MATTER NSI'S AT THE NEUTRINO FACTORY

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NSI'S

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

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NSI@production

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

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

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NSI@detection

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

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

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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

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

$$\nu_{\alpha}f \to \nu_{\beta}f$$

NEAR DETECTORS AND NSI'S

Near Detectors:

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

NSI@production

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

NSI@detection

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

NSI@propagation

$$\nu_\alpha f \rightarrow \nu_\beta f$$

NSI'S IN MATTER

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

Bounds on matter NSI's are rather weak

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

for neutral Earth-like matter

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

for neutral solar-like matter

E. Fernández Martínez, AIP Conf. Proc. 1222 (2010) 150

NSI'S IN MATTER

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

Diagonal sector

$$\begin{cases} P_{\alpha\beta}(\epsilon_{ee} - \epsilon_{\tau\tau}) \sim \mathcal{O}(\varepsilon^3)!! \\ P_{\alpha\beta}(\epsilon_{\mu\mu} - \epsilon_{\tau\tau}) \sim \mathcal{O}(\varepsilon^2) \end{cases}$$

Off-diagonal sector

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

T. Kikuchi, H. Minakata and S. Uchinami, arXiv:0809.3312

CORRELATIONS IN NSI'S

Matter NSI parameters have been studied
in many papers, even using the Neutrino Factory

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We want to study the correlations between them. To do this, we need to study MANY parameters at the same time

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This can be done using MonteCUBES, a MonteCarlo Markov Chain program built on top of GLOBES

M. Blennow and E. Fernández Martínez, arXiv:0903.3985

NSI'S AT THE NUFACT

- Long baseline
- High energies

Large matter effects!

NSI'S AT THE NUFACT

- Long baseline
- High energies

Large matter effects!

- Multi-channel facility

NSI'S AT THE NUFACT

- Long baseline
- High energies

$\Rightarrow$ **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

- Setup 1: The "baseline" IDS 25 GeV NF
- Setup 2: Higher energy: IDS 50 GeV NF
- Setup 3: One-baseline, 50 GeV NF; with tau-detector

IDS25 AND IDS50

- 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

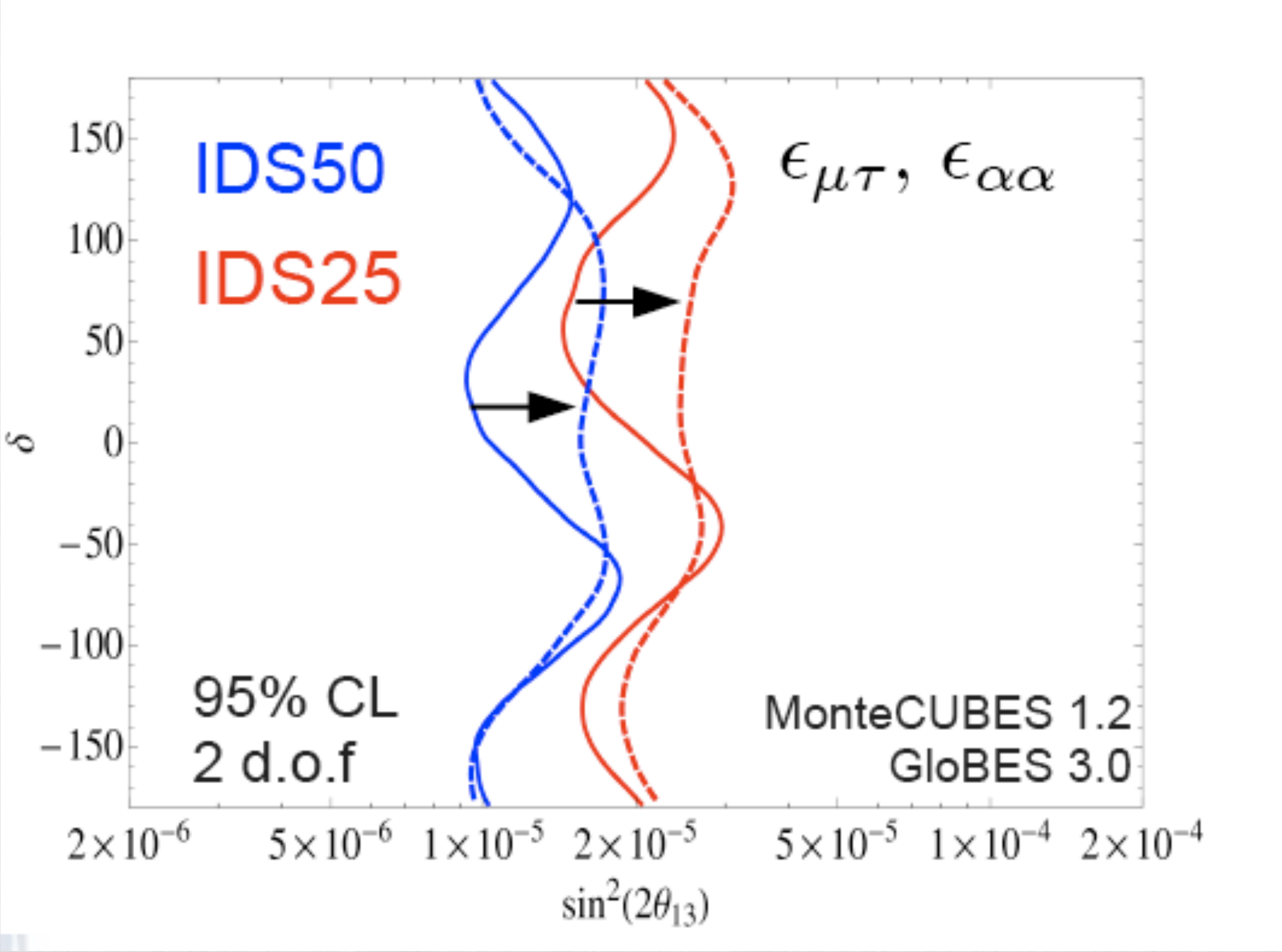
ONE BASELINE: 1B50

- 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

RESULTS

- (1) Impact of NSI on the sensitivity to θ_{13}
- (2) Sensitivity to $|\varepsilon_{\alpha\beta}|$
- (3) Study of the CP-violating phases $(\delta, \varphi_{e\mu}, \varphi_{e\tau})$ for $|\varepsilon_{e\mu}|, |\varepsilon_{e\tau}| < 10^{-2}$ (comparable to $\theta_{13} < 3°$): maximal correlation between the three phases!

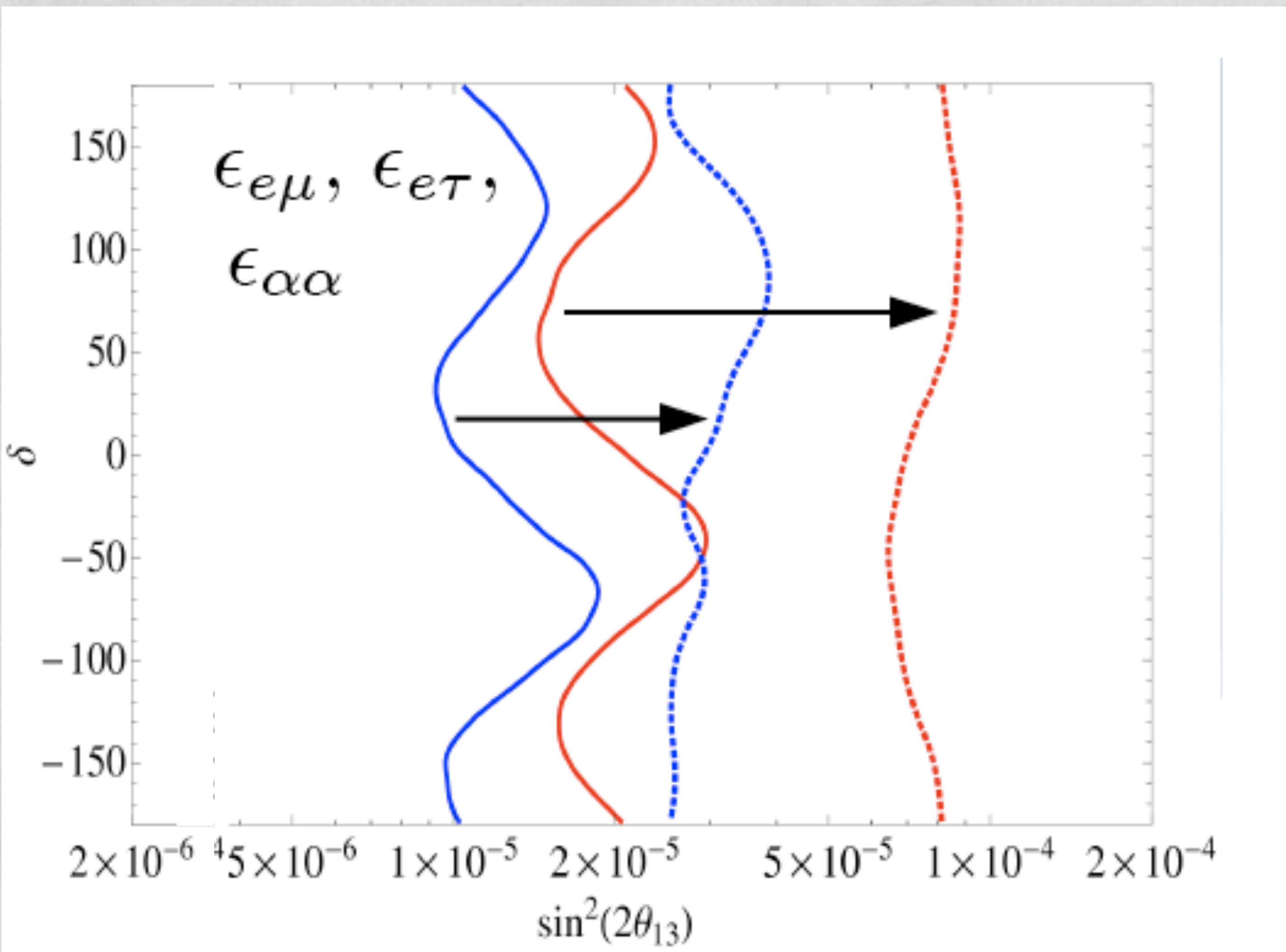
IMPACT ON Θ_{13}



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

(Marginalization performed over all standard parameters)

