will focus on NSI effects in neutrino propagation. Paying special attention to:

- Correlations among the oscillation parameters.
- CP violation effects.

NSI: what is that?

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}_{\nu}^{mass} + \sum \delta\mathcal{L}_i^{p,d,m}$$

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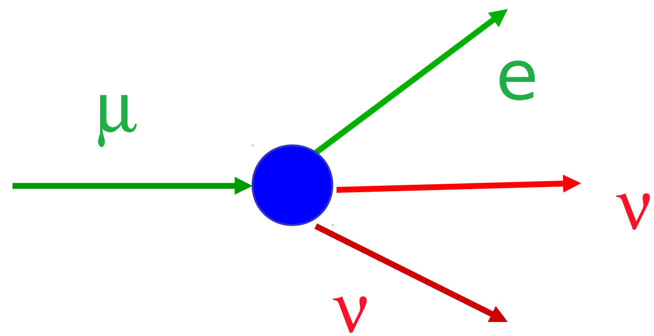
NSI@production

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



$$\delta\mathcal{L}^p : \epsilon^p_{e\alpha}(\bar{\mu}\gamma_L^\mu \nu_\mu)(\bar{\nu}_\alpha \gamma_{\mu L} e)$$

ν

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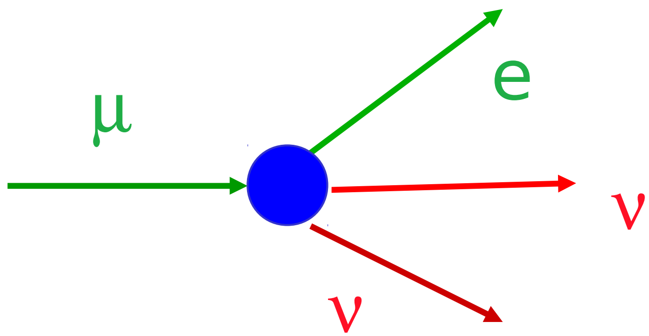

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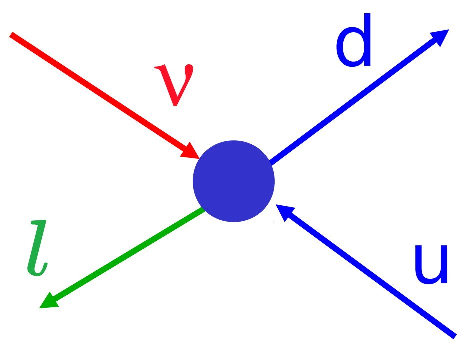
NSI@detection

$\nu_\alpha N \rightarrow l^-_\alpha N'$



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

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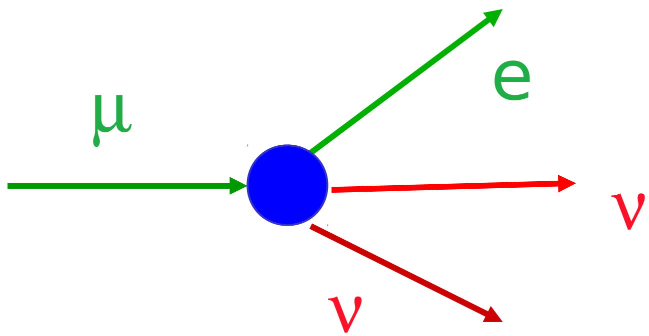

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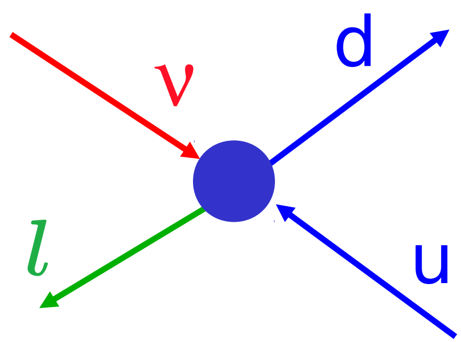
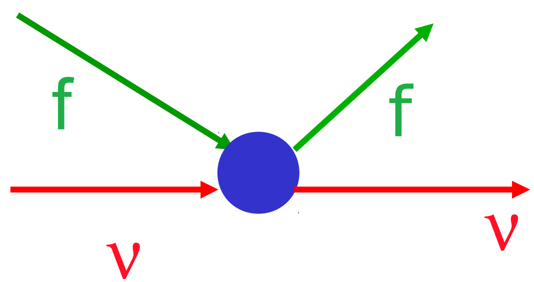


$$\delta\mathcal{L}^{d} : \epsilon_{\mu\alpha}^{d} (\bar{\nu}_\alpha \gamma_L^\mu \mu)(\bar{d}\gamma_{\mu L} u)$$

NSI@propagation

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



$$\delta\mathcal{L}^{m} : \epsilon_{\alpha\beta}^{m} (\bar{\nu}_\alpha \gamma_L^\mu \nu_\beta)(\bar{f}\gamma_\mu f)$$

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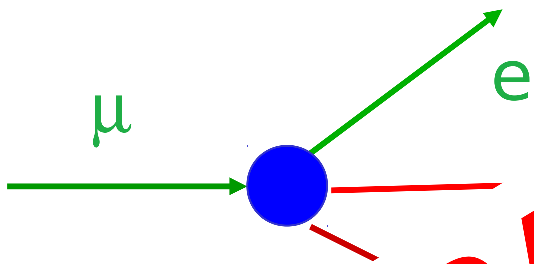
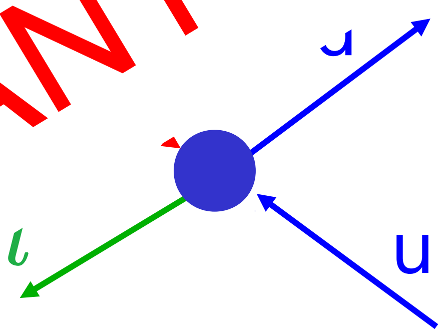


$(\bar{\mu}\gamma_L^\mu \nu_\mu)(\bar{\nu}_\alpha \gamma_{\mu L} e)$

NSI@detection

$\nu_\alpha N \to$



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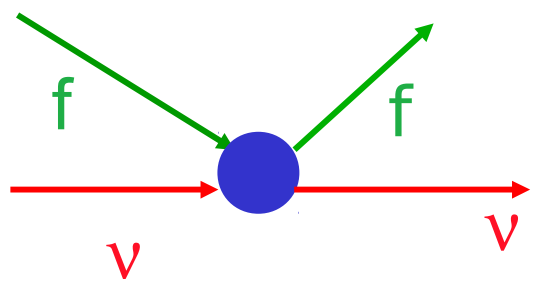

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TOO MANY PARAMETERS!

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Near Detectors

See Mattias Blennow's talk
arXiv:1005.0756 [hep-ph]
MINSIS workshop report,
arXiv:1009.0476 [hep-ph]

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Effective matter Potential:

Far Detectors

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NSI in propagation

$$\delta\mathcal{L}^m = -2\sqrt{2}G_F \sum_{f,P} \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma_L^\mu \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$$A^{NSI} = A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$$H = \frac{1}{2}U^\dagger diagonal\{m_1^2, m_2^2, m_3^2\}U + A^{NSI}$$

In the SM flavour basis

NSI in propagation

- Model independent approach. Mild experimental constraints:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

neutral Earth-like matter

$$|\varepsilon^{\odot}_{\alpha\beta}| < \begin{pmatrix} 2.5 & 0.21 & 1.7 \\ 0.21 & 0.046 & 0.21 \\ 1.7 & 0.21 & 9.0 \end{pmatrix}$$

neutral Solar-like matter

C. Biggio, M. Blennow and E.Fernandez-Martinez; ArXiv: 0907.0097

- However, theoretically, NSI parameters are not expected to be as huge. They come from New Physics at higher energies.

NSI in propagation

- NSI effects in propagation have been widely studied in the literature, even in a Neutrino Factory.

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

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

etc

- However, up to now, no correlations studied before.

- We want to study correlations ➡ Many parameters at the same time in the simulations!

- MonteCUBES allows to introduce all parameters at once (M.Blennow, E. Fernández-Martínez; arXiv:0903.3985 [hep-ph])

Why a Neutrino Factory?

- Long baseline
- High energies
- Multi-channel facility

⇒ Large matter effects!

Why a Neutrino Factory?

- Long baseline
- High energies

→ Large matter effects!

- Multi-channel facility

- Nice sensitivities to standard oscillation parameters
- But...what if θ_{13} is measured soon?

↓

Optimization of NF to search for New Physics?

Set ups

1. IDS25:

- 25 GeV muons;
- Two 50 kton MIND detectors
  - @4000 km
  - @7500 km
- 5×10^{20} useful muon decays/year/baseline/polarity

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2. IDS50: 50 GeV upgrade of the IDS25

Set ups

But the NF is multi-channel! We will study a 3rd setup:

3. 1B50:

- 50 GeV muons:
- A composite detector @ 4000 km:
  - 50 kton MIND to detect muons;
  - 4 kton MECC to detect taus
- Double flux: 10^{21} useful muon decays/year/polarity

Information from oscillation probalilities

Brief review of the analytical dependences:

- $\epsilon_{\alpha\alpha}$ appear always in the same combination:

$$\epsilon_{ee} - \epsilon_{\tau\tau} \Longleftrightarrow \mathcal{O}\left(\epsilon^3\right)$$

$\epsilon_{\mu\mu} - \epsilon_{\tau\tau} \Longleftrightarrow \mathcal{O}\left(\epsilon^2\right)$ only in $P_{\mu\mu}, P_{\mu\tau}$

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

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- Up to second order, $P_{e\mu}$ and $P_{e\tau}$ only depend on $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$:

→ cuadratic dependence

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- Linear dependence on $\epsilon_{\mu\tau}$:

$$P_{\mu\mu}^{NSI} = -P_{\mu\tau}^{NSI} = -\mathrm{Re}\left(\epsilon_{\mu\tau}\right)(AL)\, sin\left(\Delta_{31}L\right) + \mathcal{O}\left(\epsilon^2\right)$$

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Sensitivity to θ_{13} in presence of NSI

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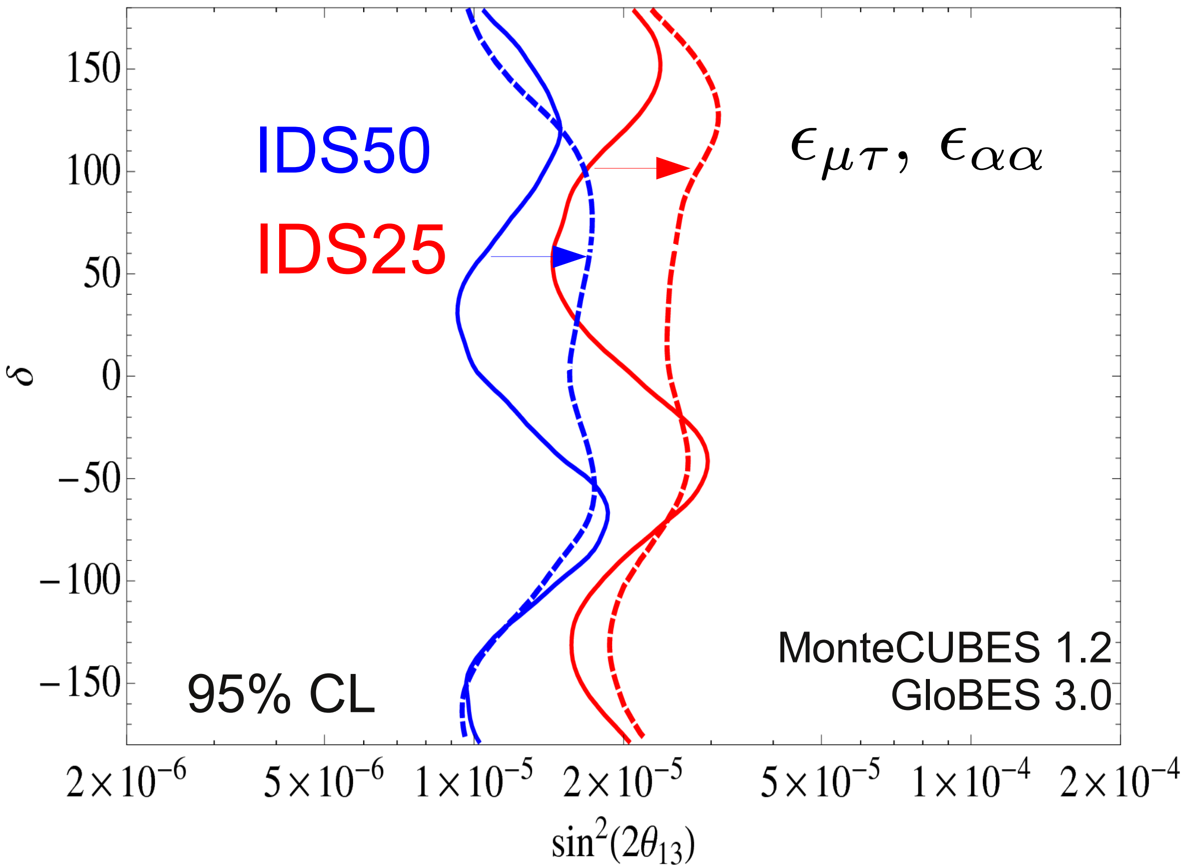

