Investigating Lorentz Invariance Violation with the long-baseline experiment P2O

Nishat Fiza
IISER Mohali, India

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Plan of the talk:

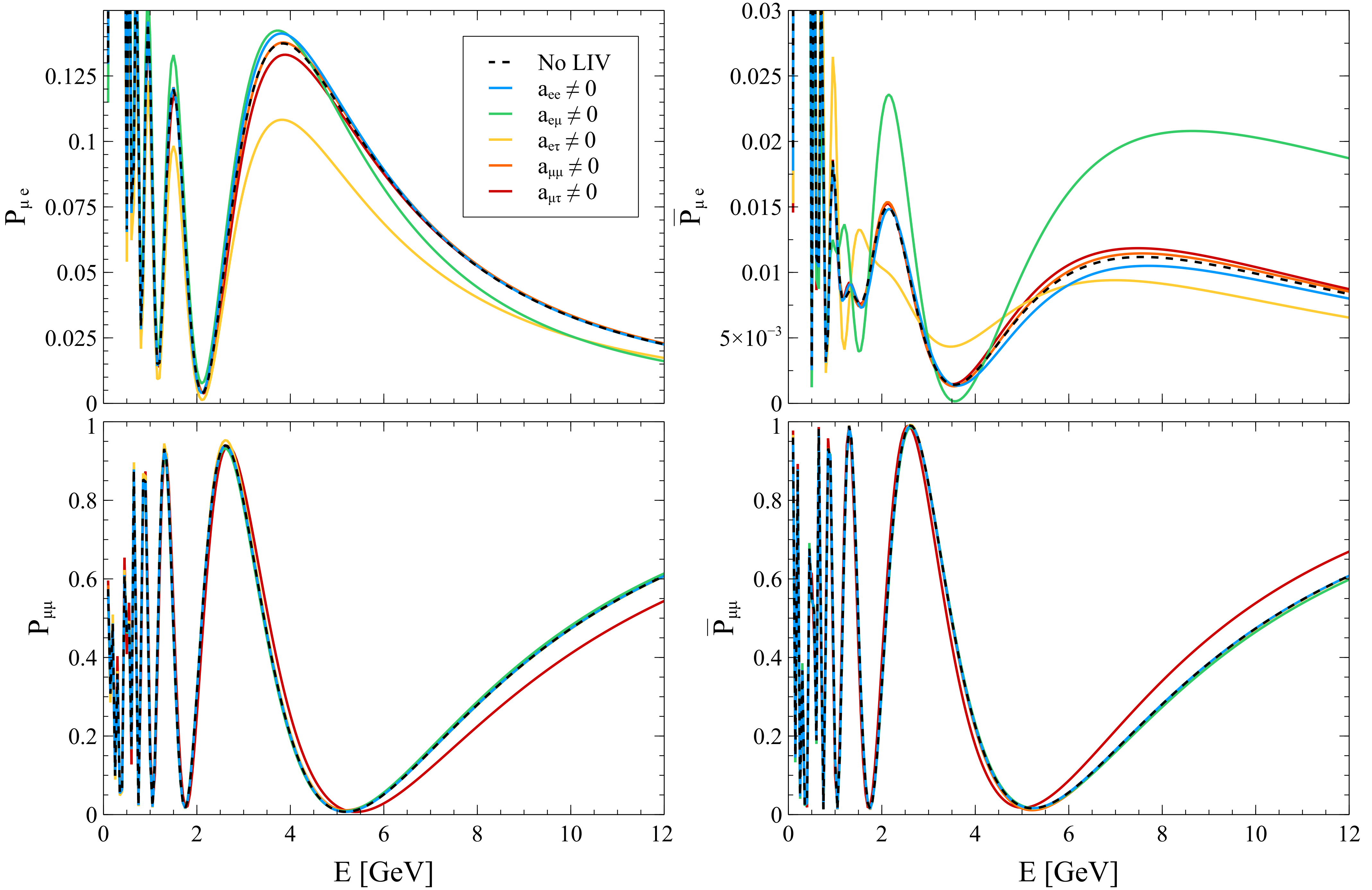
- Introduction
- Effect of LIV at probability level
- Correlation of LIV parameters with the oscillation parameters
- Bounds on the LIV parameters
- Summary

Lorentz Invariance Violation:

- CPT violation can be probed through Lorentz invariance violation
- Spontaneous breakdown of Lorentz invariance may occur at Planck scale ($M_P \sim 10^{19} GeV$)
- At low energy, LBL ν oscillation experiments can probe LIV
- Lagrangian in presence of LIV: $\mathscr{L} = \frac{1}{2}\bar{\Psi}\left(i\gamma^{\mu}\partial_{\mu} - M + \hat{\mathcal{Q}}\right)\Psi + \text{h.c.}$[1]
- $\mathscr{L}_{\text{LIV}} \supset -\frac{1}{2}\left[a^{\mu}_{\alpha\beta}\bar{\psi}_{\alpha}\gamma_{\mu}\psi_{\beta} + b^{\mu}_{\alpha\beta}\bar{\psi}_{\alpha}\gamma_{5}\gamma_{\mu}\right]$; $(a_L)^{\mu}_{\alpha\beta} = (a+b)^{\mu}_{\alpha\beta}$
- Effective Hamiltonian: $H \simeq \frac{1}{2E}U\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}U^{\dagger} + \sqrt{2}G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix}$

[1] Kostelecky, Mewes: arXiv:1112.6395

How do LIV parameters change the probability?