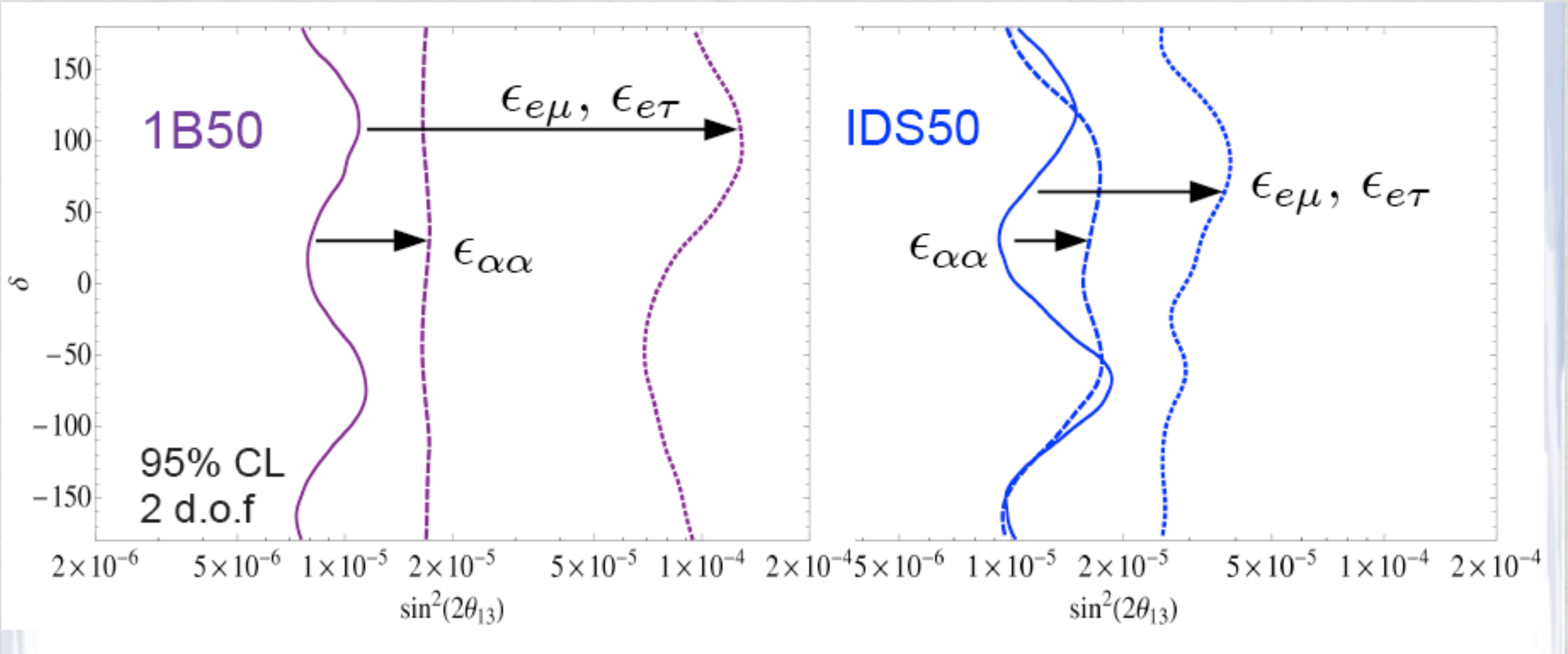
IMPACT ON Θ_{13}



Strong correlation due to simultaneous appearance in golden channel

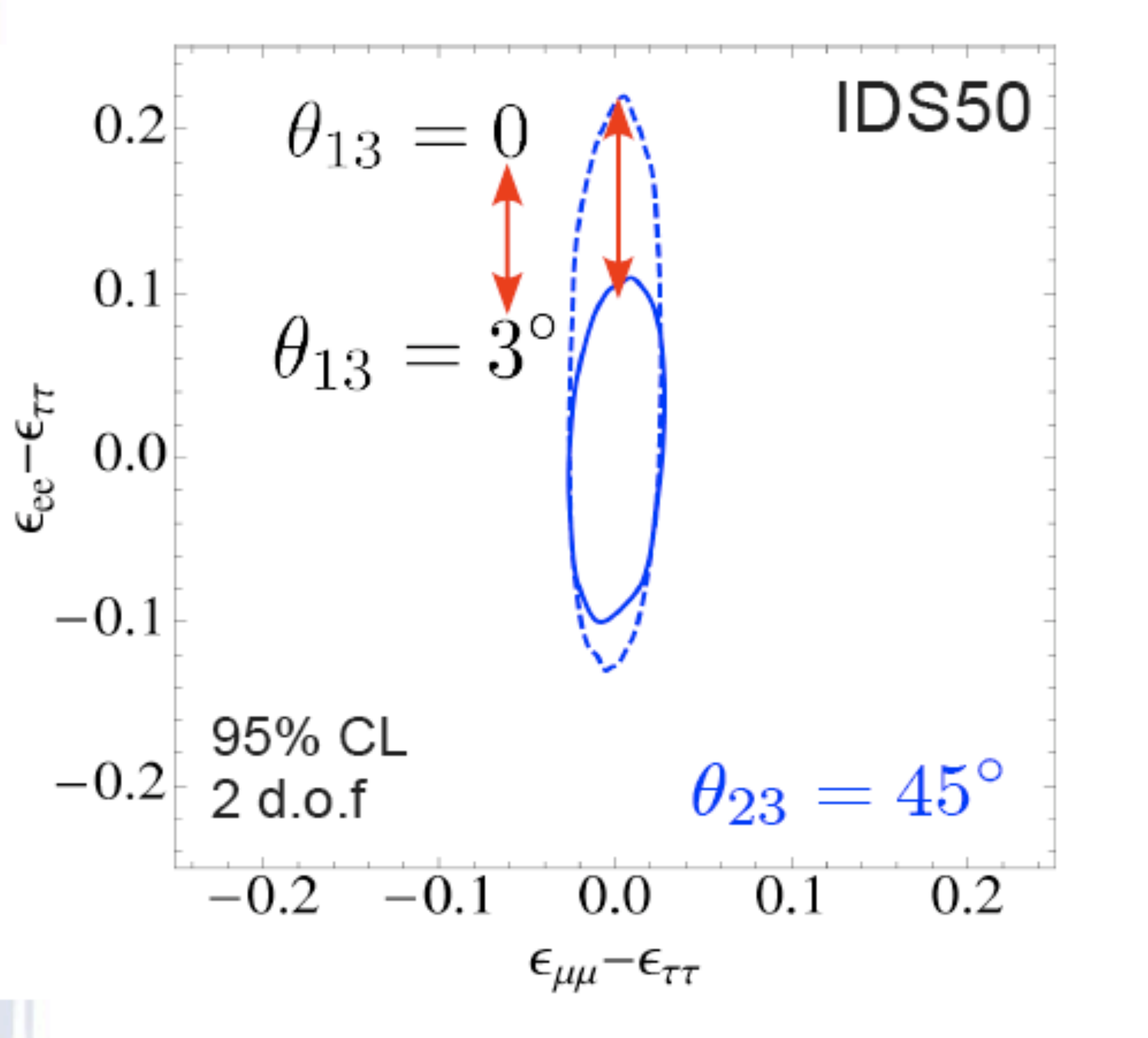
(Marginalization performed over all standard parameters)

IMPACT ON Θ13



As in the standard case, two baselines are better than two detectors

DIAGONAL PARAMETERS



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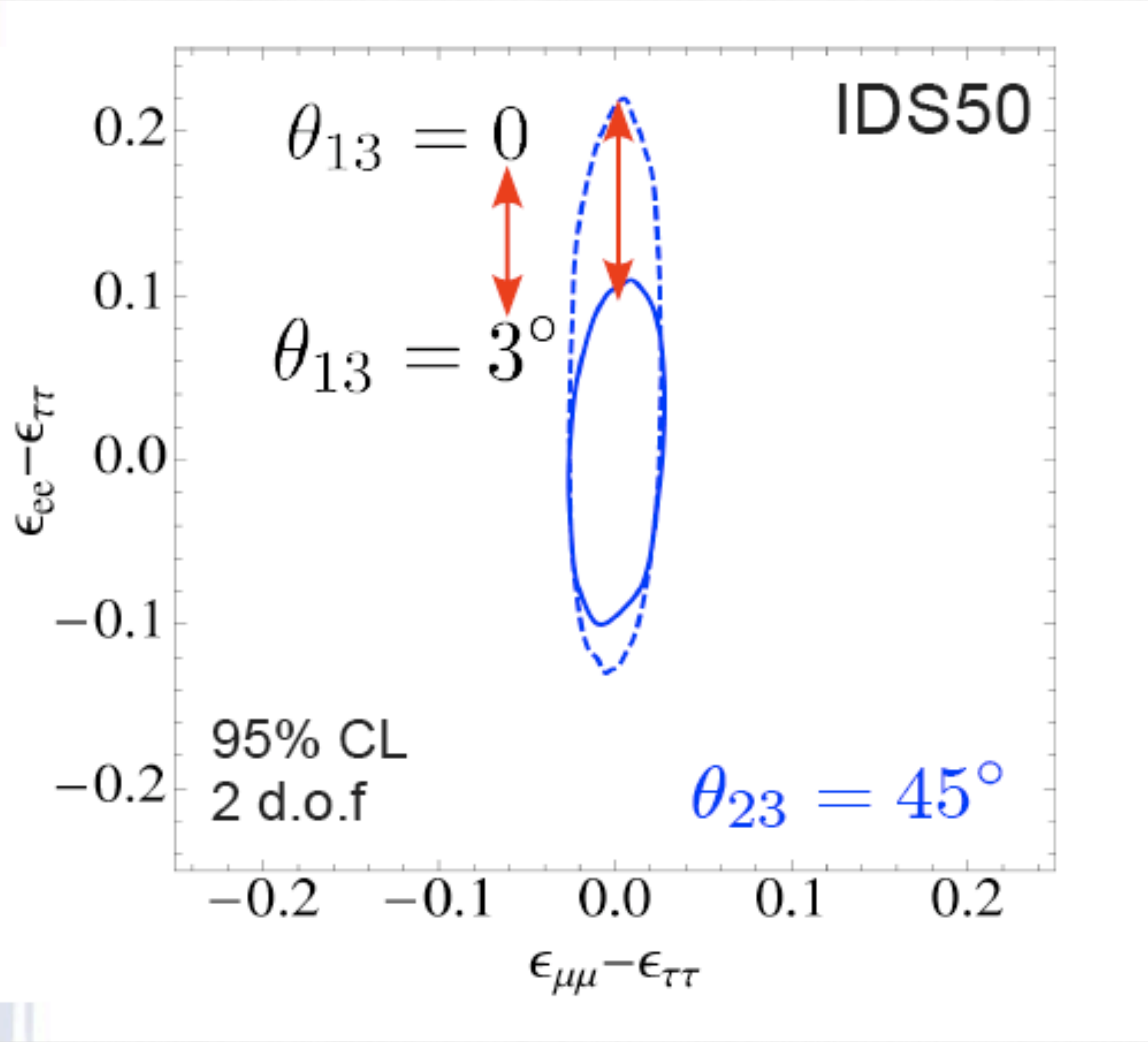
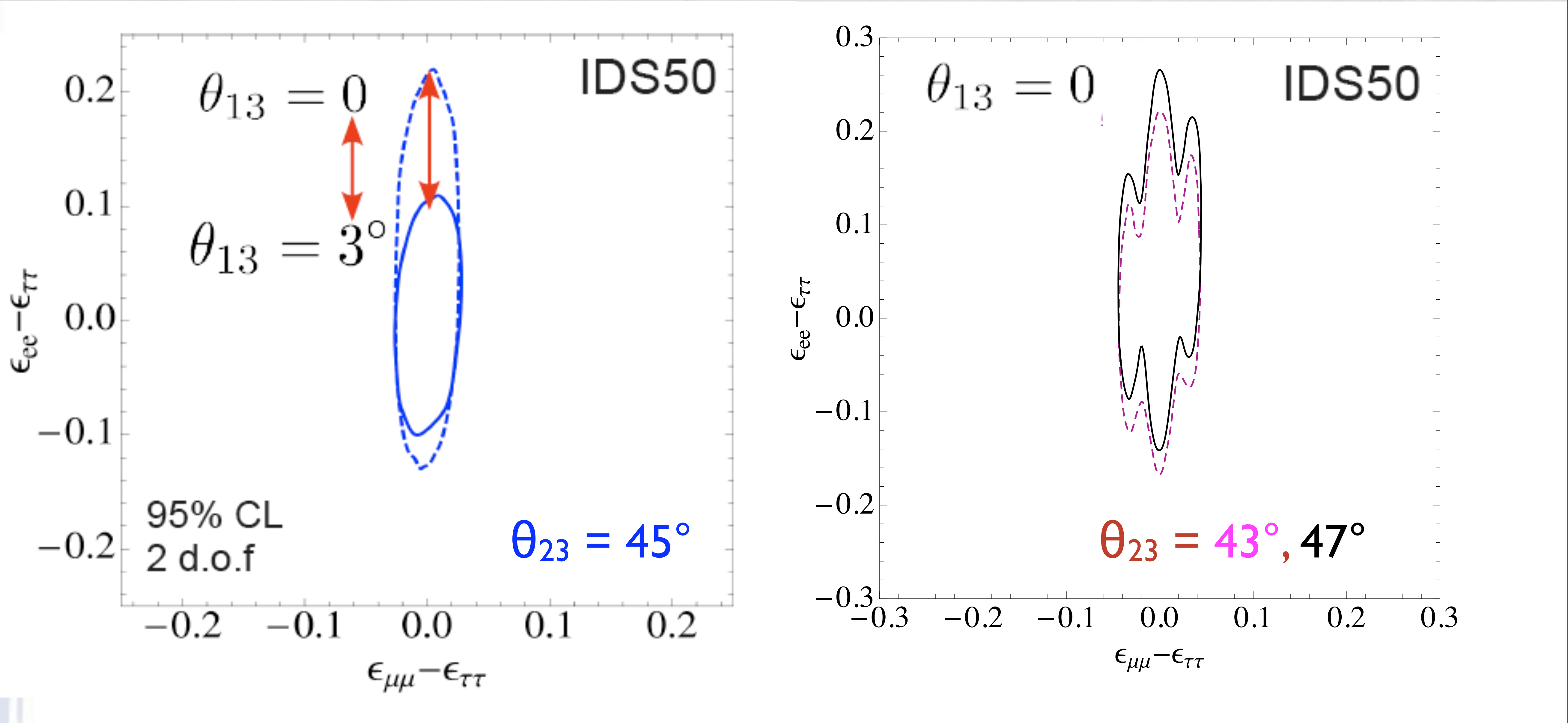
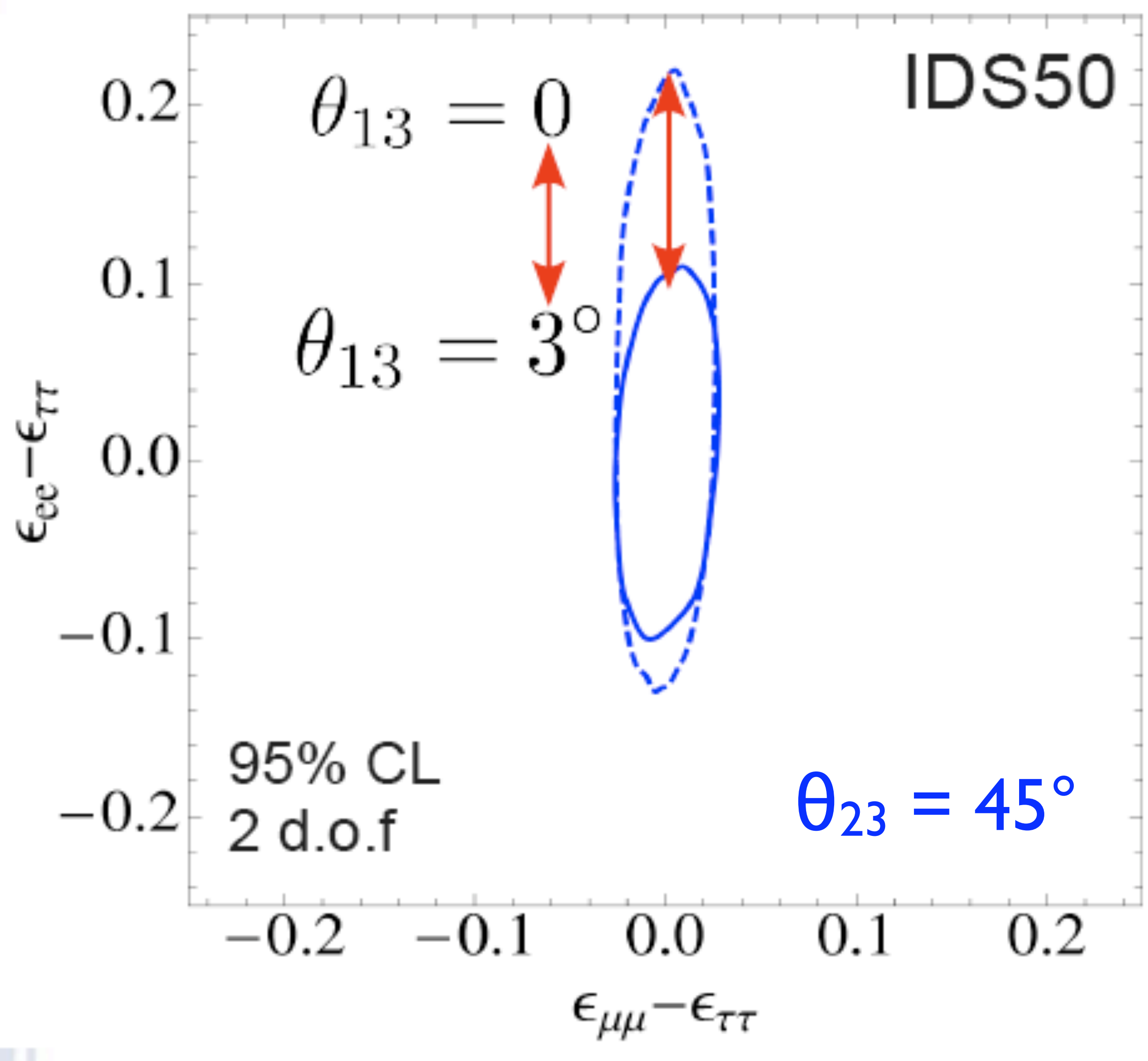