No correlation at all with $\epsilon_{\mu\tau}$

Slight worsening exclusively due to $\epsilon_{\alpha\alpha}$

(Marginalization performed over all standard parameters)

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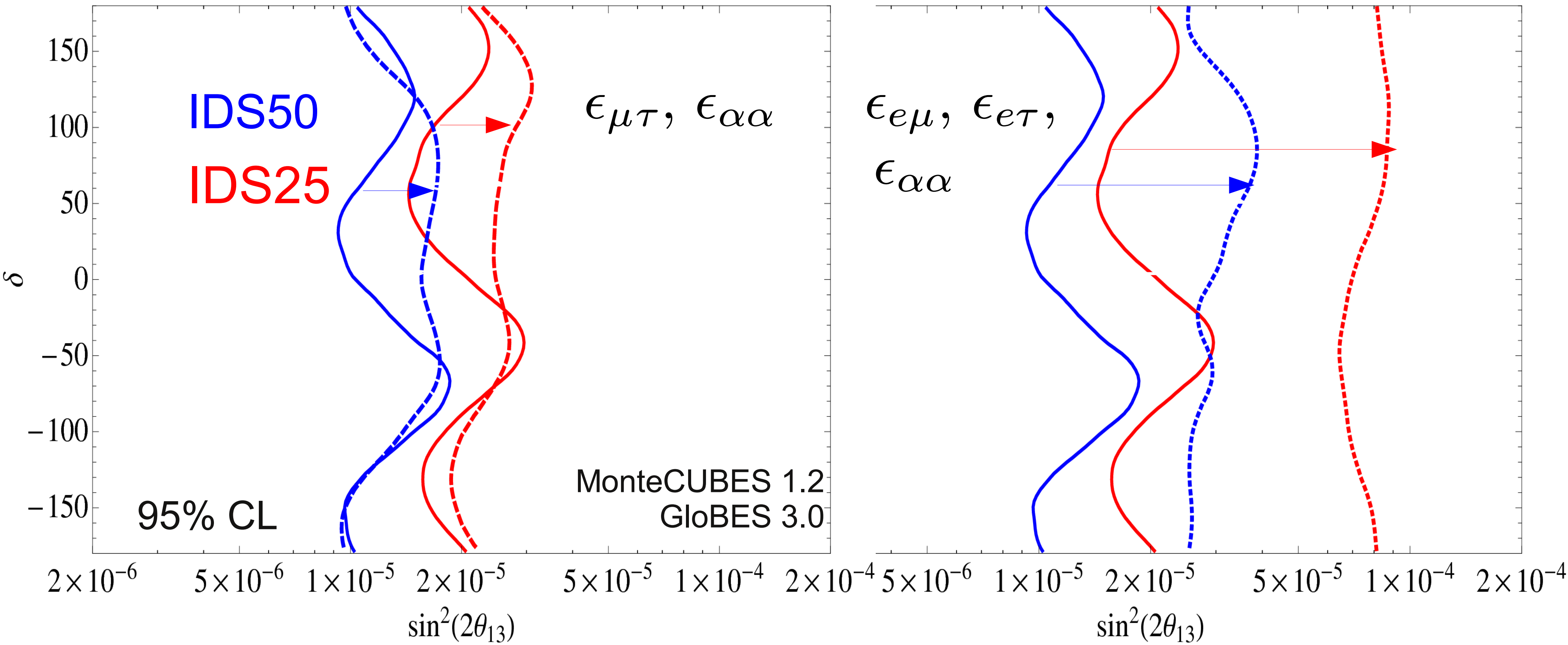

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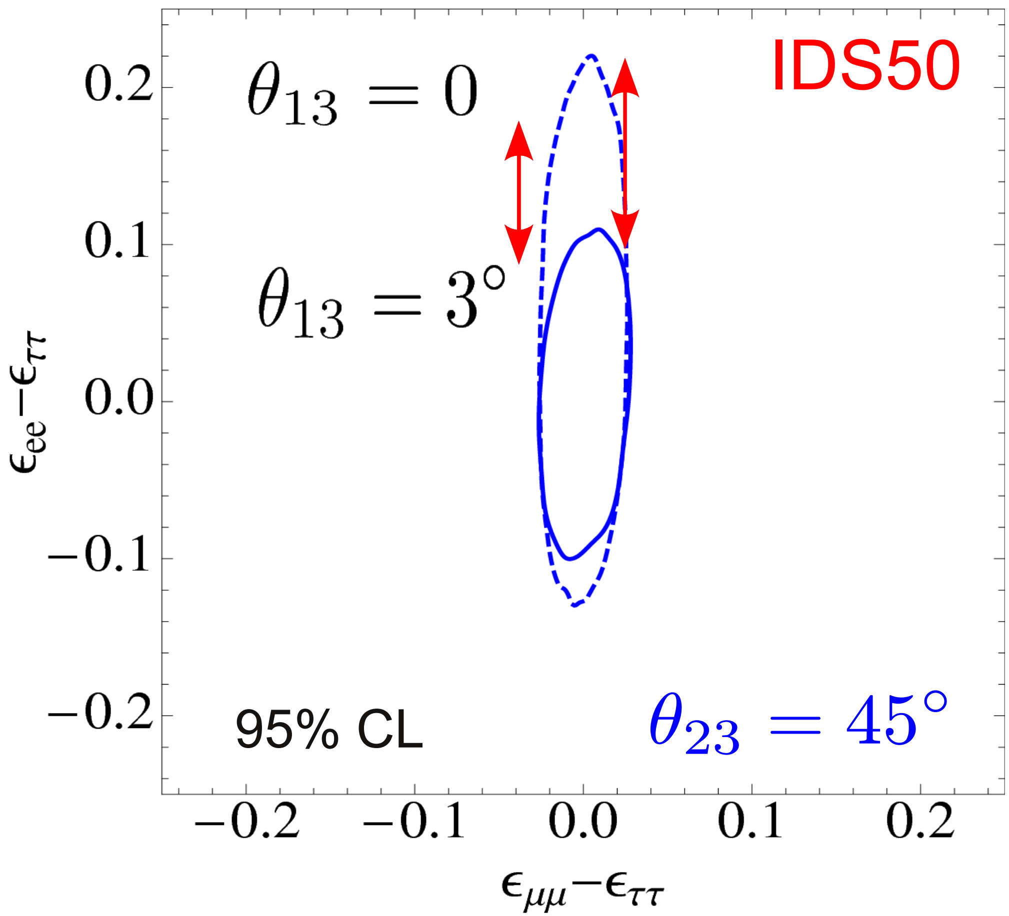
Strong correlation with $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ in Golden channel

(Marginalization performed over all standard parameters)

Sensitivity to NSI parameters

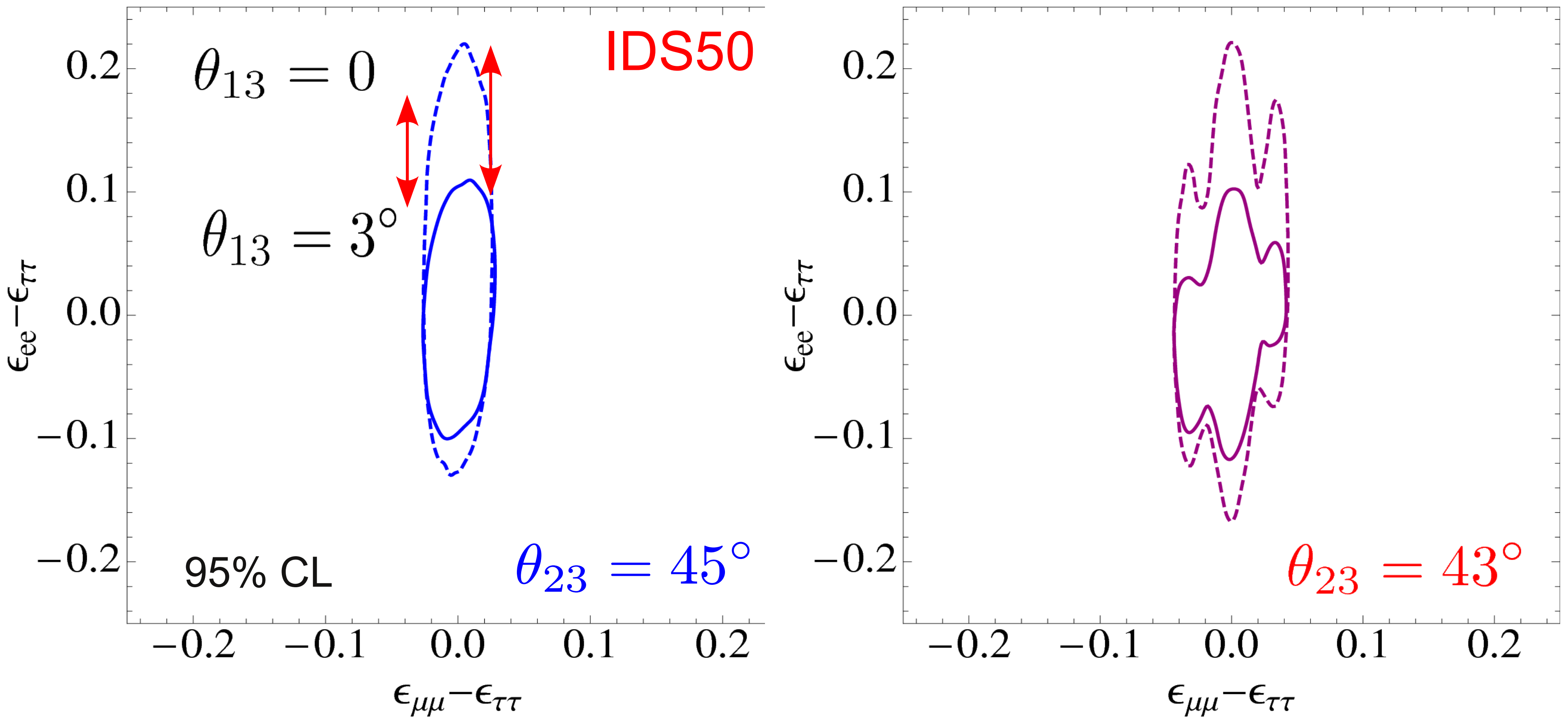
Sensitivity to $\epsilon_{\alpha\alpha}$