P2O experiment

Baseline 2595 km[2]

$$a_{\alpha\beta} = 5 \times 10^{-23} GeV \text{ where } \alpha, \beta = e, \mu, \tau$$

[2] A. V. Akindinov et al., arXiv:1902.06083

How do LIV parameters change the probability?

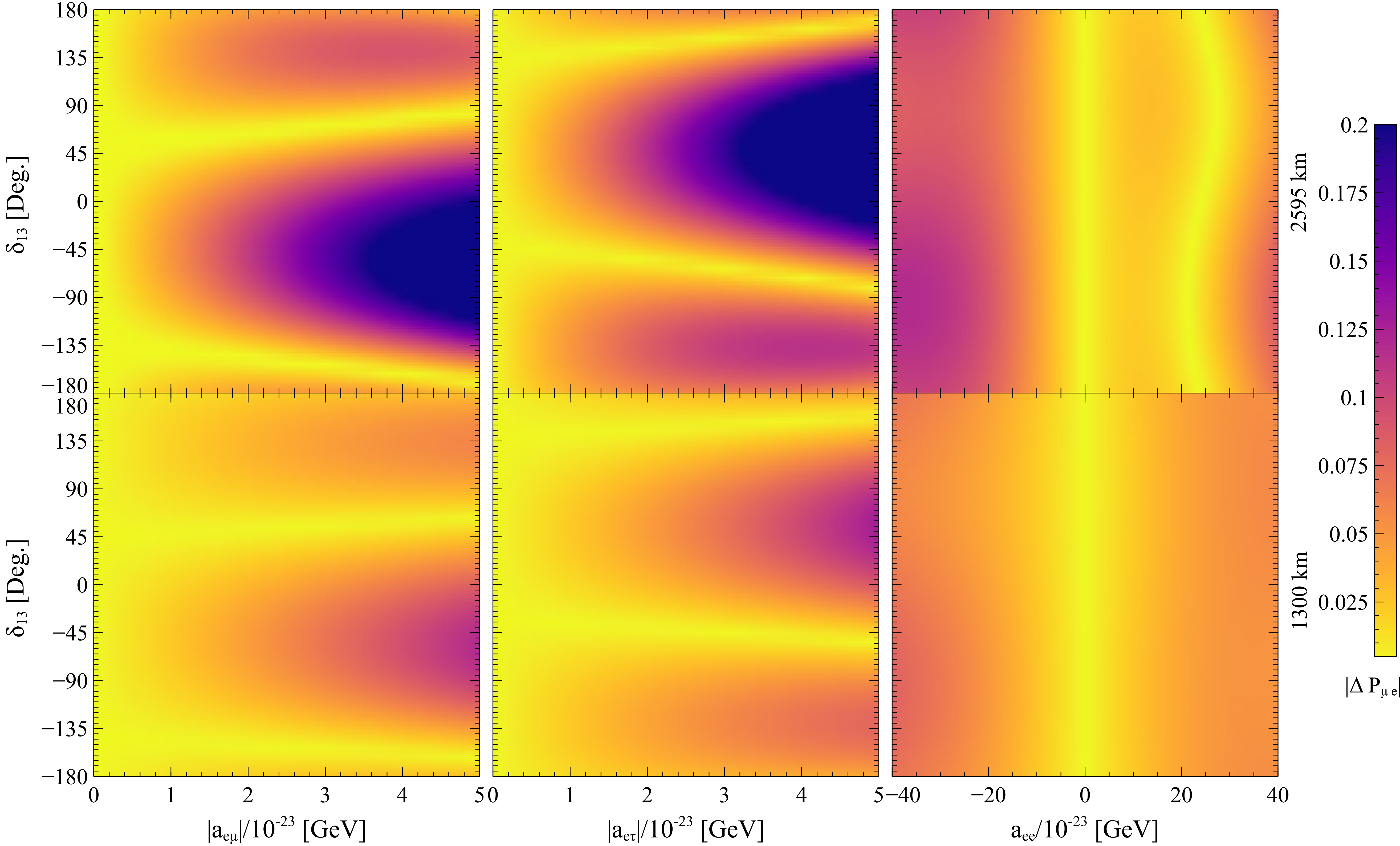
$$P_{\mu e}(SI + LIV) \simeq P_{\mu e}(SI,\, a_{ee}) + P_{\mu e}(|a_{e\mu}|) + P_{\mu e}(|a_{e\tau}|)$$

Combination of standard CC interaction between ν_e and e in earth's matter and a_{ee}

Deviation in the probability due to $|a_{e\mu}|$ and $|a_{e\tau}|$

$$|\Delta P_{\mu e}| = |P_{\mu e}(SI + LIV) - P_{\mu e}(SI)|$$

Heatplot for $|\Delta P_{\mu e}|$



$|\Delta P_{\mu e}|$ for **P2O** and **DUNE** plotted at **5 GeV** and **2.5 GeV** respectively