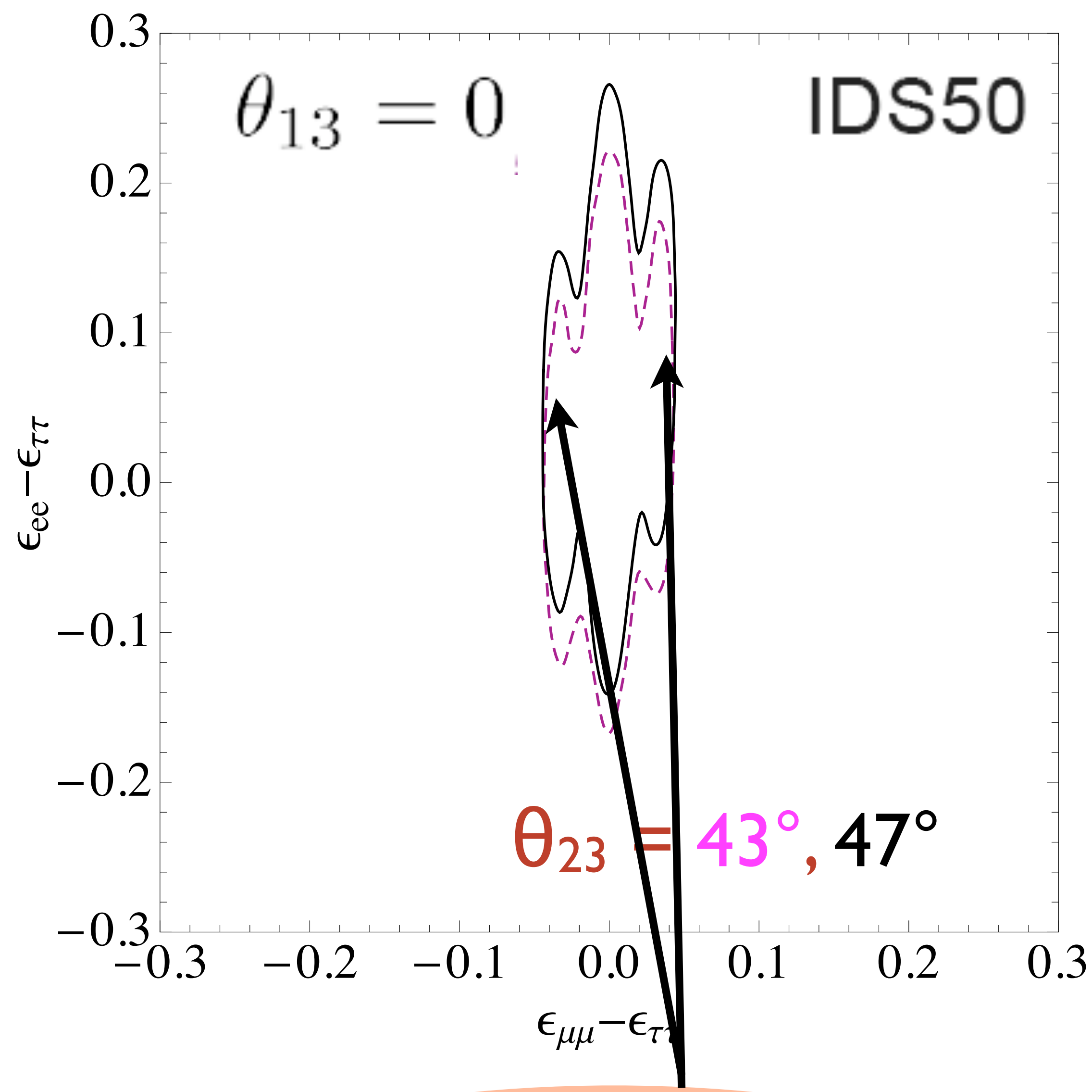
Sizable effect due to nonzero θ_{13}

DIAGONAL PARAMETERS



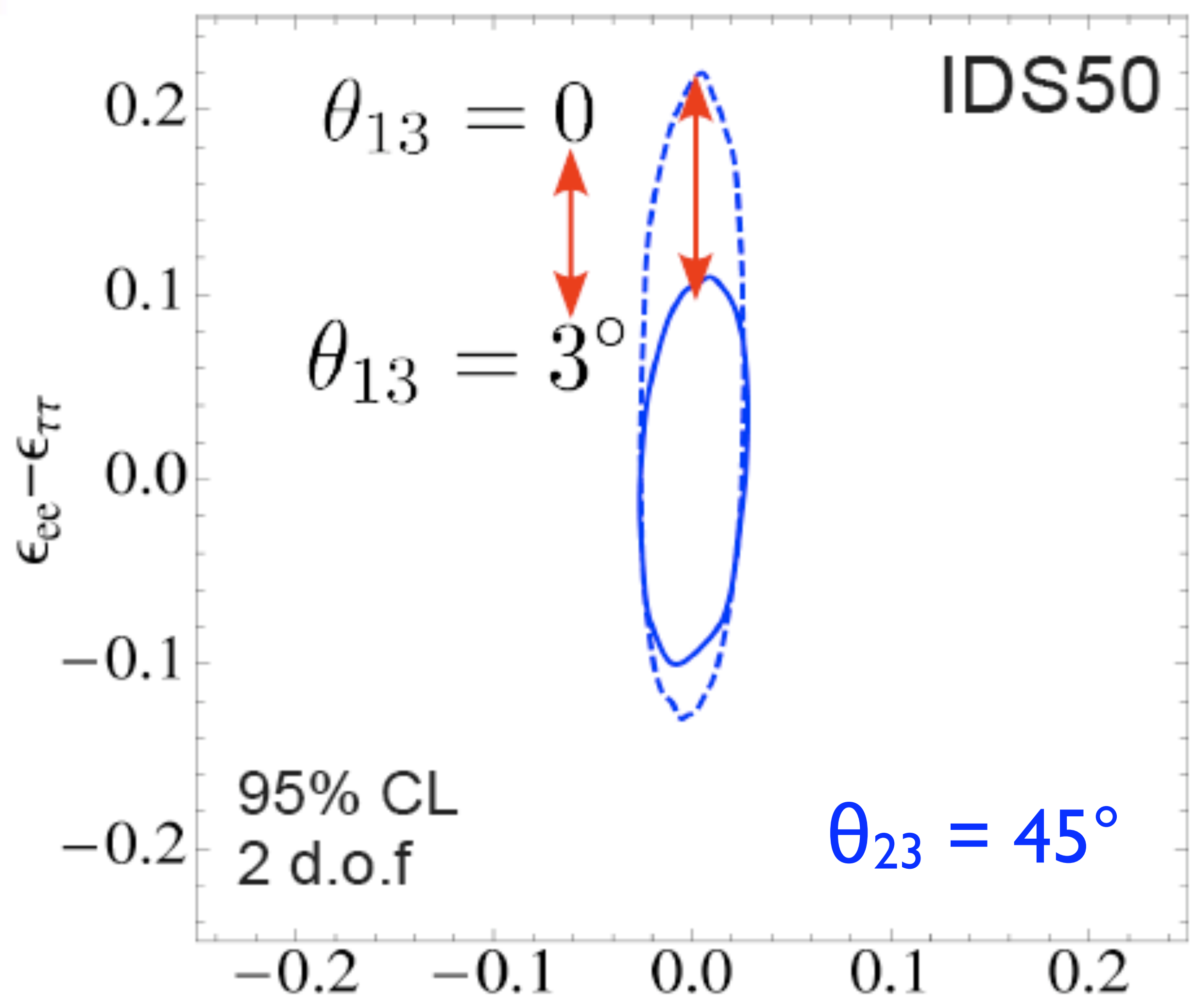
DIAGONAL PARAMETERS

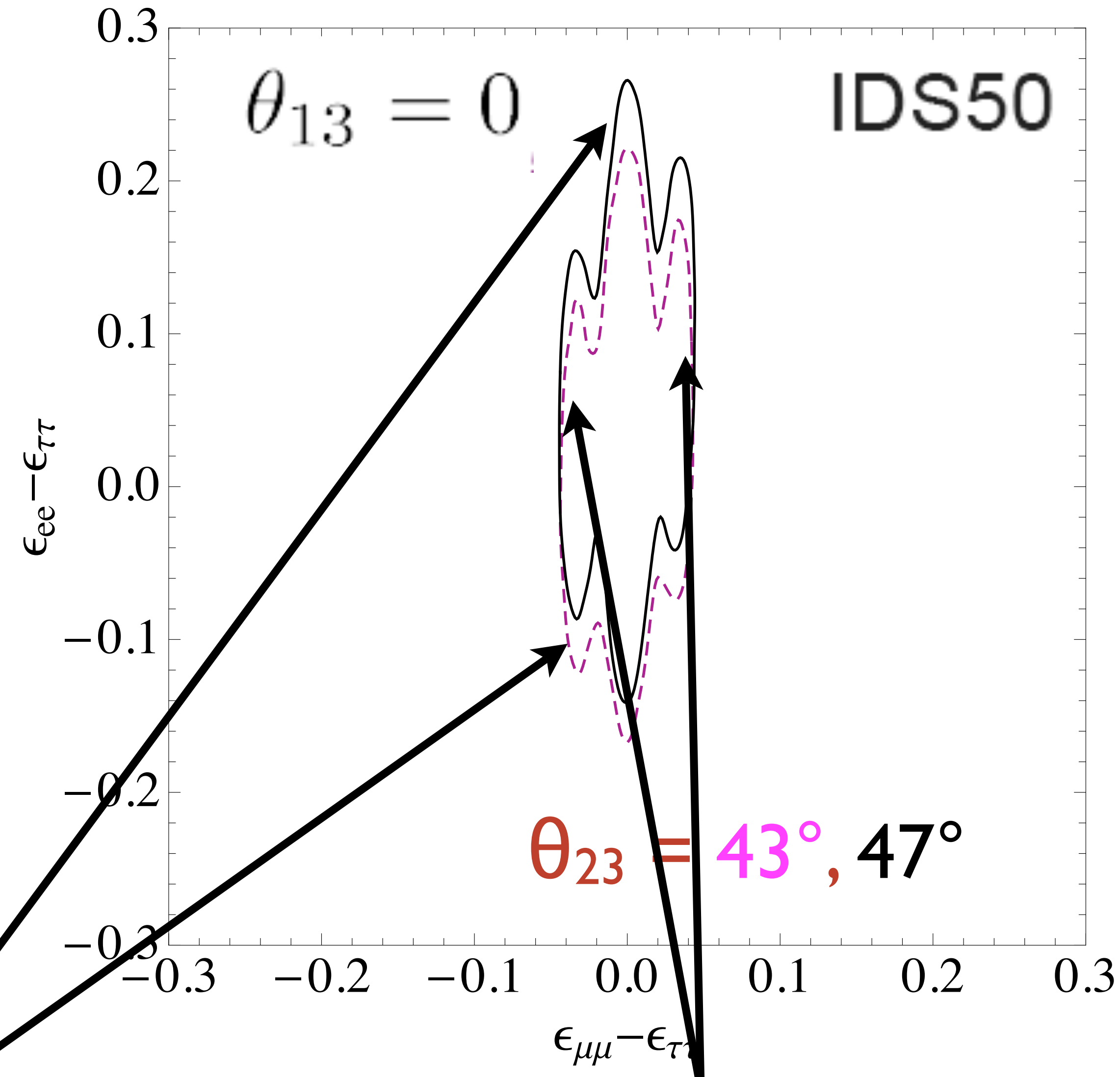




Effect due to the $\delta\theta_{23}$

DIAGONAL PARAMETERS





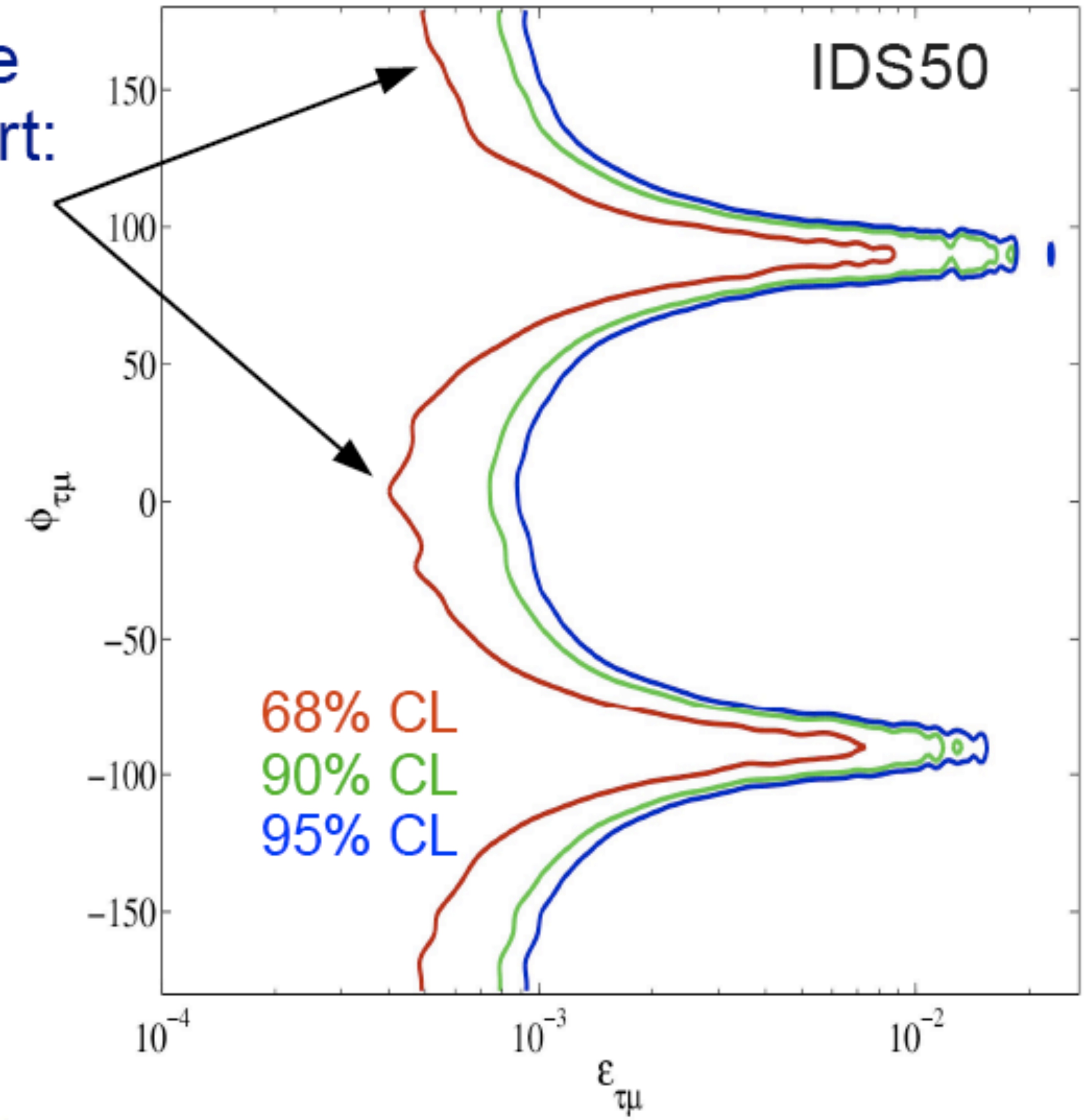
Effect due to the octant degeneracy