Sizable effect due to nonzero θ_{13}

(Marginalization performed over all standard parameters)

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



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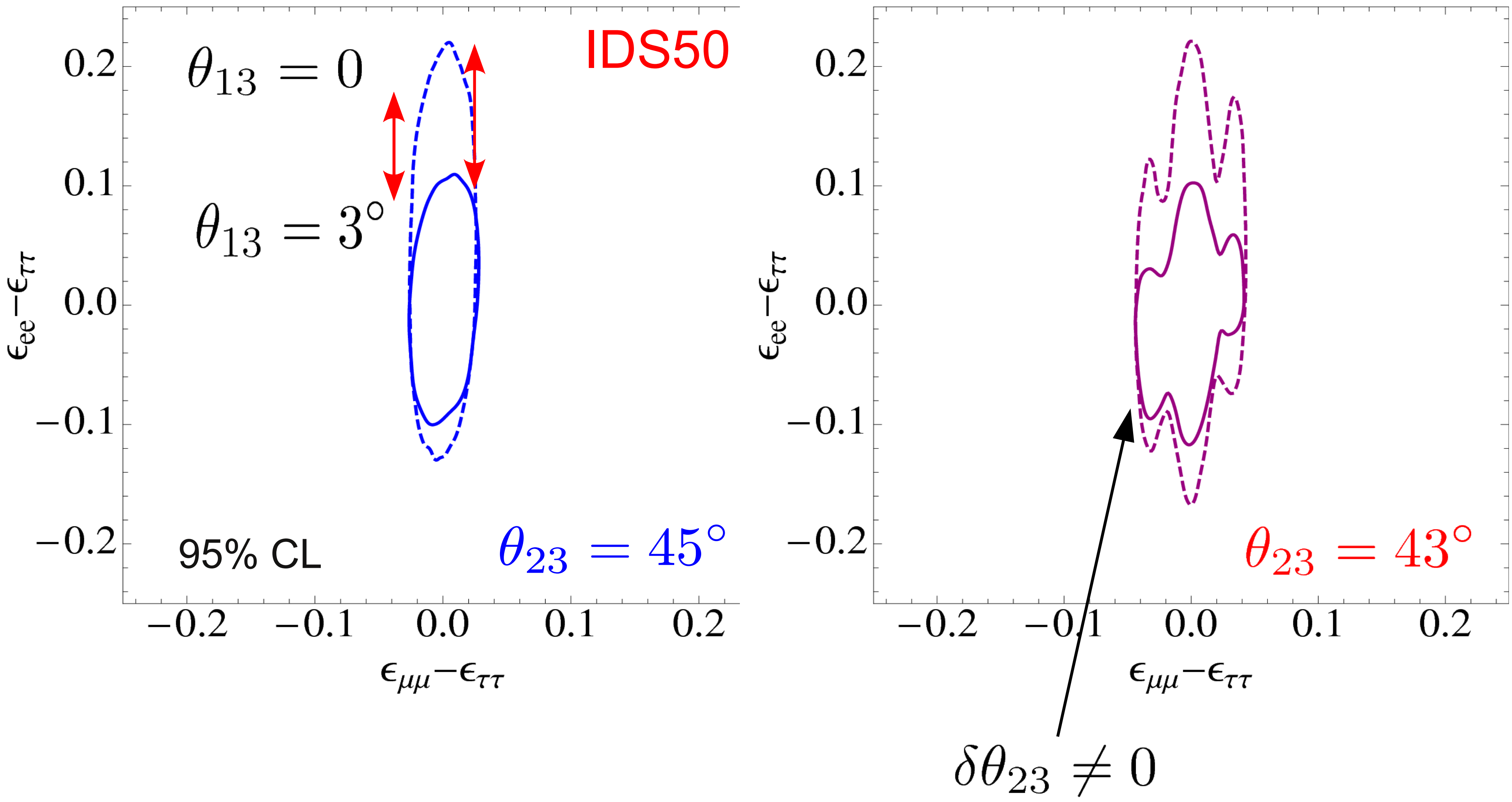

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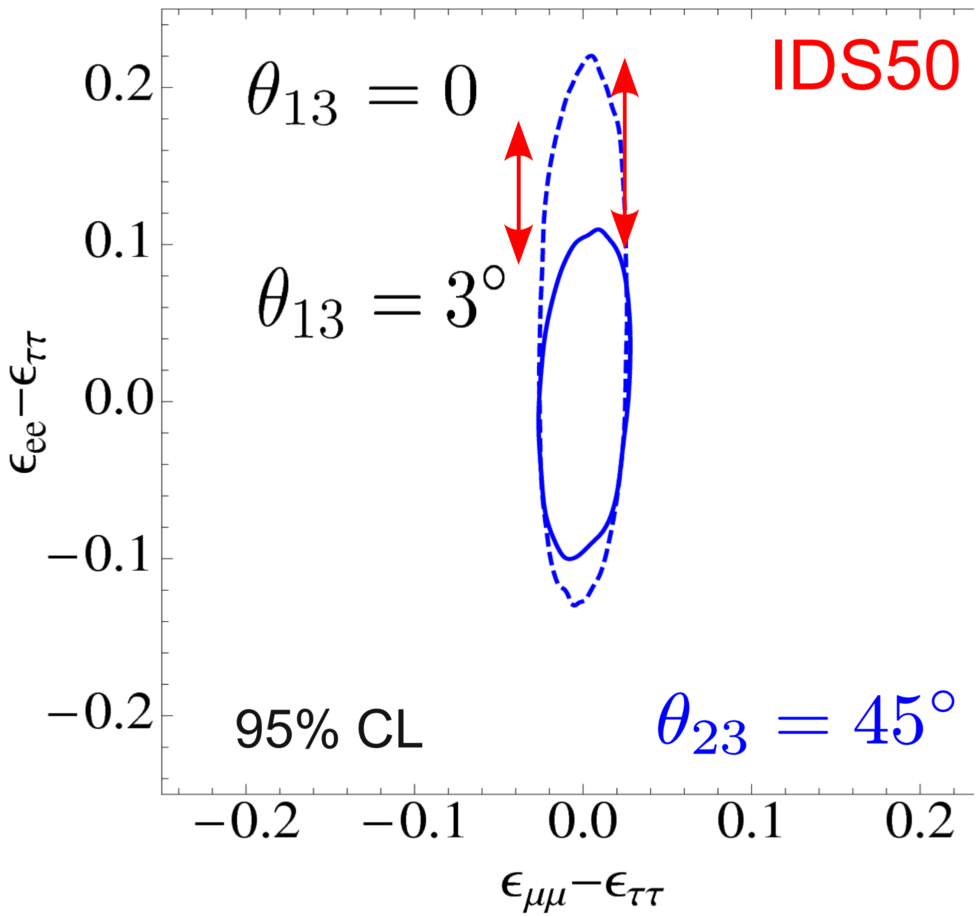
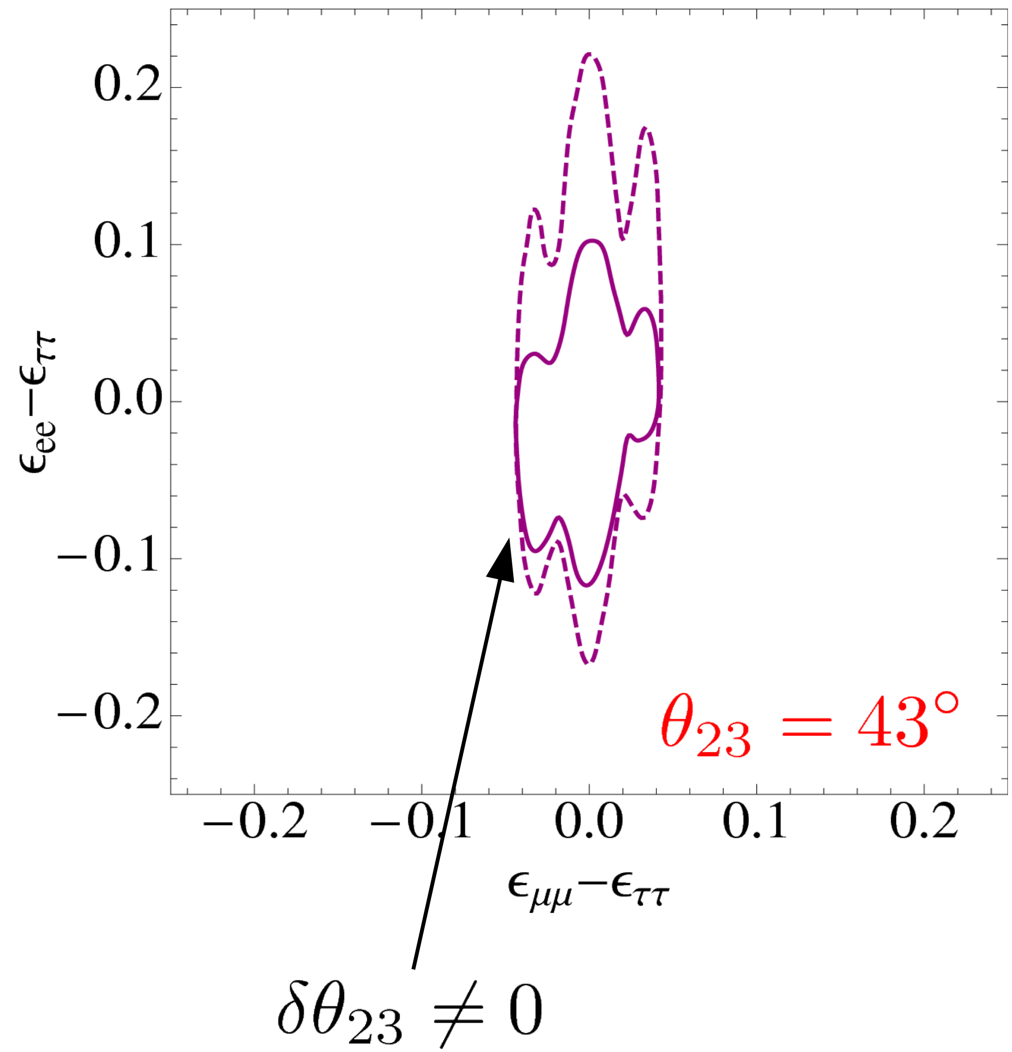