Heatplot for $|\Delta P_{\mu e}|$

$$\Delta P_{\mu e}(|a_{e\mu}|) \simeq 8|a_{e\mu}|\frac{\pi}{2}Es_{13}\sin 2\theta_{23}c_{23}\left[-\sin\delta_{13} + \frac{2}{\pi}\frac{s_{23}^2}{c_{23}^2}\cos\delta_{13}\right]$$

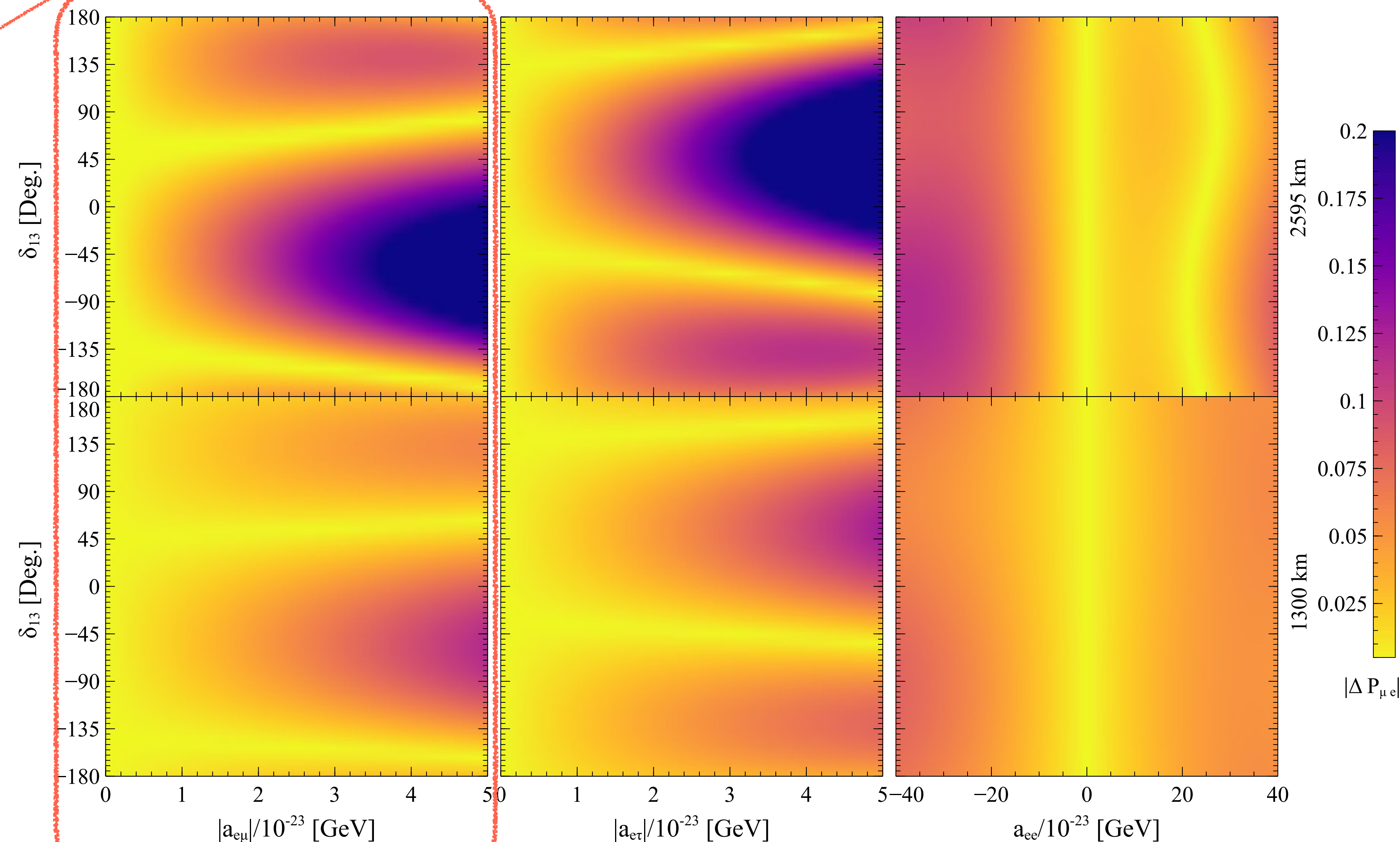
$\Delta P(|a_{e\mu}|) \simeq 0$; if we have:

$$|a_{e\mu}| = 0$$

Or

$$\tan\delta_{13} = \frac{2}{\pi}\frac{s_{23}^2}{c_{23}^2}$$

which gives:
$\delta_{13} = 39°, \ -141°$



Heatplot for $|\Delta P_{\mu e}|$

$$\Delta P_{\mu e}(|a_{e\tau}|) \simeq 8\,|a_{e\tau}|\frac{\pi}{2}E s_{13}\sin 2\theta_{23} c_{23}\left[-\sin\delta_{13} + \frac{2}{\pi}\cos\delta_{13}\right]$$