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

DISAPPEARANCE CHANNEL

- Linear dependence only on the real part:

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



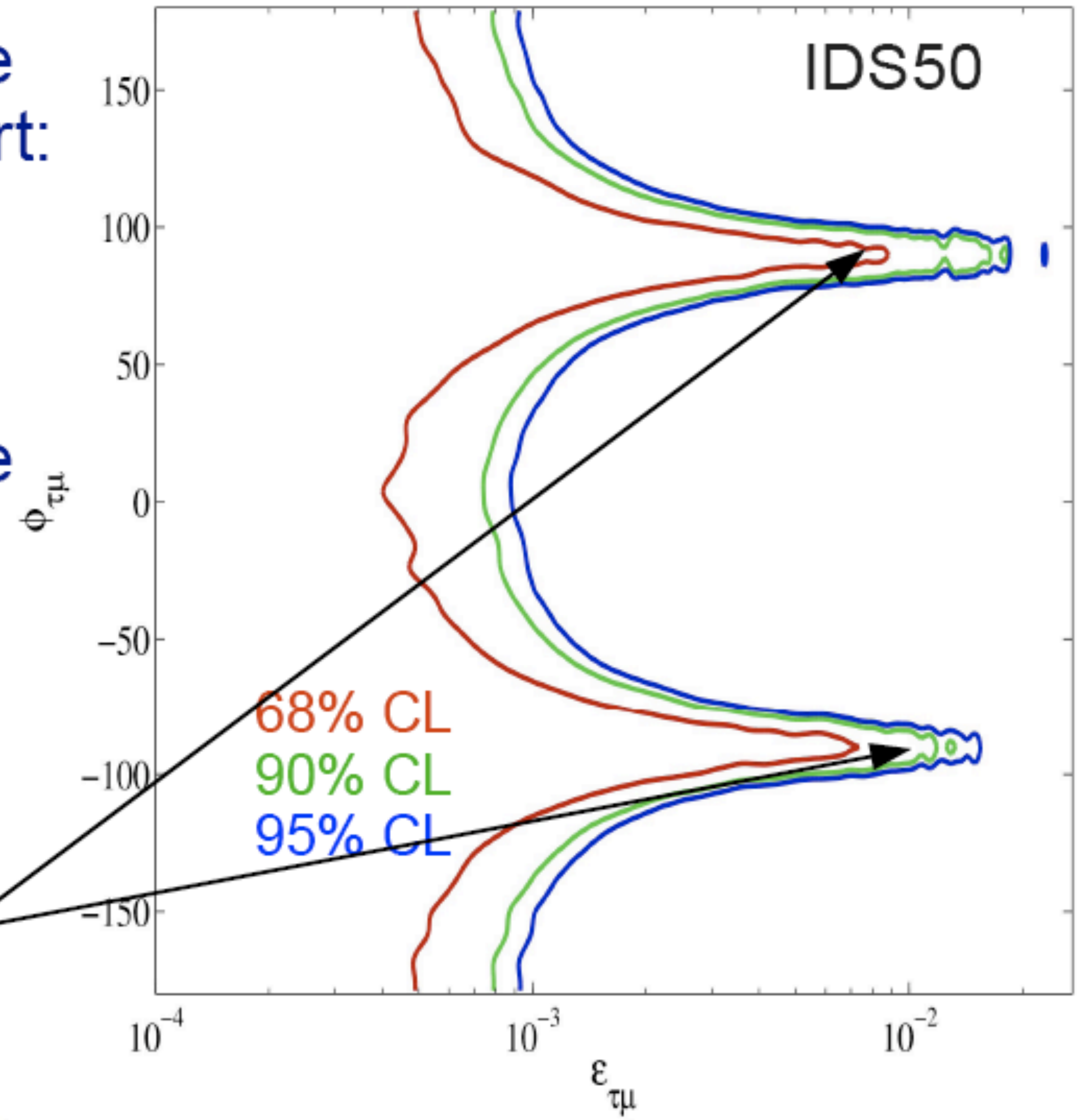
DISAPPEARANCE CHANNEL

- 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[nd] order terms:

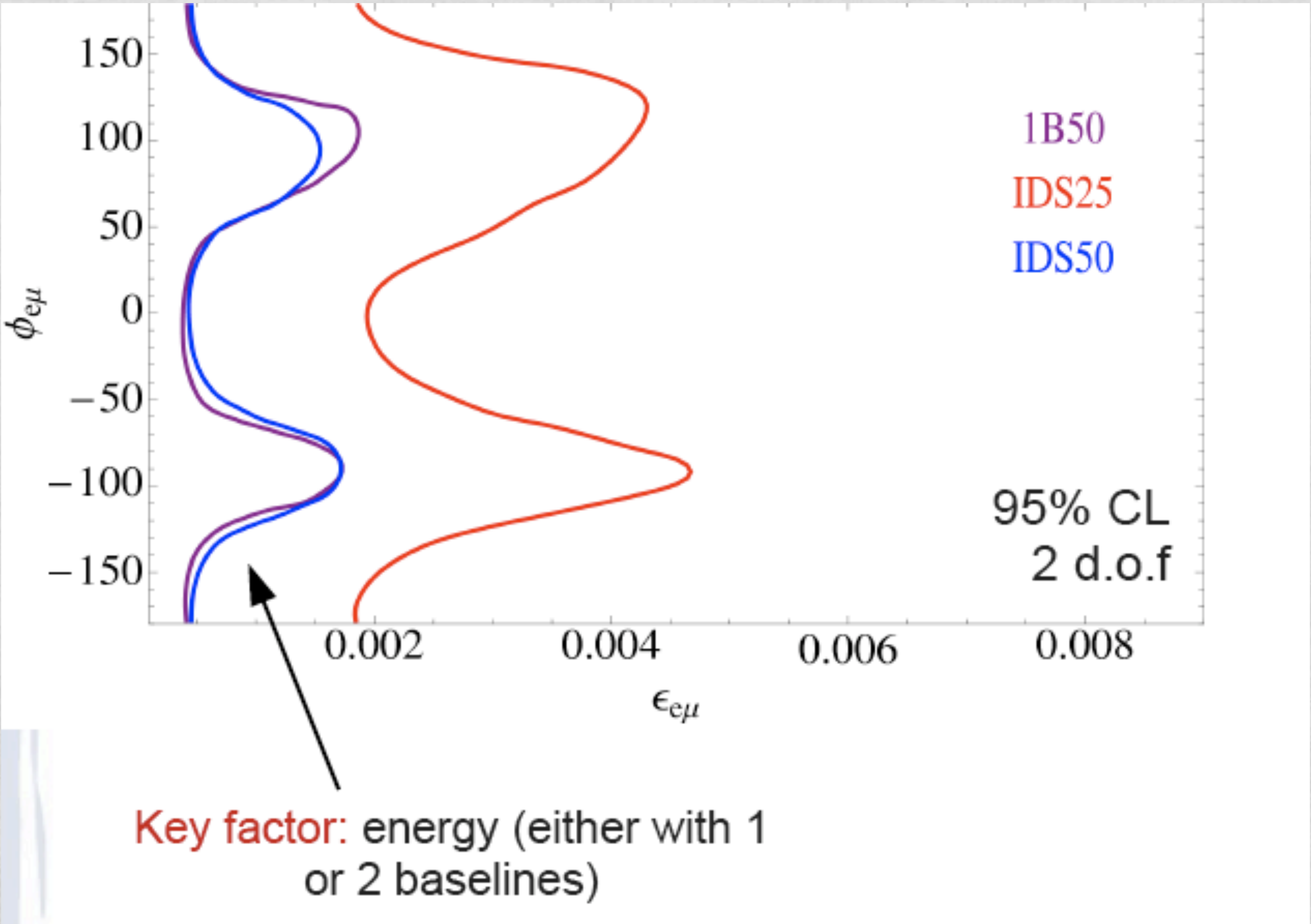
$$P_{\mu\mu}^{NSI} = P_{\mu\mu}^{NSI}(\varepsilon) + (\mathrm{Im}(\epsilon_{\mu\tau}))^2 + \dots$$



APPEARANCE CHANNEL(S)

Sensitivity to $\varepsilon_{e\mu}$

50 GeV setups are better!

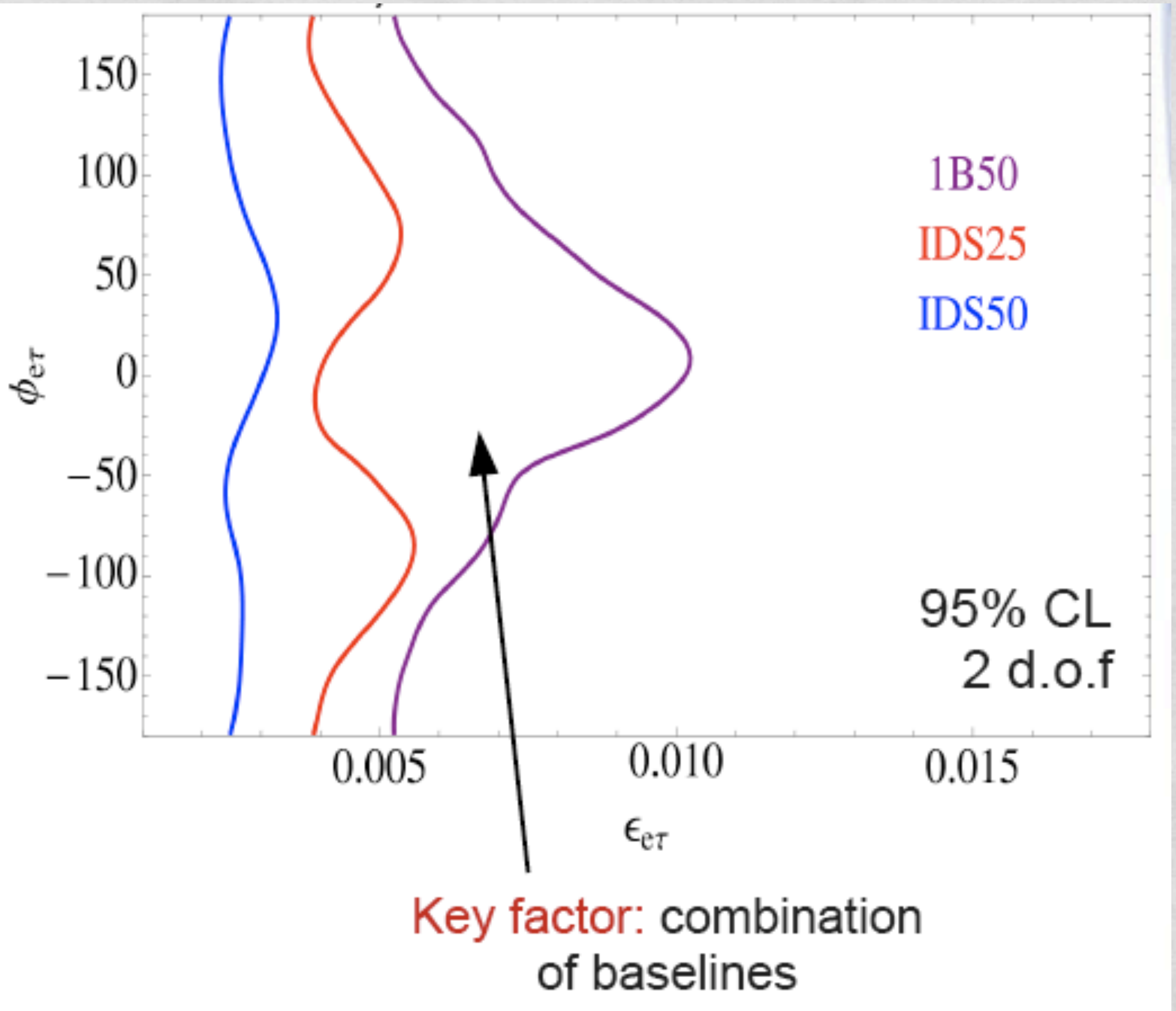


Correlations with $\varepsilon_{e\tau}$ are not extremely important

APPEARANCE CHANNEL(S)

Sensitivity to $\varepsilon_{e\tau}$

Two baselines are better. But with 50 GeV, even more!



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CP VIOLATION, I

- 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

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

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

CP VIOLATION, 2

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The 3D CP discovery potential looks like a mozzarella cheese

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When $|\varepsilon_{e\mu}| << |\varepsilon_{e\tau}|$, the two parameters are competitive and very involved correlations between them and δ arise.

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When $|\varepsilon_{e\mu}| << |\varepsilon_{e\tau}|$, the two parameters are competitive and very involved correlations between them and δ arise.

The 3D CP discovery potential looks like an emmental cheese

CP VIOLATION, 3

The 3D CP discovery potential also depends on θ_{13}

We consider two possibilities:

$\theta_{13} > 3°$, such that it can be tested at T2K and/or Double Chooz;
in this case, we fix θ_{13} and cut slices of the cheese along δ

$\theta_{13} < 3°$, such that it cannot be tested at T2K and/or Double Chooz;
in this case, we marginalize over θ_{13}
(no time to discuss this case in detail)

SYMMETRIC NSI'S

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

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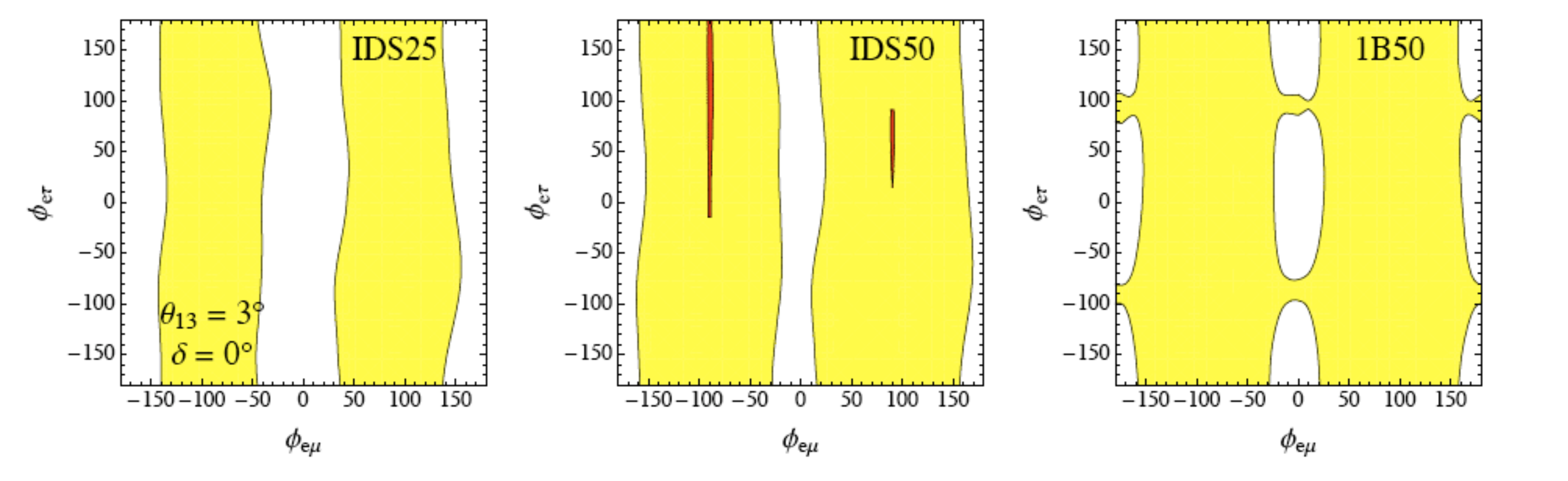