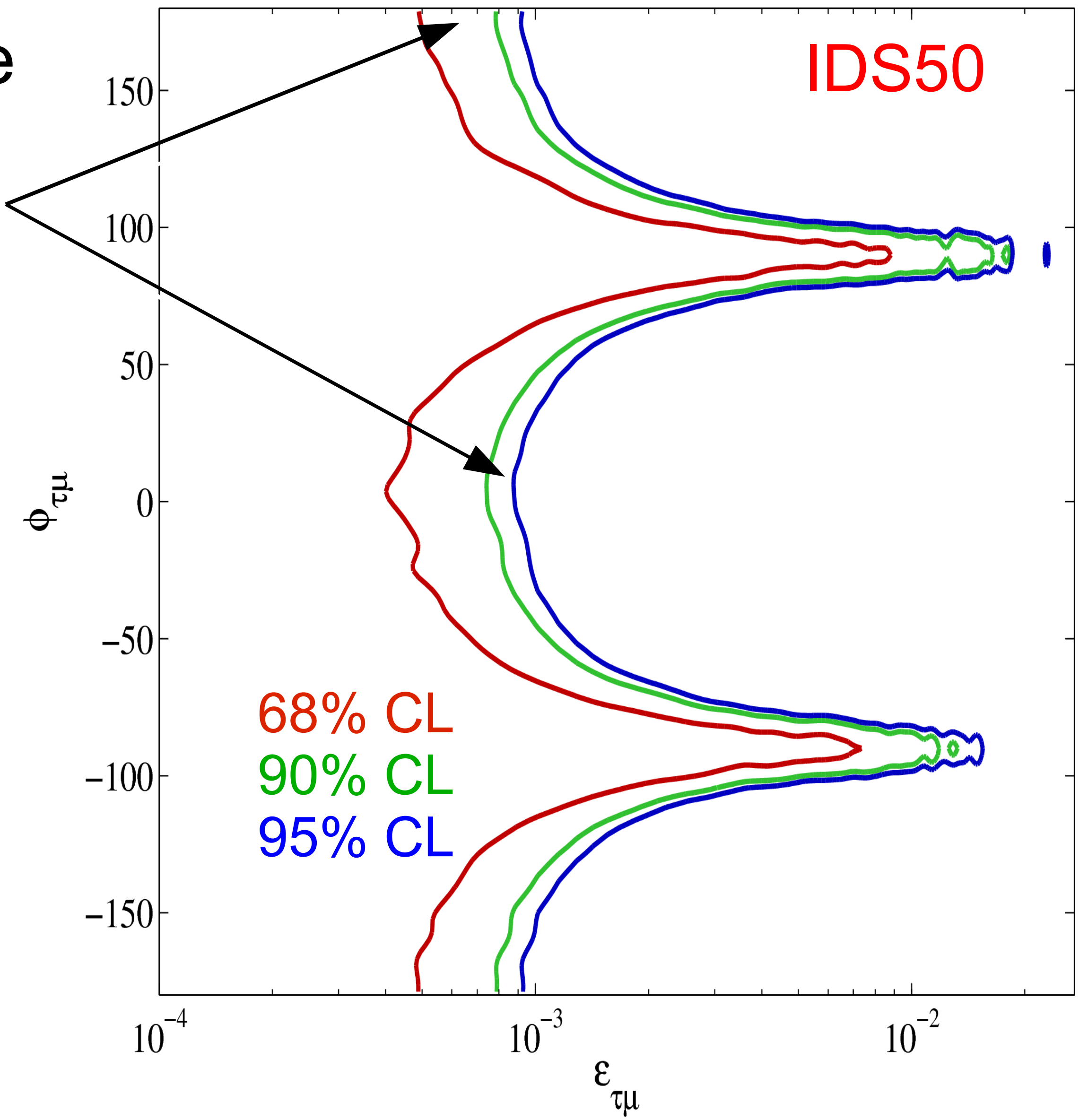
Independent of the set up

(Marginalization performed over all standard parameters)

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

- Linear dependence on the real part:

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



(Marginalization performed over all standard parameters)

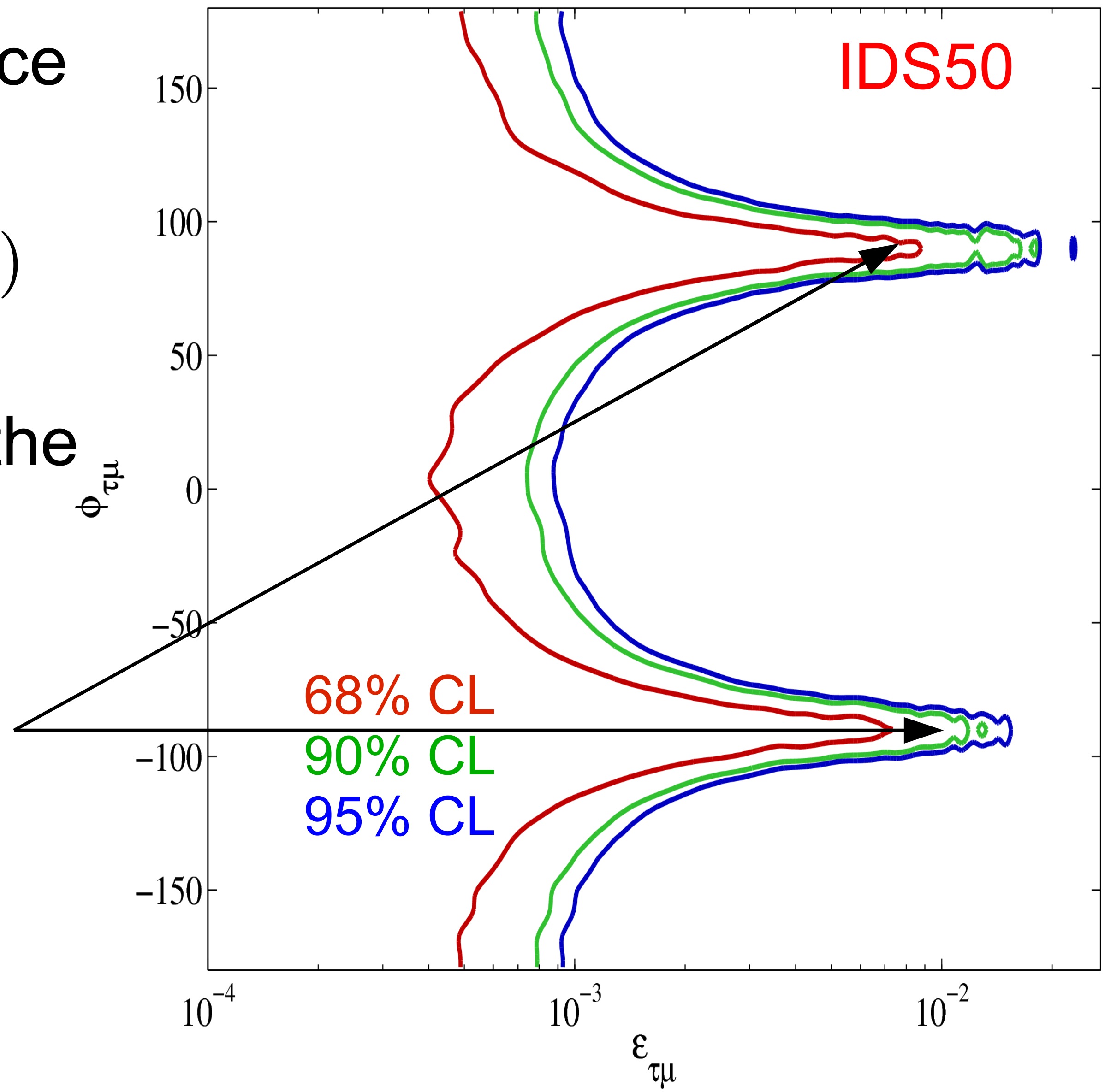
Sensitivity to $\epsilon_{\mu\tau}$

- Linear dependence on the real part:

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

- Dependence on the imaginary part through 2[nd] order terms:

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



(Marginalization performed over all standard parameters)

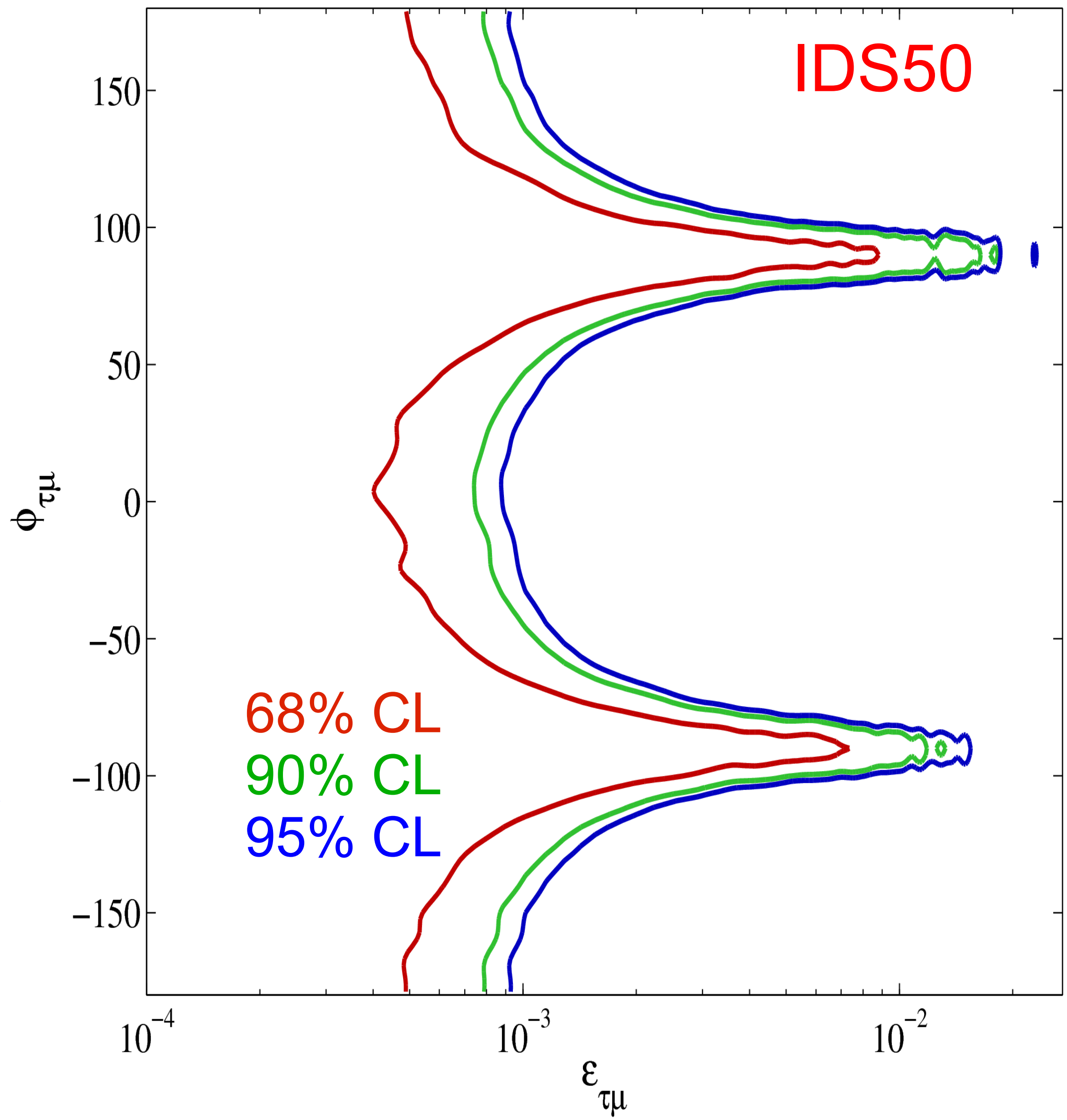
Sensitivity to $\epsilon_{\mu\tau}$

- Good news:

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

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

- Same result for all setups under study.