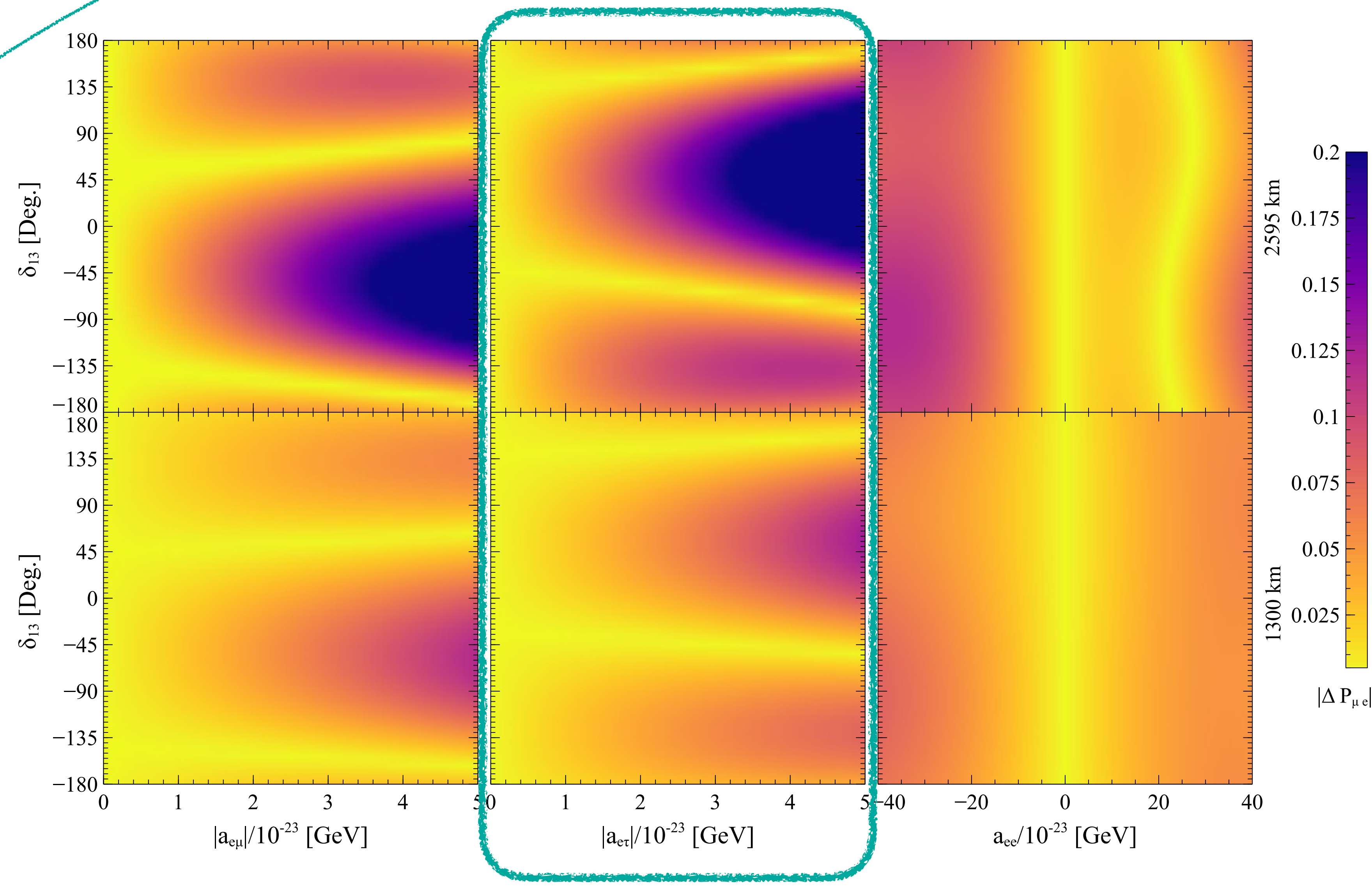
$\Delta P(|a_{e\tau}|) \simeq 0$; if we have:

$$|a_{e\tau}| = 0$$

Or

$$\tan\delta_{13} = \frac{2}{\pi}$$

which gives:
$\delta_{13} = -33°,\ 147°$



Heatplot for $|\Delta P_{\mu e}|$

$$\underbrace{\left[\frac{\sin[1-\hat{A}(1+\hat{a}_{ee})]\Delta}{1-\hat{A}(1+\hat{a}_{ee})} - \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right]}_{I_-} \times \underbrace{\left[\frac{\sin[1-\hat{A}(1+\hat{a}_{ee})]\Delta}{1-\hat{A}(1+\hat{a}_{ee})} + \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right]}_{I_+} = 0$$