99% CL, 3 dof's

$\theta_{13} = 3°$ $\delta = 0$

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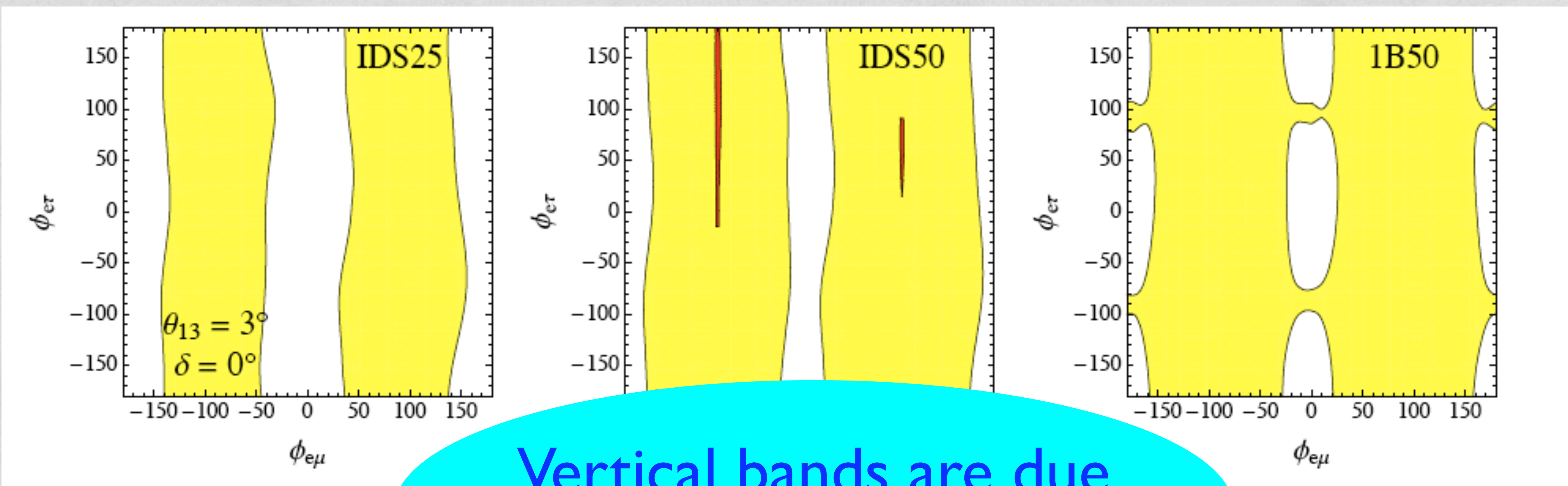

Vertical bands are due to $|\varepsilon_{e\mu}|$ dominance

99% CL, 3 dof ... 3° $\delta = 0$

SYMMETRIC NSI'S

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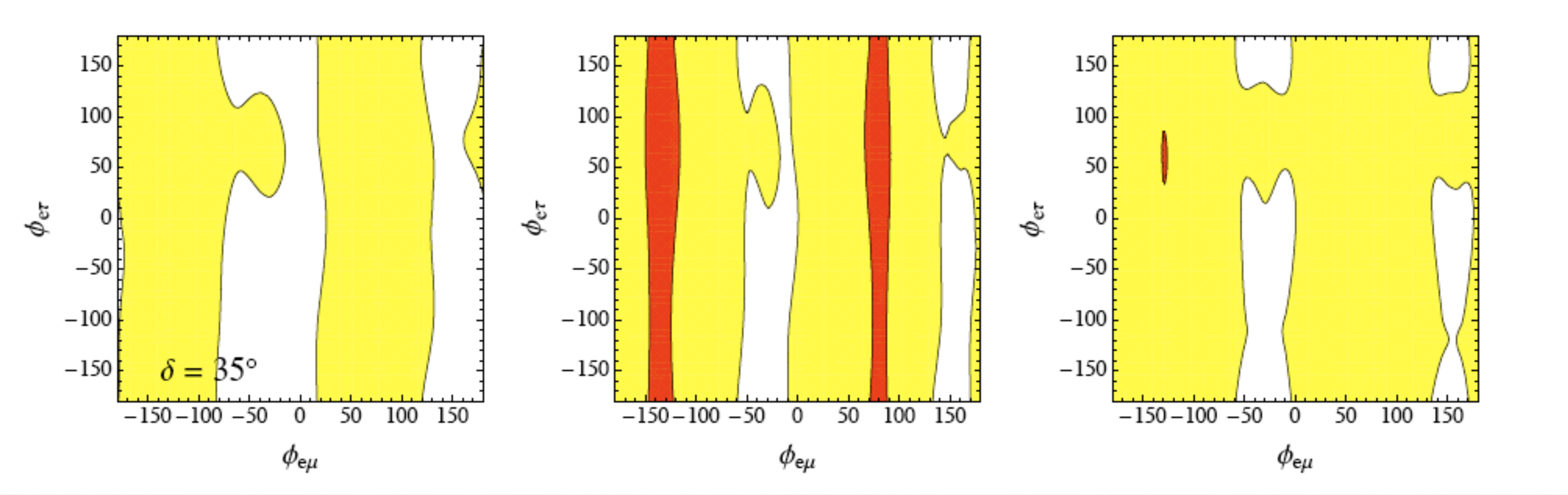
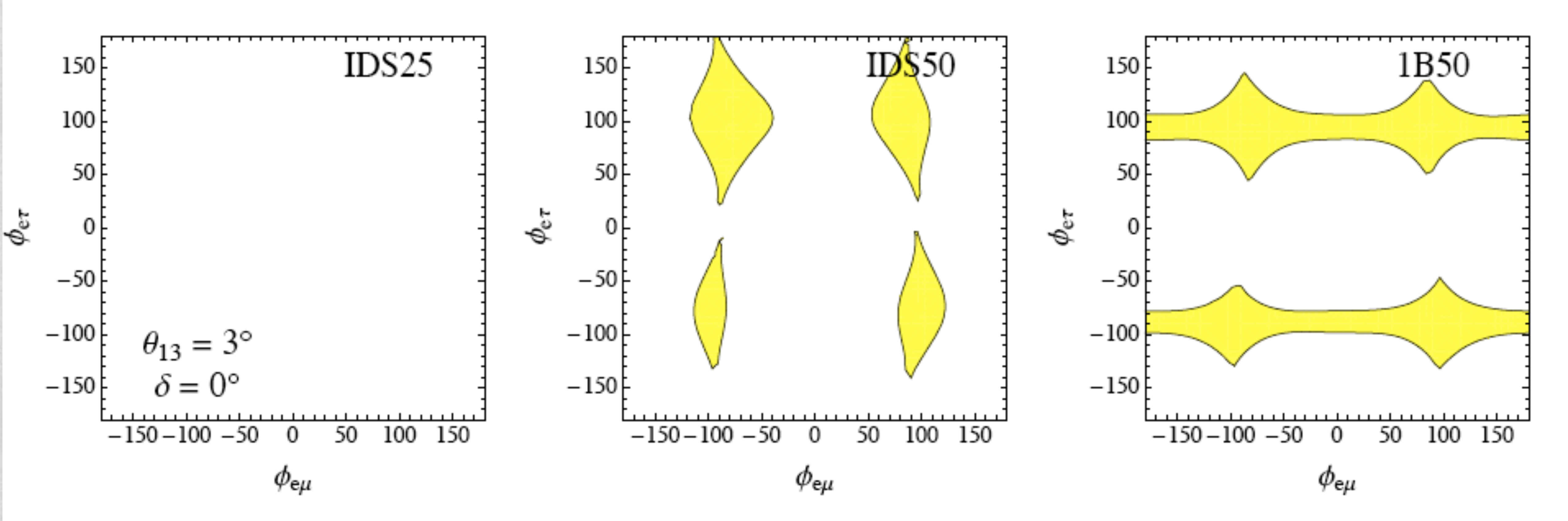


99% CL, 3 dof's

$\theta_{13} = 3°$ $\delta = 35°$

ASYMMETRIC NSI

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



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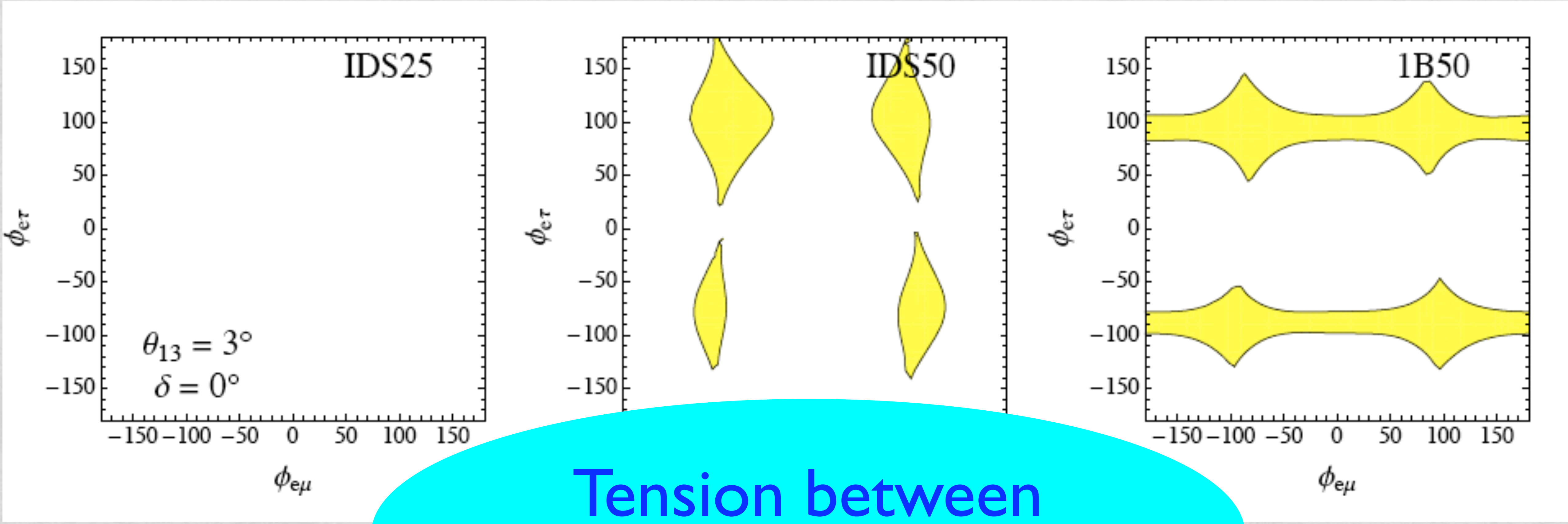
ASYMMETRIC NSI