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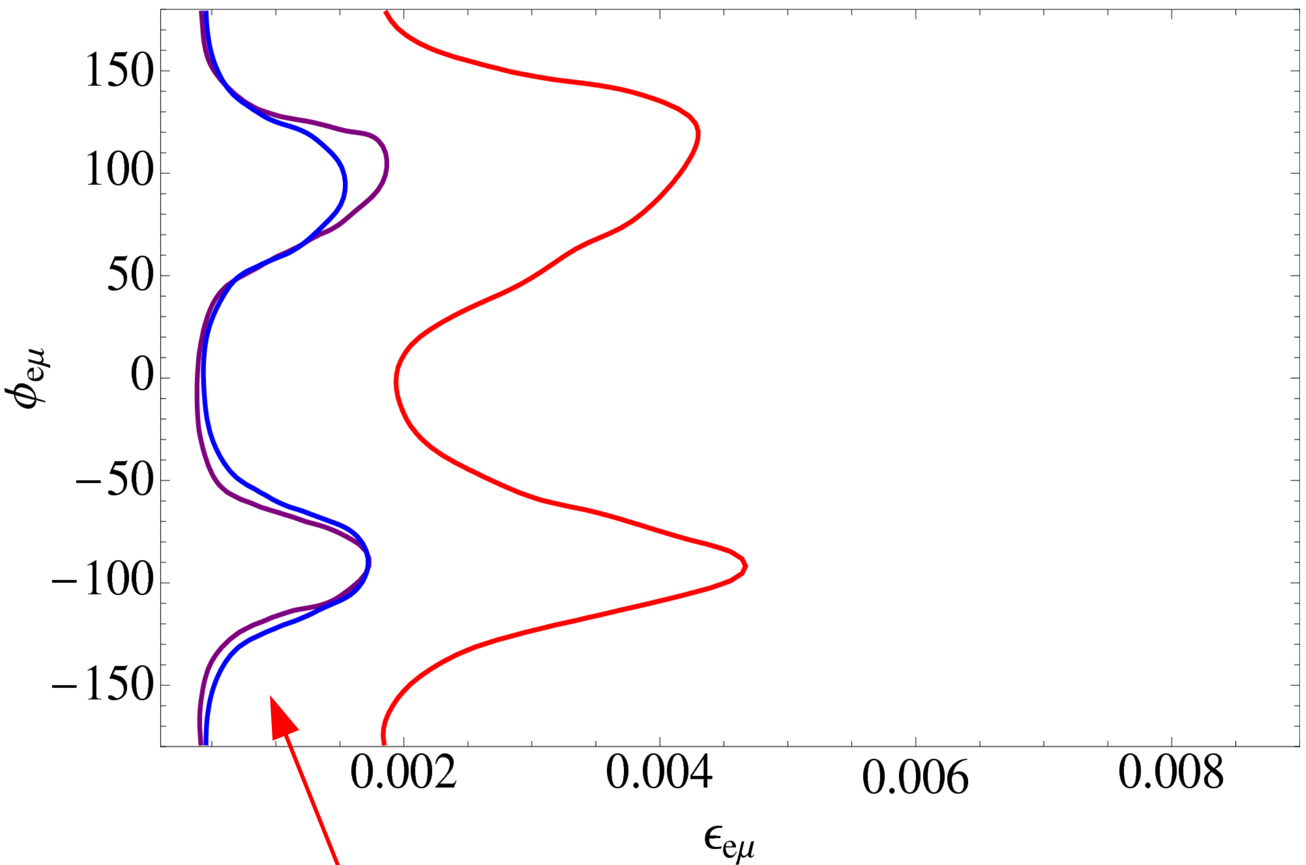
Sensitivity to $\epsilon_{e\mu}$, $\epsilon_{e\tau}$



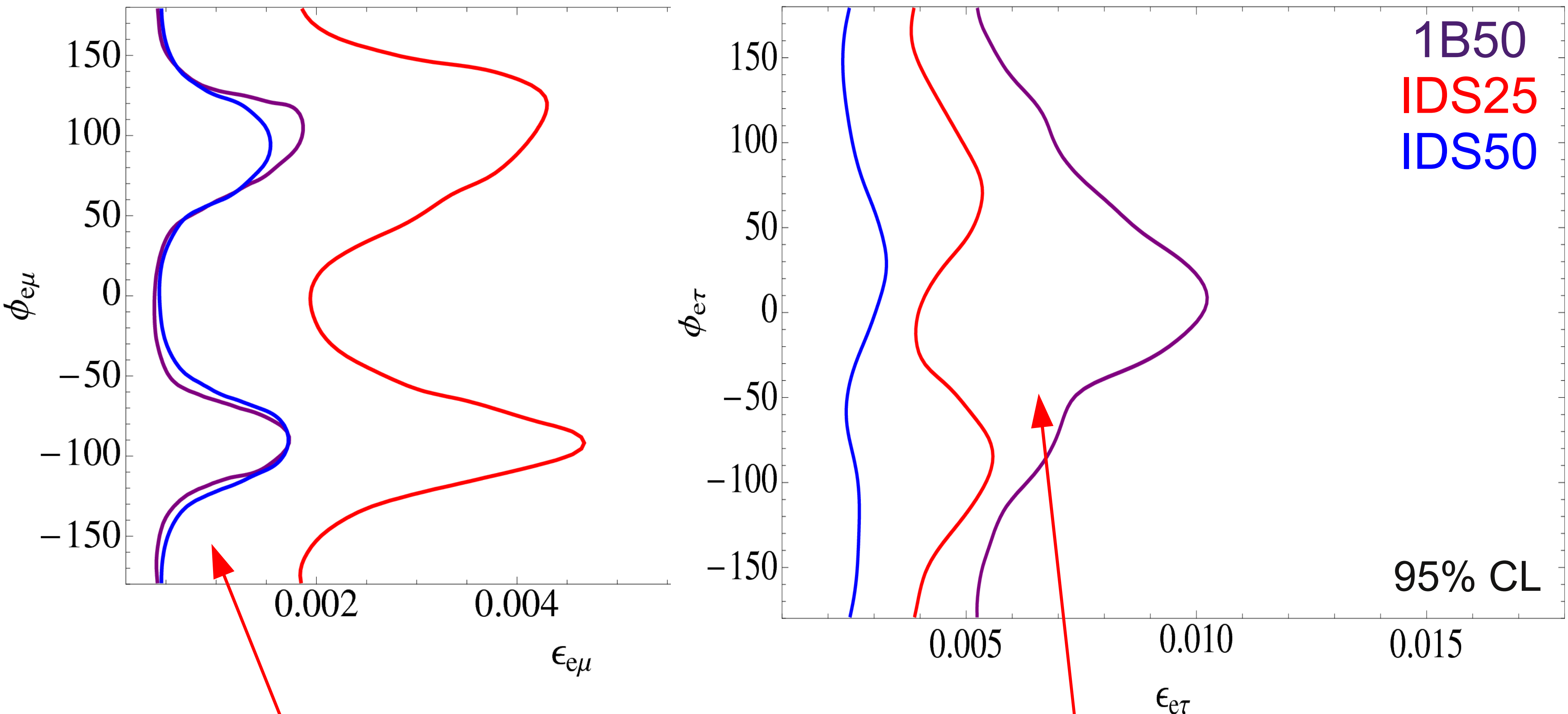
1B50
IDS25
IDS50

95% CL

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

(Marginalization performed over all standard parameters)

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



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

Key factor: combination of baselines

(Marginalization performed over all standard parameters)

New CP violation effects

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We have studied the region of the $(\delta, \phi_{e\mu}, \phi_{e\tau})$ parameter space for which a CP-violating signal can be distinguised from a CP-conserving one.

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The result depends strongly on the input values of θ_{13}, $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$. We distinguiss 2 cases:

- $\theta_{13} > 3°$, such that it can be tested at T2K and/or Double Chooz/Daya Bay. ⟶ We fix θ_{13}

- $\theta_{13} < 3°$, such that it can not be tested.
  ⟶ We marginalize over θ_{13}

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New CP violation effects: $\epsilon_{e\mu} \approx \epsilon_{e\tau}$

$|\epsilon_{e\mu}| = |\epsilon_{e\tau}| = 10^{-2}$

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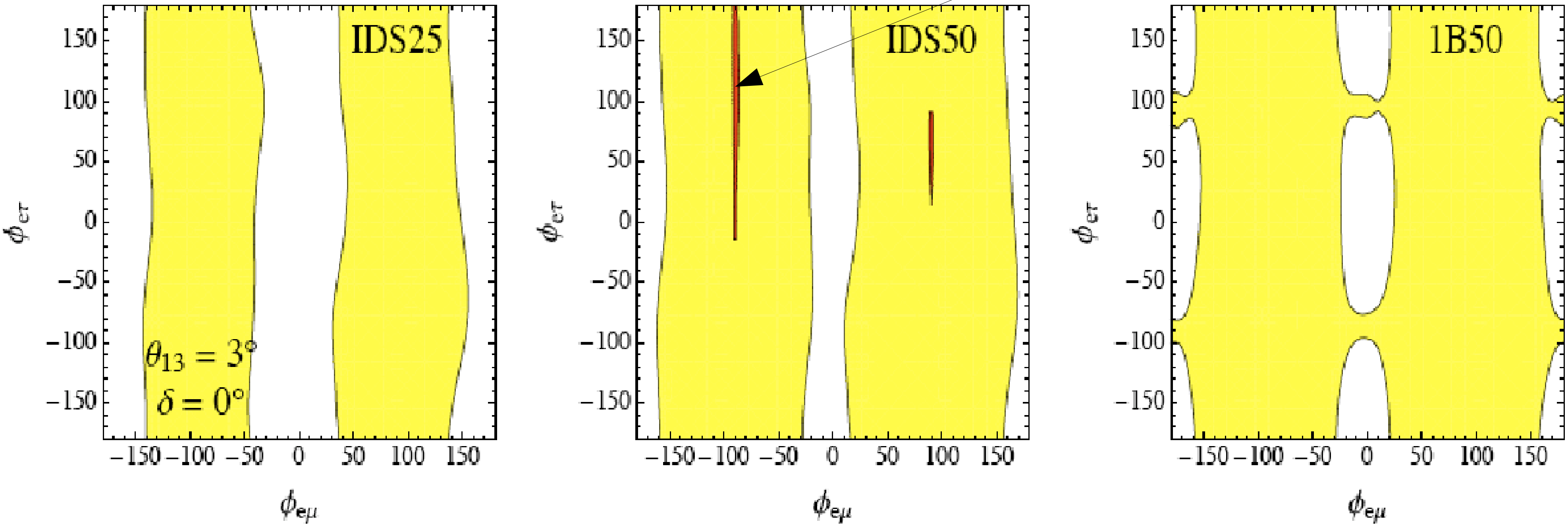

$\theta_{13} = 3^o$ $\delta = 0$

99 % CL .

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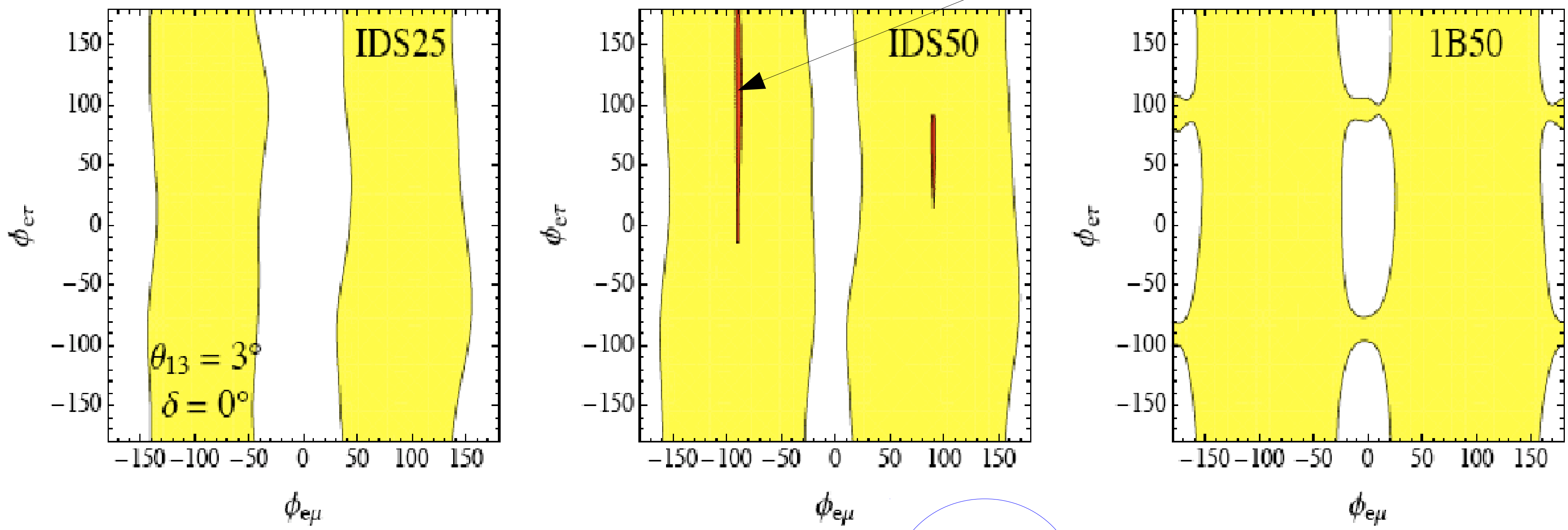