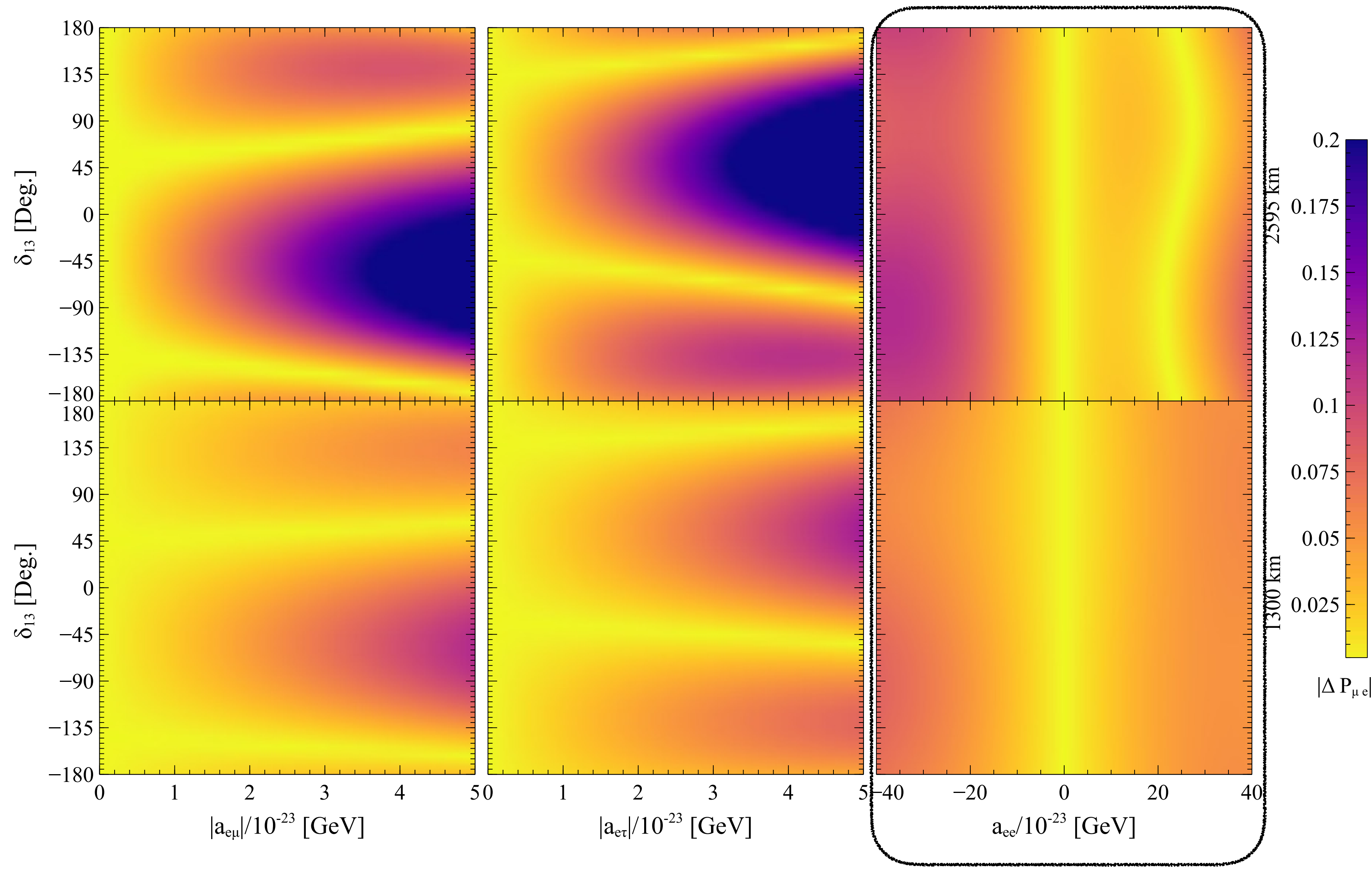
$I_- \rightarrow$ $a_{ee} = 0$

$I_+ \rightarrow$ $a_{ee} \simeq 24.8 \times 10^{-23}\ GeV$

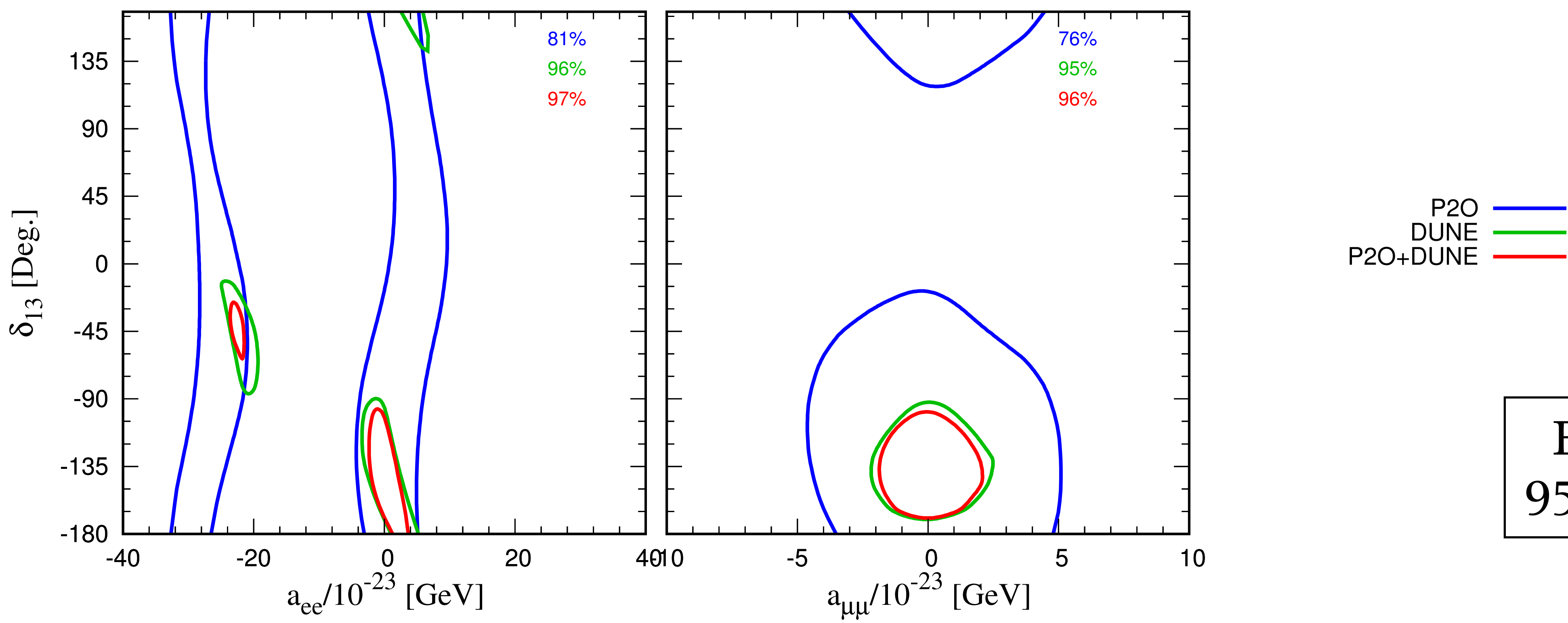