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



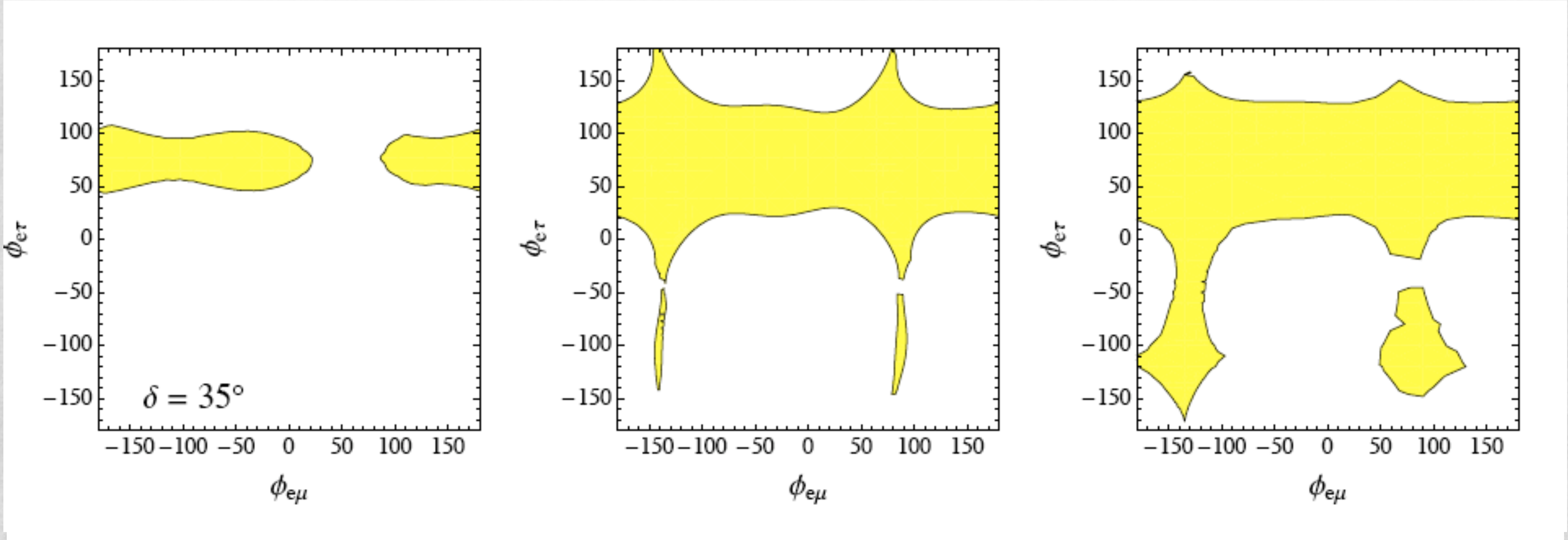
Tension between

$|\varepsilon_{e\mu}|$ and $|\varepsilon_{e\tau}|$

99% CL, 3 dof ... 3° δ = 0

ASYMMETRIC NSI

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



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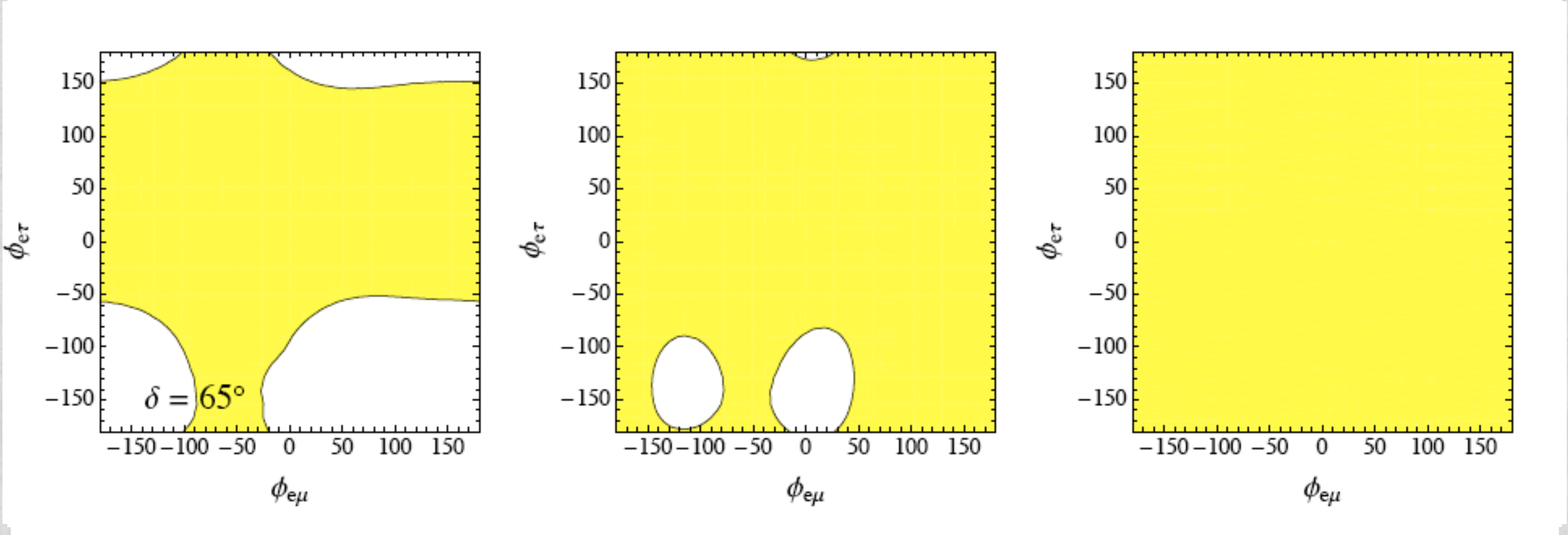
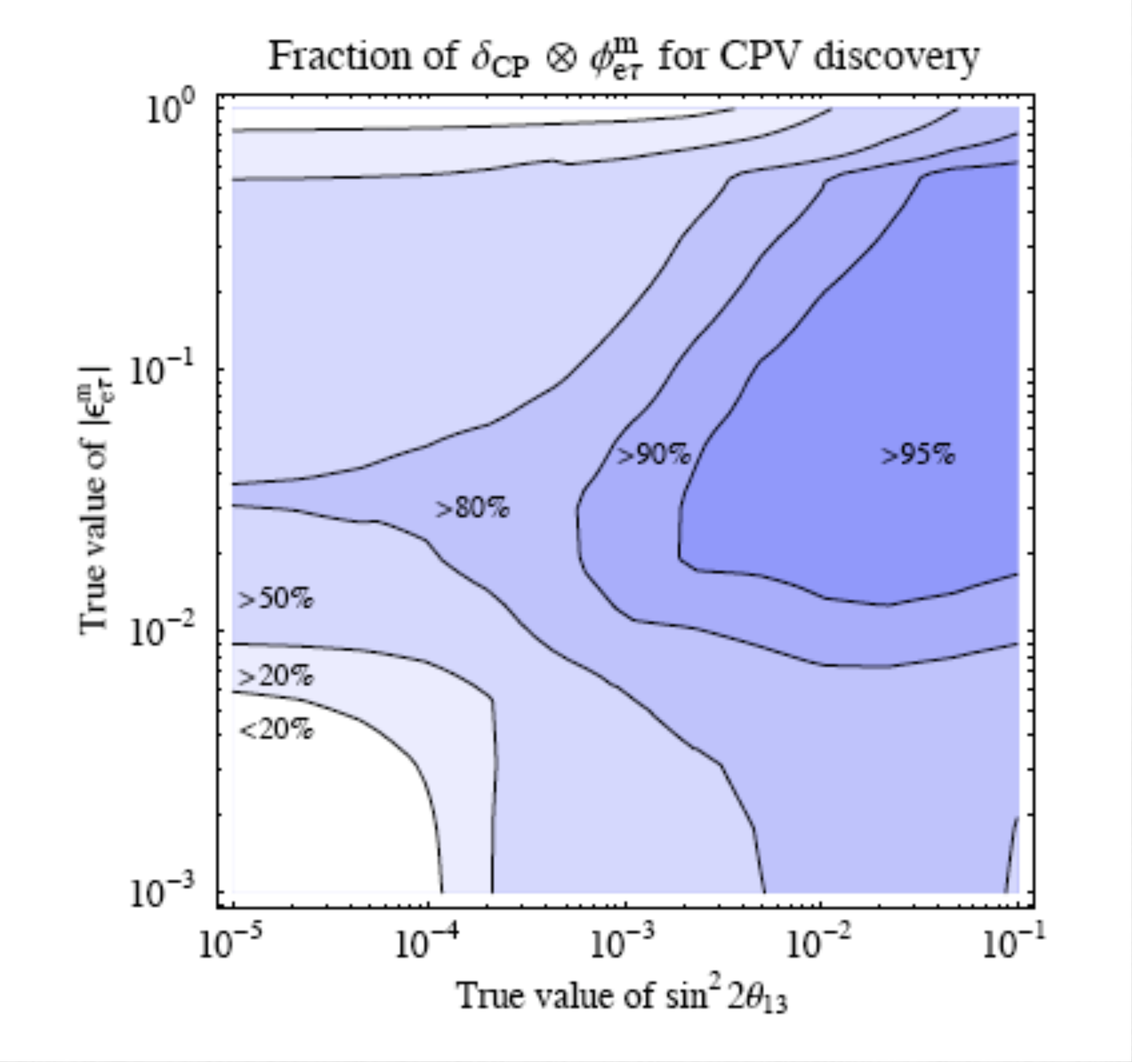


99% CL, 3 dof's

$\theta_{13} = 3°$ $\delta = 65°$

3D CP-FRACTION

2D CP-fraction



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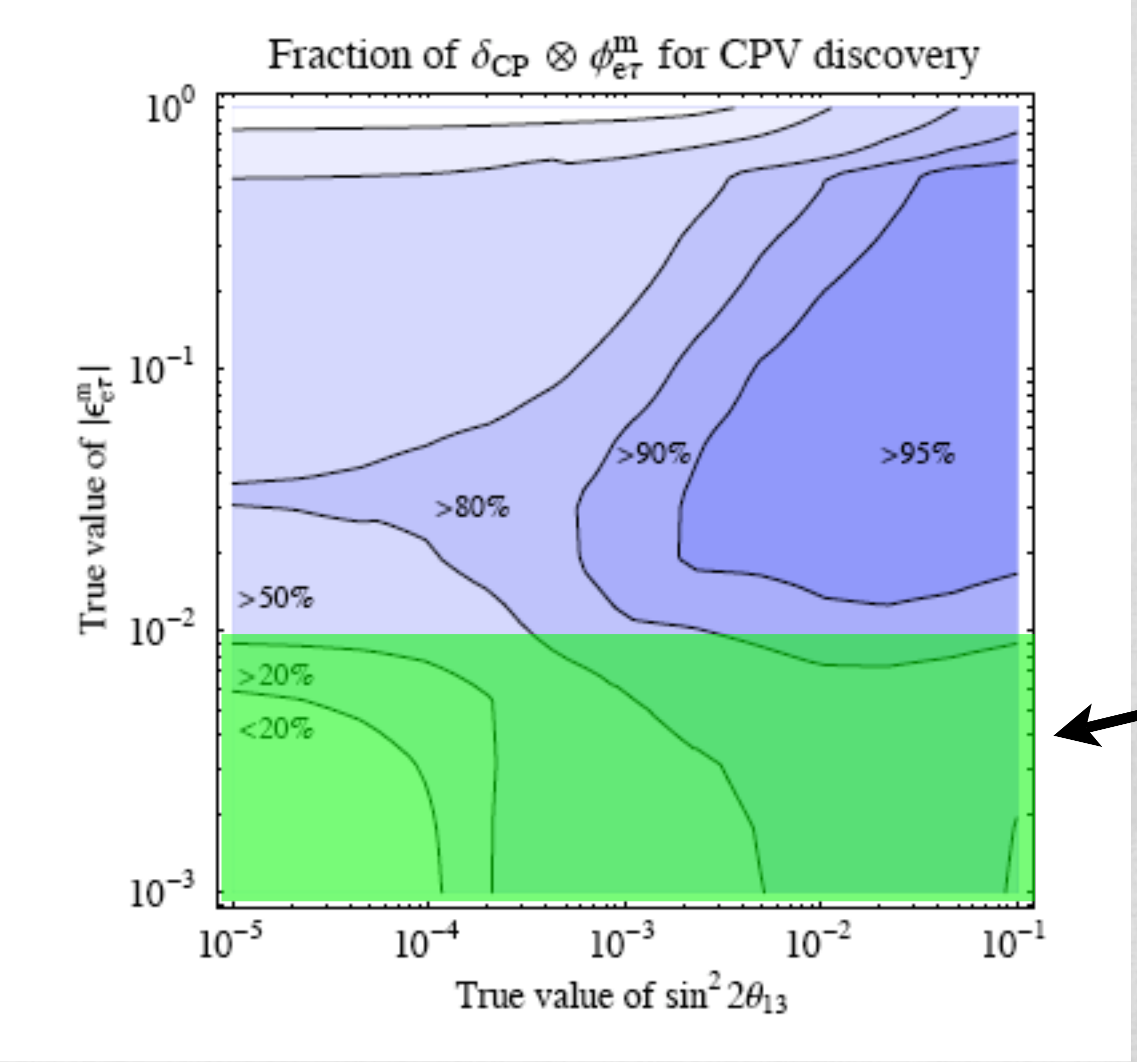
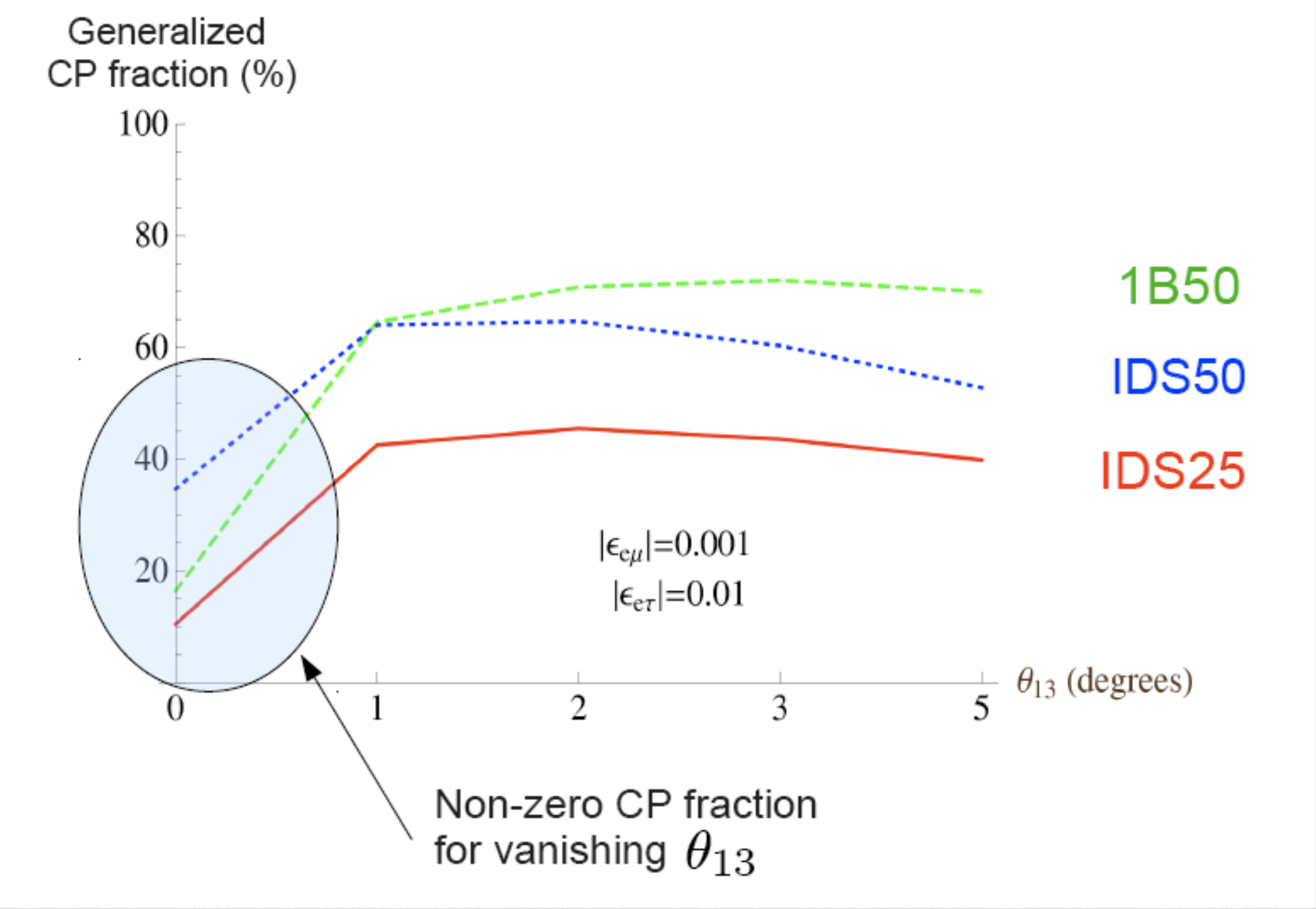
2D CP-fraction