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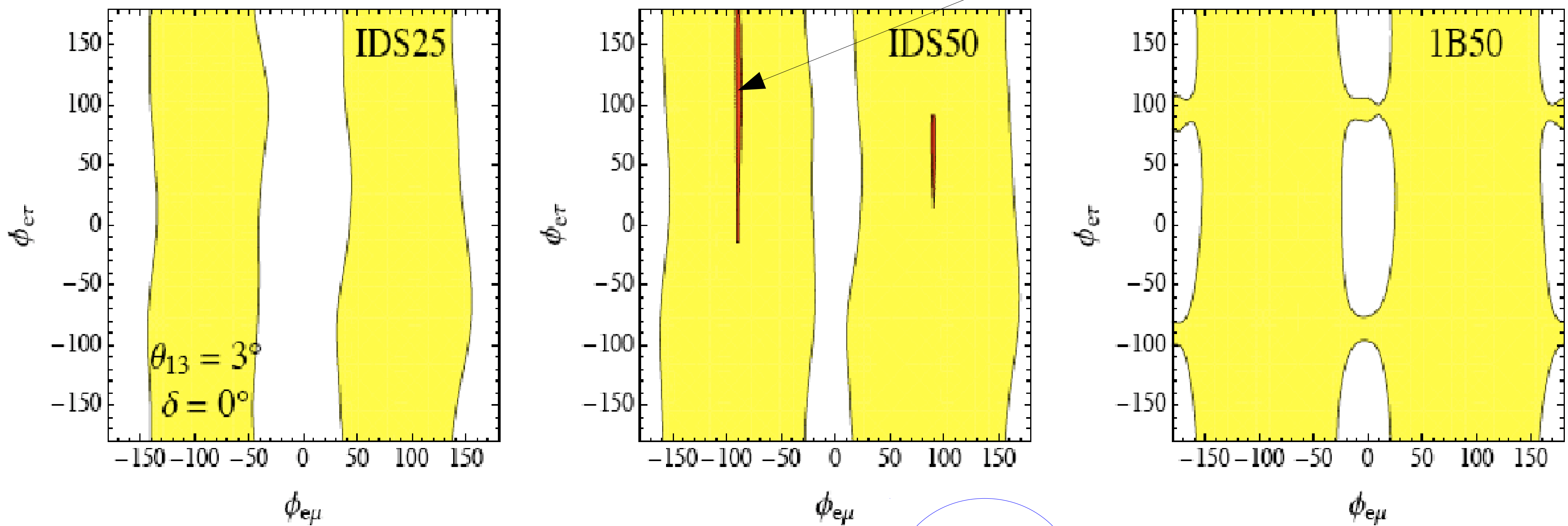

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Pure NSI CP violation effect !

$\epsilon_{e\mu}$ dominates over the rest $\epsilon_{\alpha\beta}$ ⟺ vertical bands

New CP violation effects

Easy to understand from oscillation probability:

$$
\begin{aligned}
P_{e\mu} \quad = \quad & \Bigg| A^{SM}_{e\mu} + \\
& + \epsilon_{e\mu} \left[\sin\left(\frac{AL}{2}\right) e^{-i\frac{\Delta_{31}L}{2}} + \left(\frac{A}{\Delta_{31}-A}\right) \sin\left(\frac{\Delta_{31}-A}{2}L\right) \right] \\
& - \epsilon_{e\tau} \left[\sin\left(\frac{AL}{2}\right) e^{-i\frac{\Delta_{31}L}{2}} - \left(\frac{A}{\Delta_{31}-A}\right) \sin\left(\frac{\Delta_{31}-A}{2}L\right) \right] \Bigg|^2
\end{aligned}
$$

partial cancelation

New CP violation effects: $\epsilon_{e\mu} \ll \epsilon_{e\tau}$

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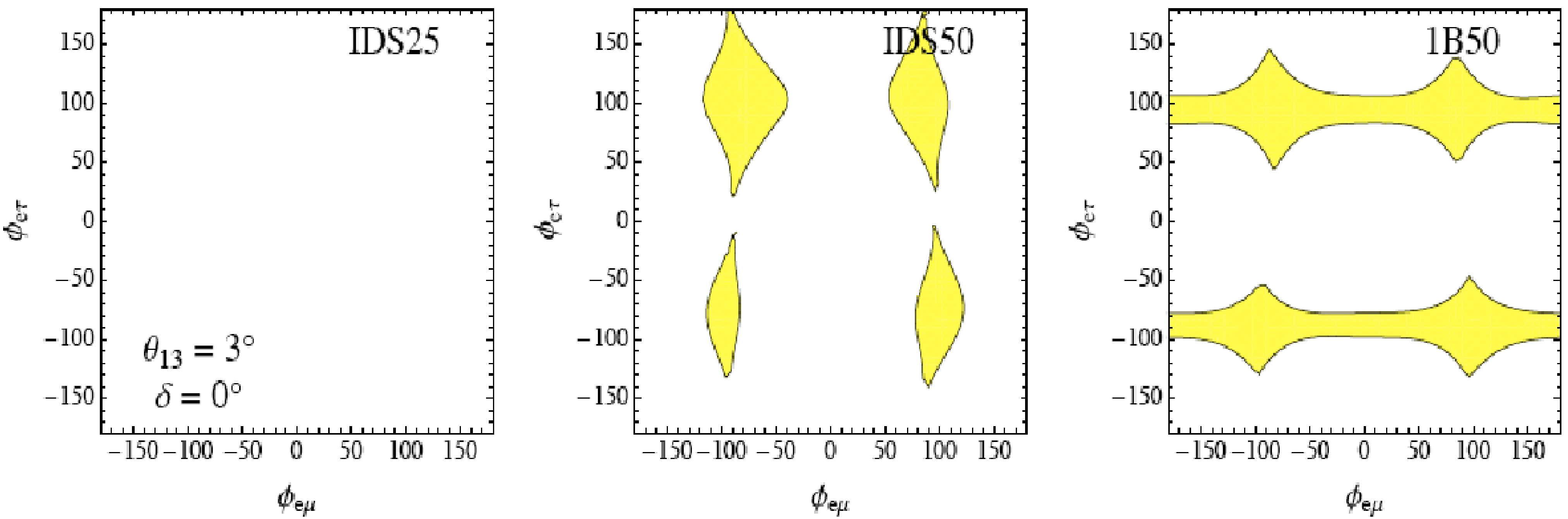

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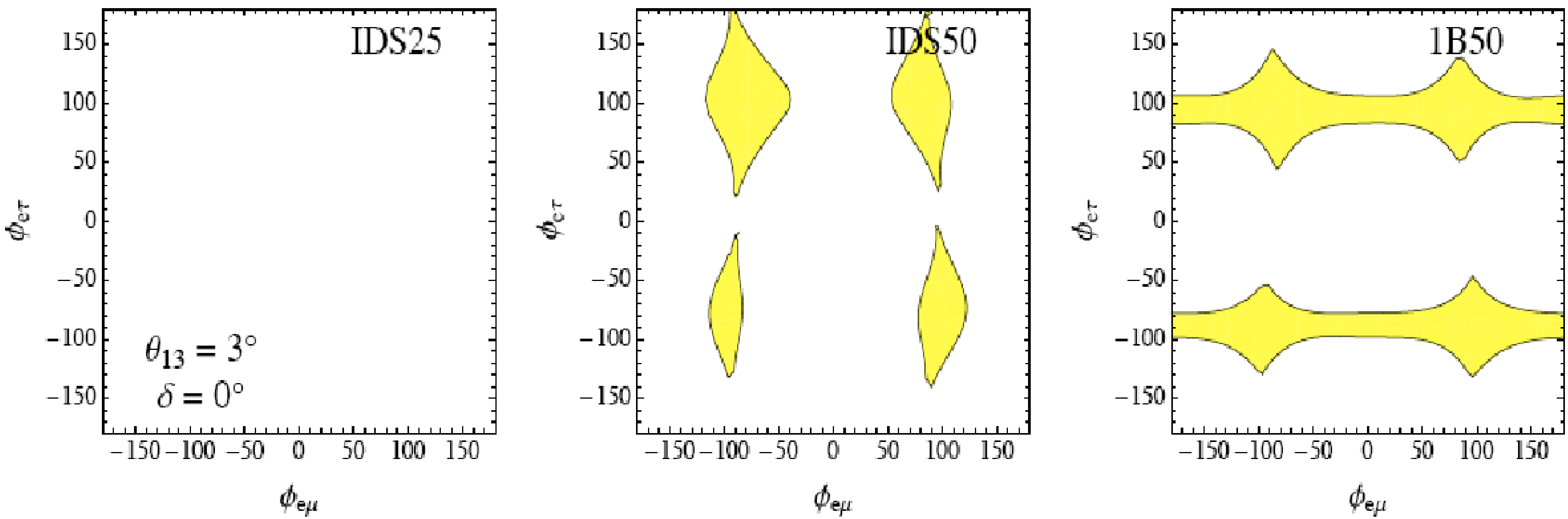
$|\epsilon_{e\mu}| = 10^{-3}$ $|\epsilon_{e\tau}| = 10^{-2}$ The NSI parameters are competitive



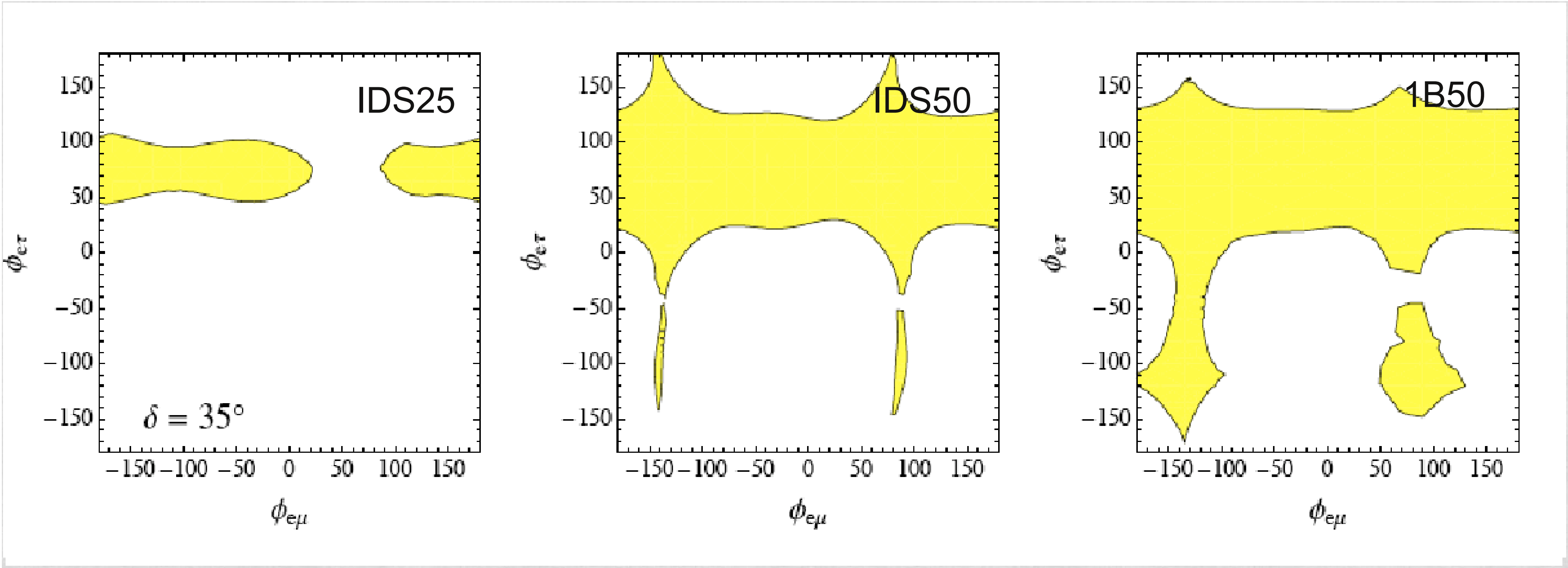
$\theta_{13} = 3^o$ $\delta = 0$

99 % CL .