where, $$\Delta = \frac{\Delta m_{31}^2 L}{4E}$$

$$\hat{A} = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$$

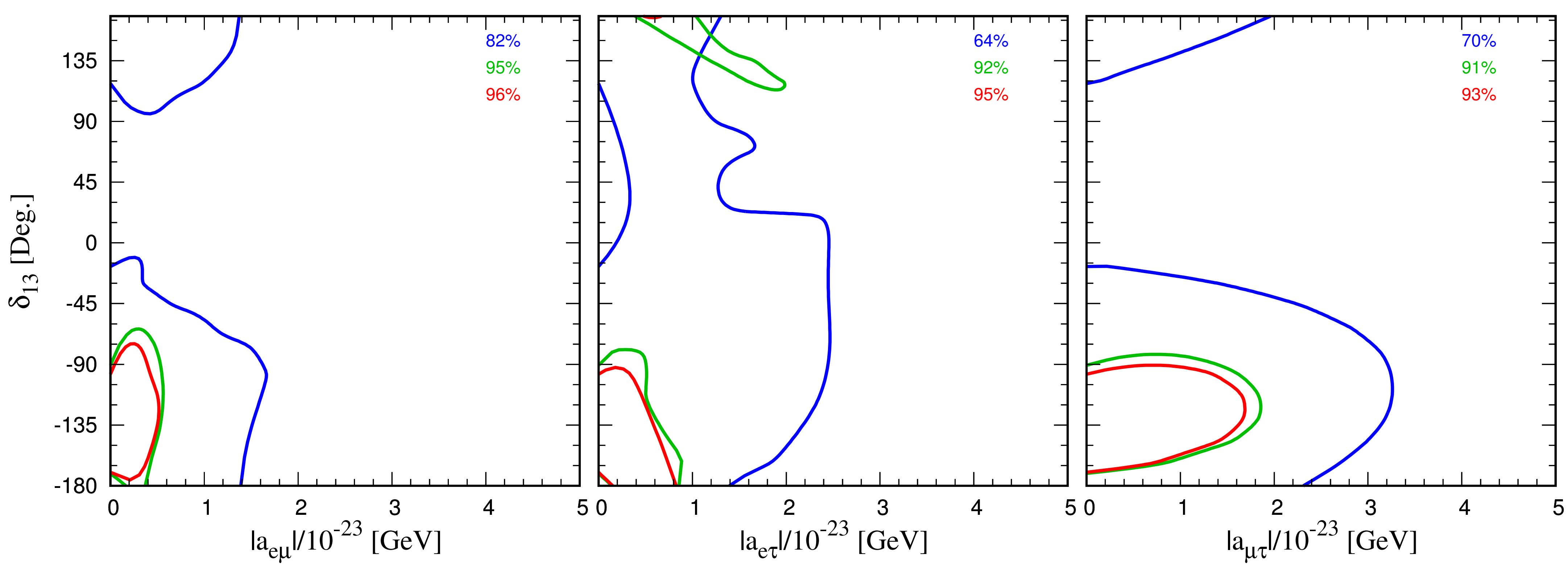
$$\hat{a}_{ee} = \frac{a_{ee}}{\sqrt{2}G_F N_e}$$