W. Winter, arXiv:0808.3583

We have studied this region
but with two active NSI parameters
$|\varepsilon_{e\mu}|$, $|\varepsilon_{e\tau}|$

3D CP-FRACTION



CONCLUSIONS, I

- Sensitivity to NSI parameters at the IDS50 (1B50)
  - sensitivity to $|\varepsilon_{\mu\tau}|, |\varepsilon_{e\mu}|, |\varepsilon_{e\tau}| \leq 10^{-3}$ (correlations are not very important)
  - sensitivity to $\varepsilon_{ee}-\varepsilon_{\tau\tau} \leq 10^{-1}$ (matter uncertainty), $\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau} \leq 10^{-2}$ (importance of θ_{23} and $\delta\theta_{23}$)
  - sensitivity to θ_{13} worsens due to $\varepsilon_{\alpha\alpha}$, $|\varepsilon_{e\mu}|, |\varepsilon_{e\tau}|$

CONCLUSIONS,2

- We have studied the 3D discovery potential in $(\delta,\varphi_{e\mu},\varphi_{e\tau})$ for $|\varepsilon_{e\mu}|,|\varepsilon_{e\tau}|< 10^{-2}$ ($\theta_{13}< 3°$)
- If $|\varepsilon_{e\mu}| \approx |\varepsilon_{e\tau}|$, the former dominates and the correlations with δ are rather simple ("mozzarella shape")
- If $|\varepsilon_{e\mu}| << |\varepsilon_{e\tau}|$, the two parameters are competitive, involved correlations between them and δ arise ("emmental shape")
- A 50 GeV Neutrino Factory (either one or two-baselined) is very powerful and could discover CP violation in > 20% of the parameter space for $|\varepsilon_{e\mu}| = 10^{-3}$,$|\varepsilon_{e\tau}|< 10^{-2}$ even for vanishing $\theta 13$

BACKUP

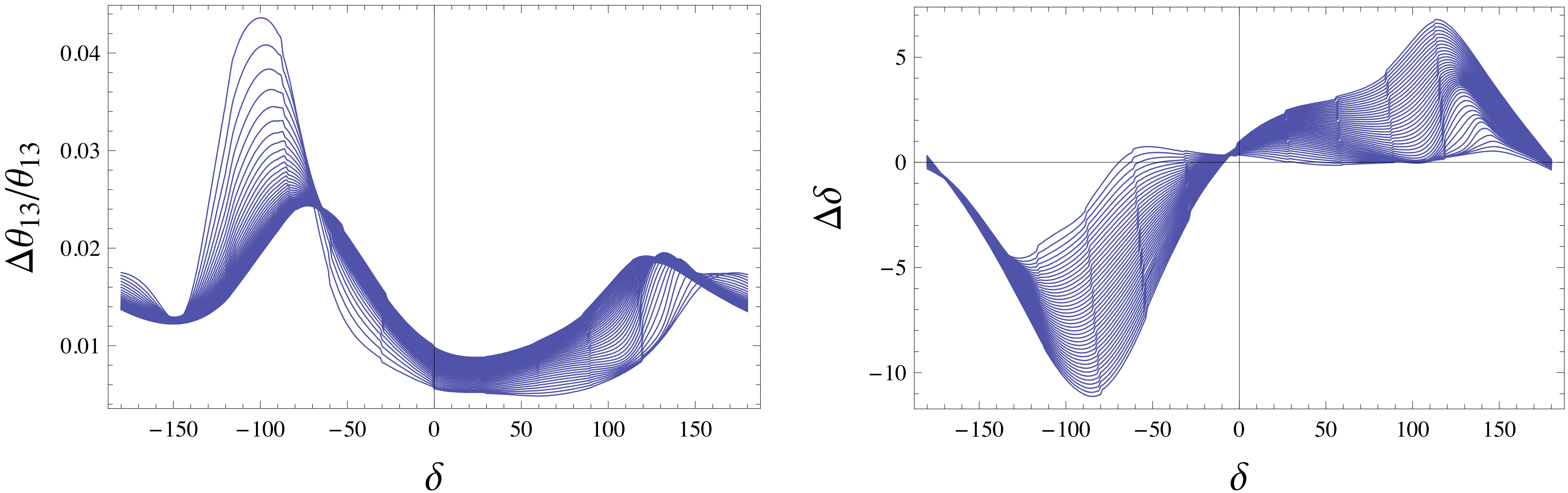
PRIORS

For NSI parameters: we have gaussian priors with standard deviations around zero for the moduli; flat priors for the phases.

$\|\epsilon_{ee}\|$	0.75	$\|\epsilon_{e\mu}\|$	0.01
$\|\epsilon_{\mu\mu}\|$	0.05	$\|\epsilon_{e\tau}\|$	0.25
$\|\epsilon_{\tau\tau}\|$	0.4	$\|\epsilon_{\mu\tau}\|$	0.25

For standard parameters: we include a 5% error over the PREM density profile, and a 10% error over the atmospheric parameters. Flat priors for θ_{13} and δ.

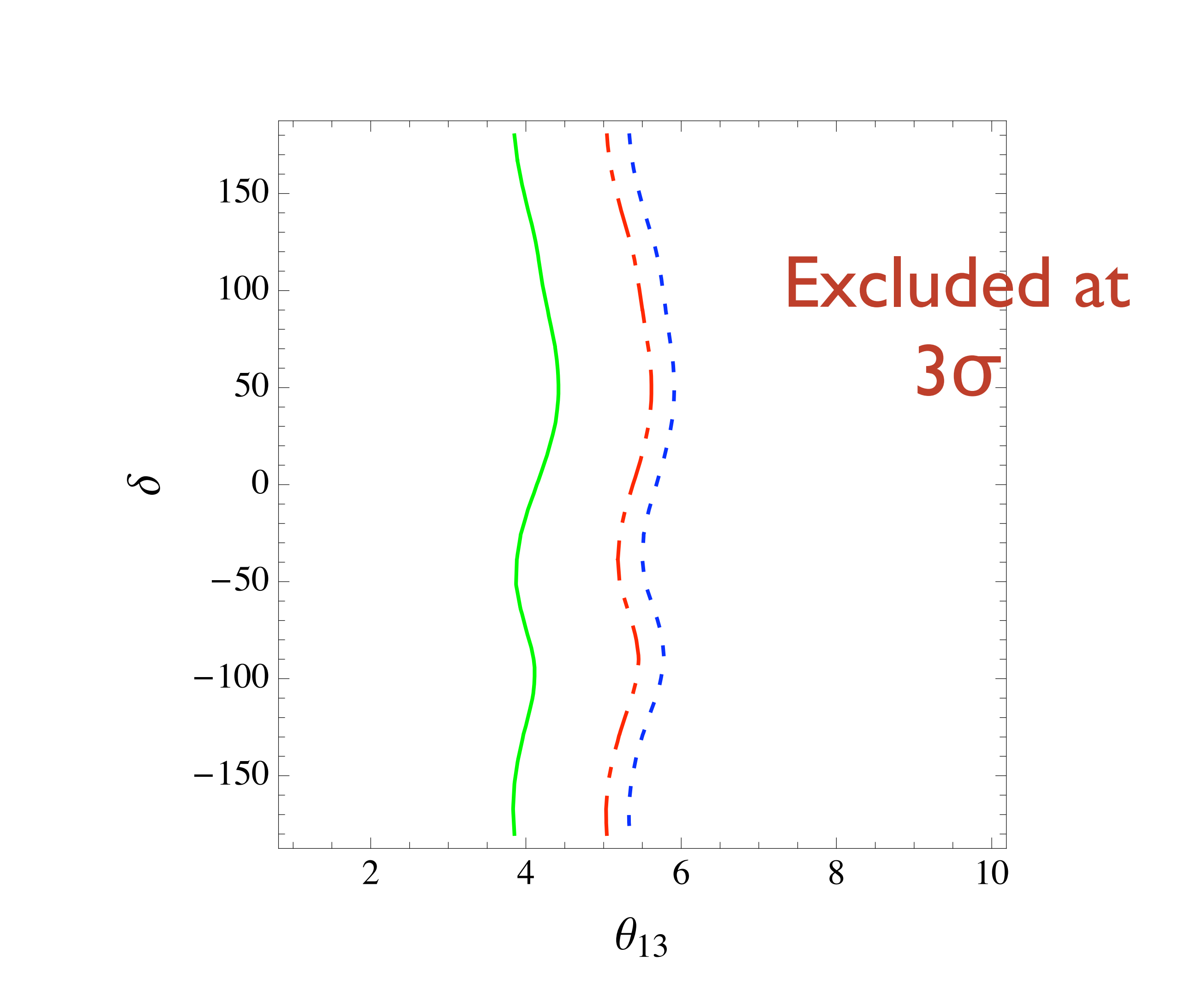
OTHER PLOTS, I



L = 4000 Km + 7500 Km

OTHER PLOTS, 2

- How good is the hypothesis that tau-contaminated data can be fitted with the golden muon distribution, only?
- The answer is: VERY POOR!!!!!!



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