Pure NSI CP violation effect !

New CP violation effects: $\epsilon_{e\mu} \ll \epsilon_{e\tau}$

$|\epsilon_{e\mu}| = 10^{-3}$ $|\epsilon_{e\tau}| = 10^{-2}$



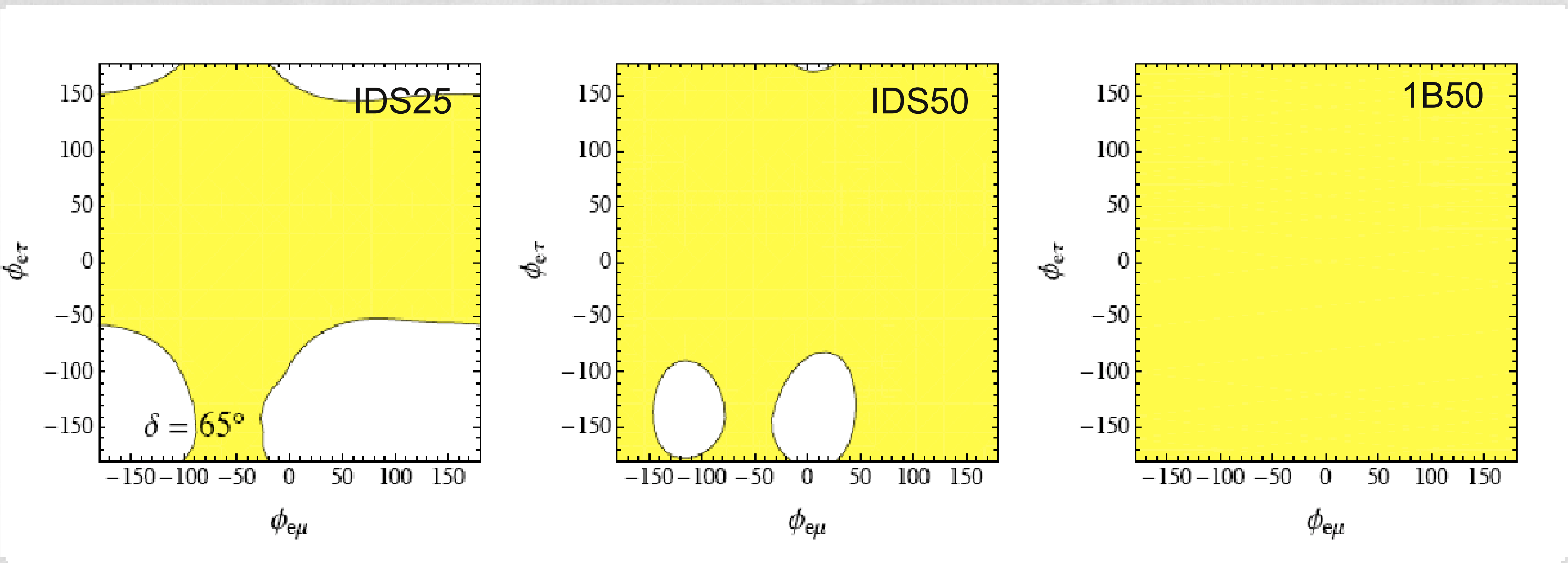
99 % CL .

$\theta_{13} = 3^o$ $\delta = 35$

The 3 CP-phases play the game

New CP violation effects: $\epsilon_{e\mu} \ll \epsilon_{e\tau}$

$|\epsilon_{e\mu}| = 10^{-3}$ $|\epsilon_{e\tau}| = 10^{-2}$



99 % CL .

$\theta_{13} = 3^o$ $\delta = 65$

Standard CP violation effect dominates over NSI effects

Conclusions

- NSI affect θ_{13} sensitivity:
  - Strong correlation with $\epsilon_{e\mu},\ \epsilon_{e\tau}.$
  - No correlation with $\epsilon_{\mu\tau}$ and (almost) $\epsilon_{\alpha\alpha};$

- Sensitivity to diagonal NSI parameters:
  - Sizable effects due to $\delta\theta_{23} \neq 0, \theta_{13} \neq 0;$
  - No correlation with non diagonal parameters
  - $(\epsilon_{ee} - \epsilon_{\tau\tau}) < 10^{-1}$ (limitated by matter uncertany)
  - $(\epsilon_{\mu\mu} - \epsilon_{\tau\tau}). < \mathcal{O}(10^{-2})$

- Sensitivity to off-diagonal NSI parameters:
  - $\epsilon_{e\mu}$: higher energies are the key
  - $\epsilon_{e\tau}$: the MB is the key (stronger correlations)
  - $\epsilon_{\mu\tau} < 10^{-3} - 10^{-2}$. Independent of the set up.

$\Big\}\ \mathcal{O}(10^{-3})$ (for $\epsilon_{e\mu}$, $\epsilon_{e\tau}$)

Conclusions

- CP violation:
  - CP violation exclusively due to NSI could be measured for reasonable input values of the NSI parameters. Even for $\theta_{13} = 0$
  - $\epsilon_{e\mu} \approx \epsilon_{e\tau}$. $\epsilon_{e\mu}$ dominates, correlations only between $\delta, \phi_{e\mu}$
  - $\epsilon_{e\mu} \ll \epsilon_{e\tau}$. More complex behaviour, involved correlations among 3 CP phases: $\delta, \phi_{e\mu}, \phi_{e\tau}$
- In general higher energies set ups perform better.

Thank you!

Back-up

New CP violation effects

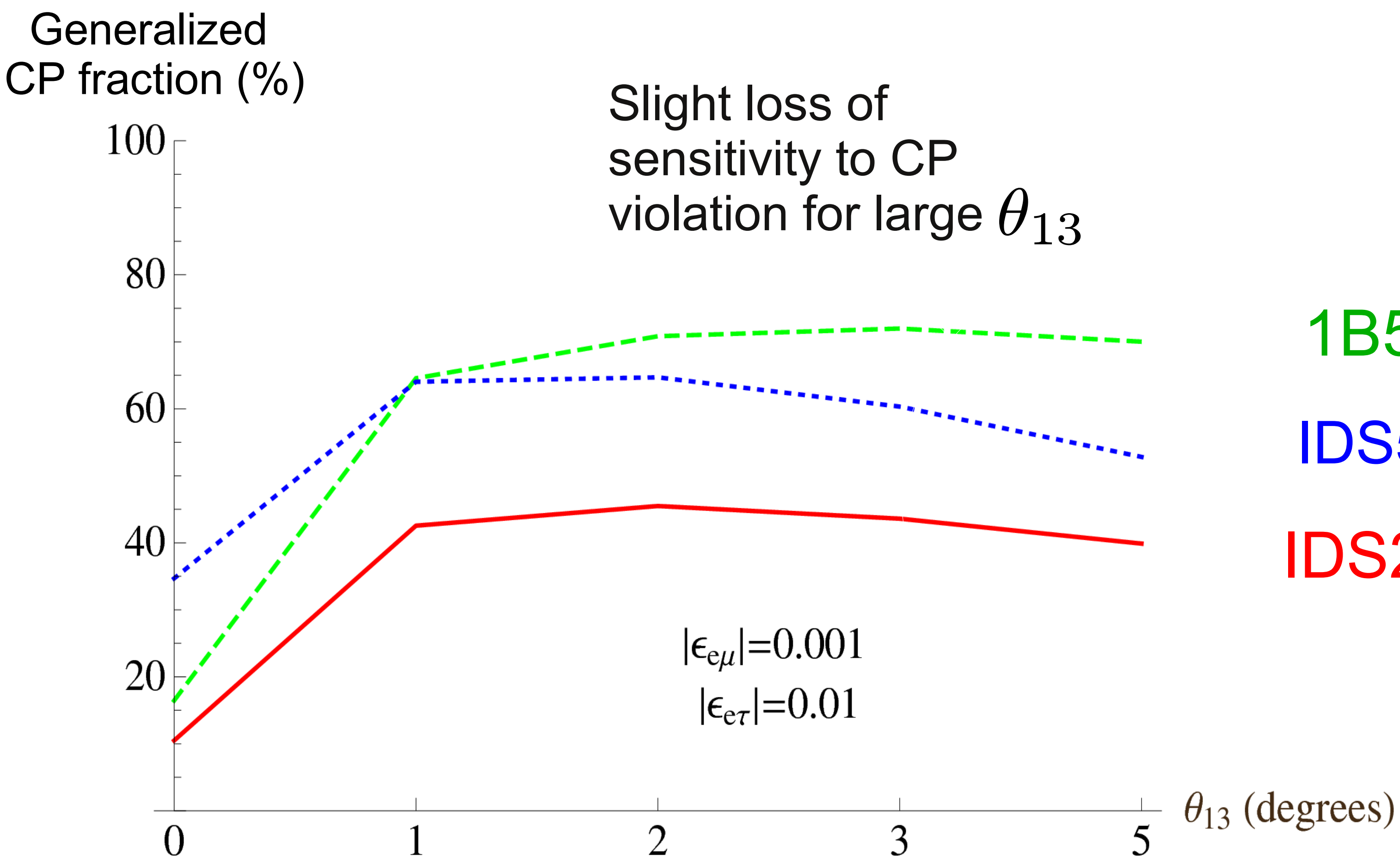
- We have measured the 3D CP discovery potential: the region of the $(\delta,\varphi_{e\mu},\varphi_{e\tau})$ parameter space for which a CP-violating signal can be distinguished from a CP-conserving one

- This corresponds to check if, given the input triple $(\delta,\varphi_{e\mu},\varphi_{e\tau})$, the χ^2 at the CP-conserving points $\{(0,0,0), (0,0,\pi), (0,\pi,0), (\pi,0,0), (0,\pi,\pi), (\pi,0,\pi), (\pi,\pi,0),(\pi,\pi,\pi)\}$ is larger than a given (3dof's) CL