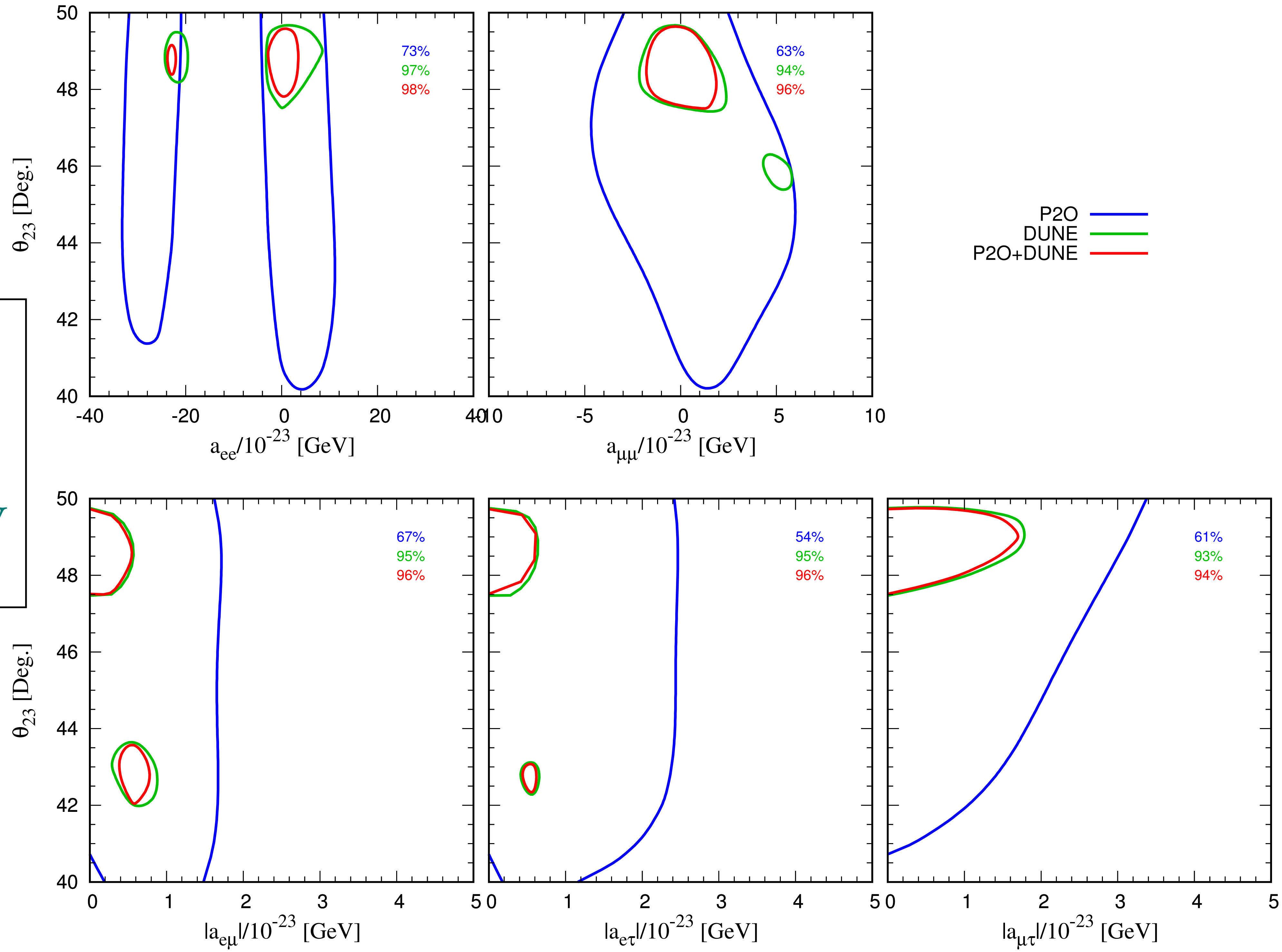
Exclusion region in correlation with δ_{13}



Exclusion region at 95% confidence level



Exclusion region in correlation with θ_{23}



Combining the simulated data for DUNE and P2O lifts the octant degeneracy in case of θ_{23}

Degenerate region in correlation to a_{ee}

$$\Delta\chi^2(a_{ee}) \sim \Delta P_{\mu e}(a_{ee})$$

$$\sim \left[\frac{\sin[1-\hat{A}(1+\hat{a}_{ee})]\Delta}{1-\hat{A}(1+\hat{a}_{ee})} - \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right] \times \left[\frac{\sin[1-\hat{A}(1+\hat{a}_{ee})]\Delta}{1-\hat{A}(1+\hat{a}_{ee})} + \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right]$$

- Marginalization over the mass hierarchy
- For inverted hierarchy, $\hat{A}$ and Δ changes sign