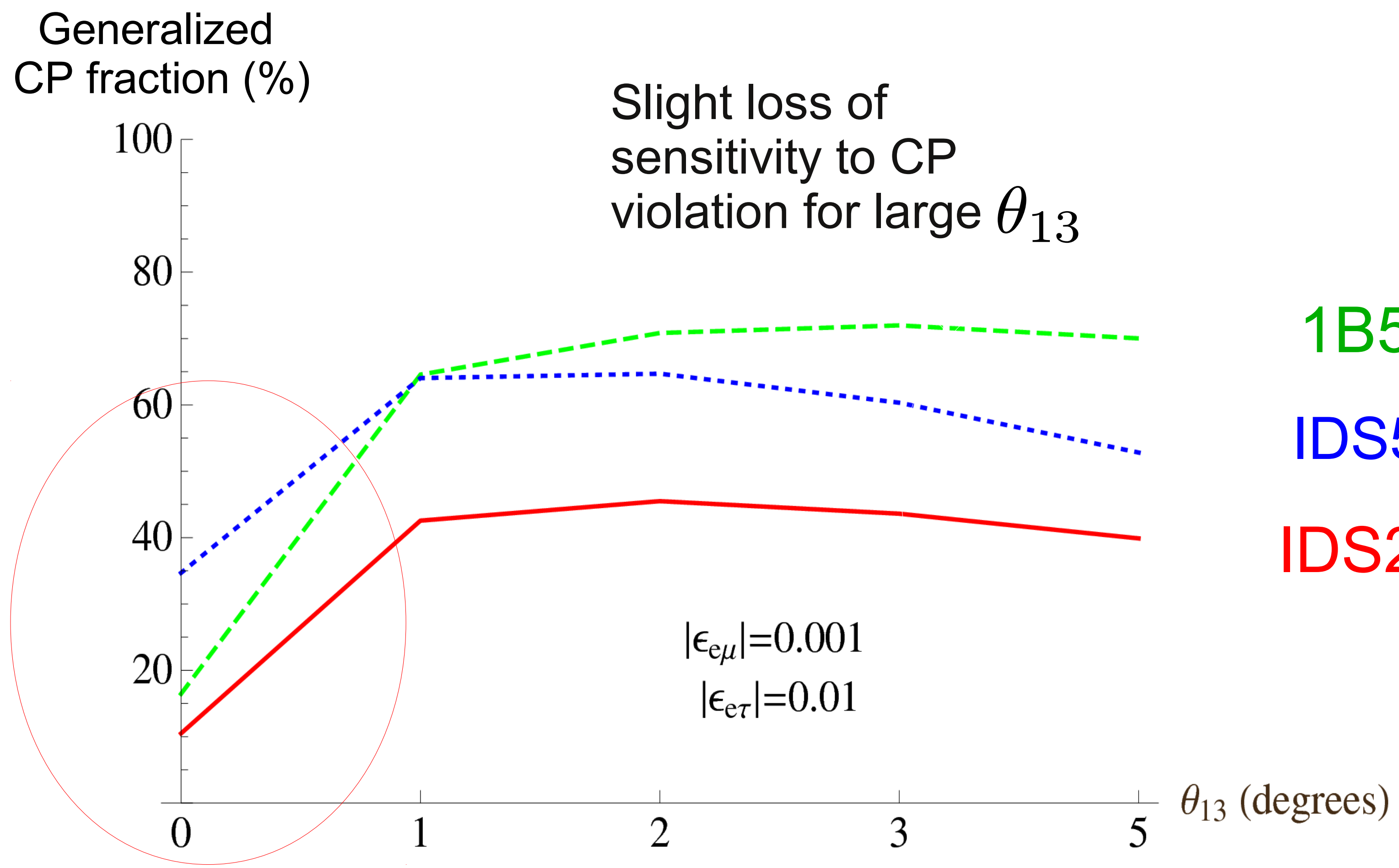
$$\chi^2_{CPC}(\theta_{13},\bar{\theta}_{13};\{\bar{\phi}\}) = \min_{\{\phi\}_{CPC}} \left(\chi^2(\theta_{13},\bar{\theta}_{13};\{\phi\}_{CPC},\{\bar{\phi}\})\right)$$

W. Winter, Phys. Lett. B671 (2009) 77, arXiv:0808.3583

Generalized CP-fraction



Generalized CP-fraction

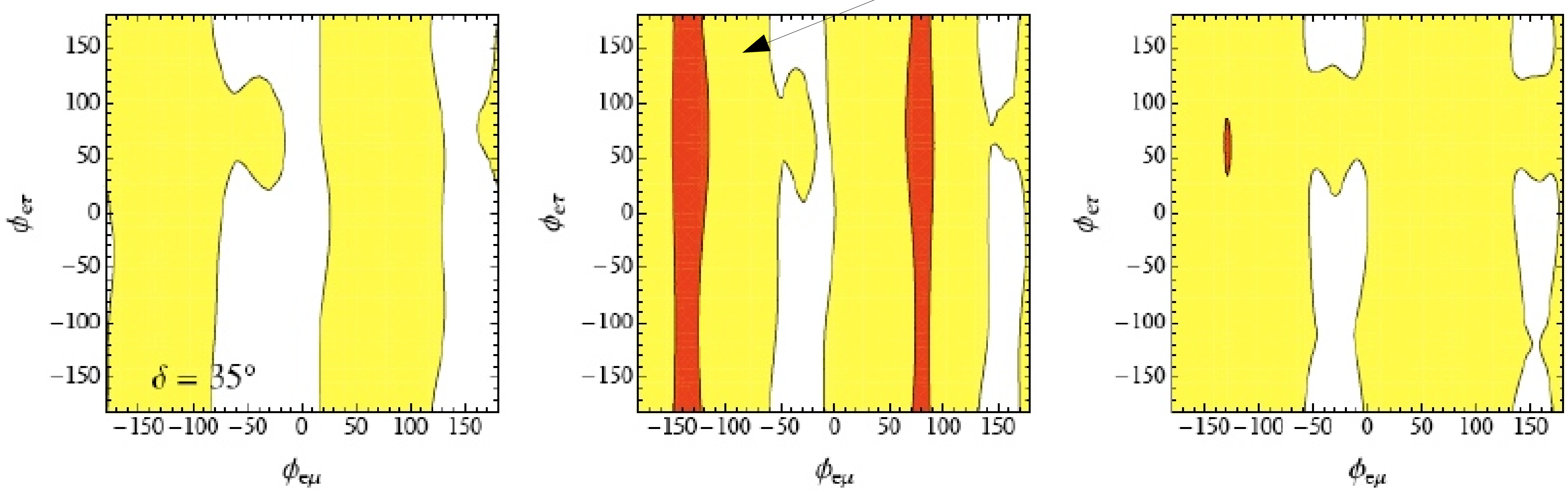


Non-zero CP fraction for vanishing θ_{13} !

New CP violation effects: $\epsilon_{e\mu} \approx \epsilon_{e\tau}$

$|\epsilon_{e\mu}| = |\epsilon_{e\tau}| = 10^{-2}$

$|\epsilon_{e\mu}| = |\epsilon_{e\tau}| = 10^{-3}$

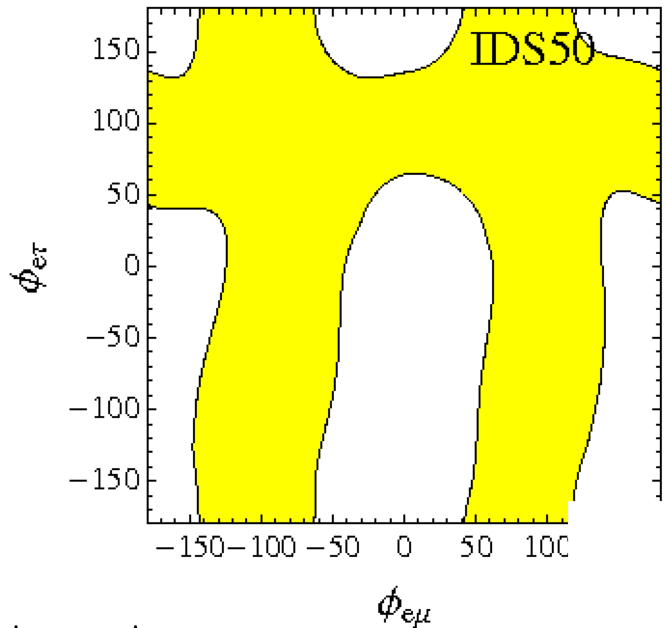


$\theta_{13} = 3^o$ $\delta = 35$

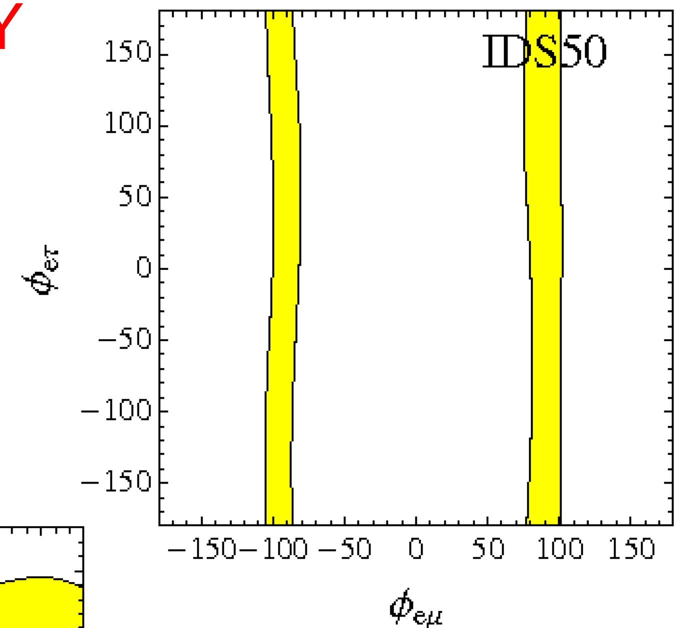
99 % CL .

New CP violation effects: $\theta_{13} = 0$

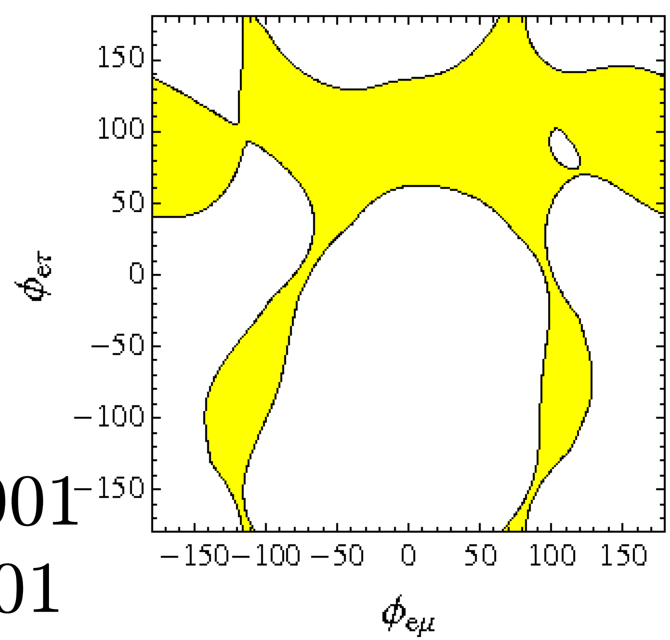
PRELIMINARY



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



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



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

99 % CL 2 d.o.f.
Marginalization performed over $\theta_{13},\ \delta$

Oscillation Probabilities

$$
\begin{aligned}
P_{\mu\mu}^{NSI} & = -P_{\mu\tau}^{NSI} = -\left\{\mathrm{Re}\left(\epsilon_{\mu\tau}\right)\right\}(AL)\sin\left(\Delta_{31}L\right) \\
- & \quad \delta\theta_{23}\left(\epsilon_{\mu\mu}-\epsilon_{\tau\tau}\right)\left[(AL)\sin\left(\Delta_{31}L\right)-4\tfrac{A}{\Delta_{31}}\sin^2\frac{\Delta_{31}L}{2}\right] \\
+ & \quad \left(\epsilon_{\mu\mu}-\epsilon_{\tau\tau}\right)^2\left(\tfrac{A}{\Delta_{31}}\right)^2\sin^2\frac{\Delta_{31}L}{2} \\
- & \quad \tfrac{1}{2}\left(\mathrm{Re}(\epsilon_{\mu\tau})\right)^2(AL)^2\cos\left(\Delta_{31}L\right) \\
- & \quad \left(\mathrm{Im}(\epsilon_{\mu\tau})\right)^2\tfrac{A}{\Delta_{31}}(AL)\sin\left(\Delta_{31}L\right)\ . \\
+ & \quad \mathcal{O}(\epsilon_{e\mu}^2)+\mathcal{O}(\epsilon_{e\mu}^2)+\mathcal{O}(\epsilon_{e\mu,\tau}\theta_{13})+\ldots
\end{aligned}
$$