where, $\Delta = \frac{\Delta m^2_{31} L}{4E}$

$\hat{A} = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$

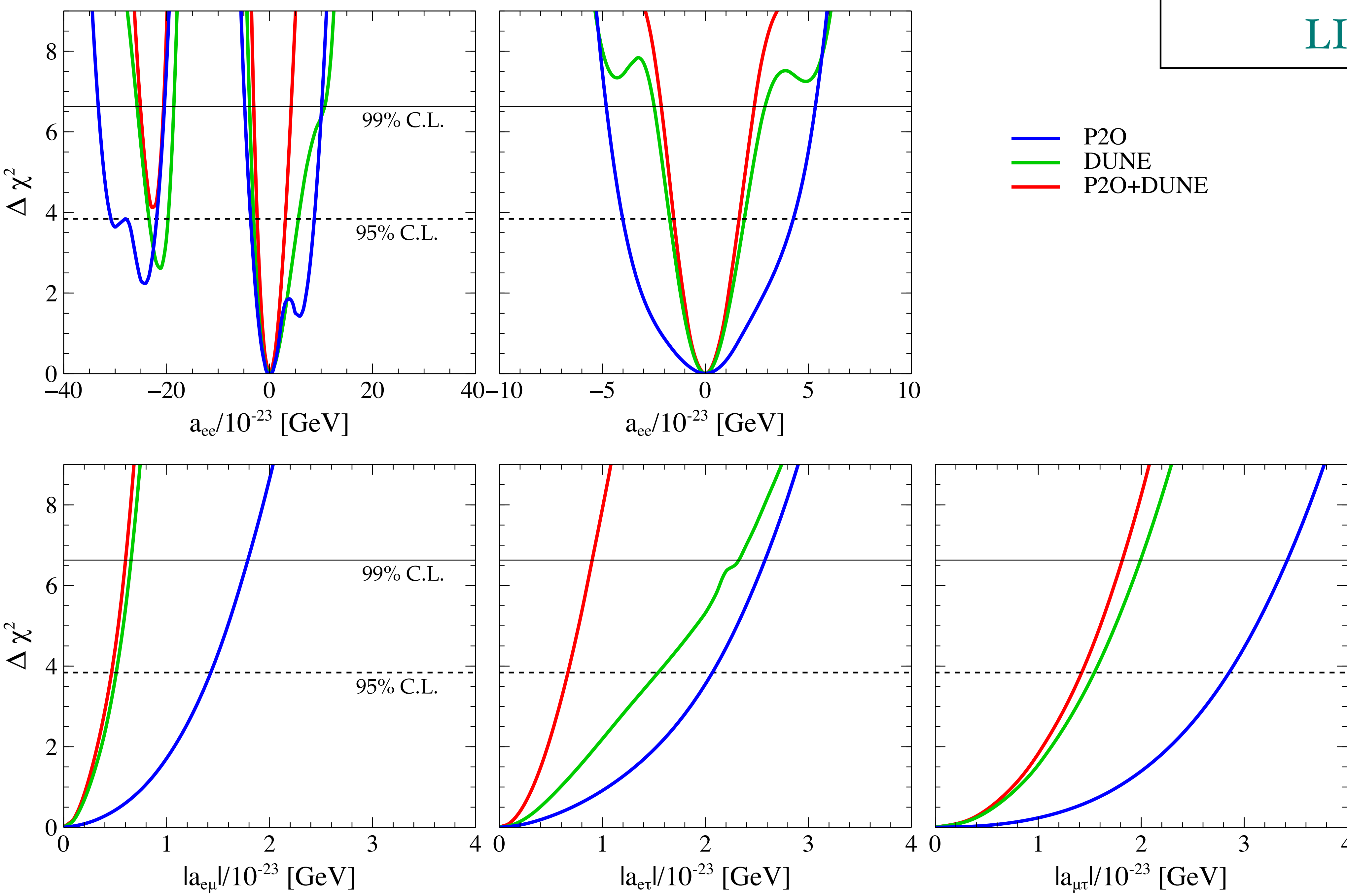
$$\Delta\chi^2 \sim \left[\frac{\sin[1+\hat{A}(1+\hat{a}_{ee})]\Delta}{1+\hat{A}(1+\hat{a}_{ee})} + \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right] \times \left[\frac{\sin[1+\hat{A}(1+\hat{a}_{ee})]\Delta}{1+\hat{A}(1+\hat{a}_{ee})} - \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right]$$

$a_{ee} = 0$

$a_{ee} \simeq -22 \times 10^{-23}\ GeV$

Results:

Expected sensitivity of DUNE and P2O experiment to the LIV parameters



Bounds on the LIV parameters

(At 95% confidence level)

Parameter	Bounds from DUNE $[10^{-23}$ GeV$]$	Bounds from P2O $[10^{-23}$ GeV$]$	Bounds from (P2O+DUNE) $[10^{-23}$ GeV$]$
a_{ee}	$[-24 < a_{ee} < -20] \cup [-3.2 < a_{ee} < 5.6]$	$[-30.8 < a_{ee} < -21.9] \cup [-3.9 < a_{ee} < 8.6]$	$-2.6 < a_{ee} < 3.3$
$a_{\mu\mu}$	$-1.9 < a_{\mu\mu} < 2.0$	$-4.0 < a_{\mu\mu} < 4.3$	$-1.6 < a_{\mu\mu} < 1.6$
$\|a_{e\mu}\|$	0.6	1.6	0.4
$\|a_{e\tau}\|$	1.3	2.1	0.7
$\|a_{\mu\tau}\|$	1.5	2.9	1.3

Summary

- We consider P2O to study LIV
- Effect of LIV on probability
- Effect of LIV parameters on $|\Delta P_{\alpha\beta}|$
- $\Delta\chi^2$ analysis of LIV parameters in correlation to standard oscillation parameters
- Bounds on the LIV parameters


Thank you!!!
...

Back-up

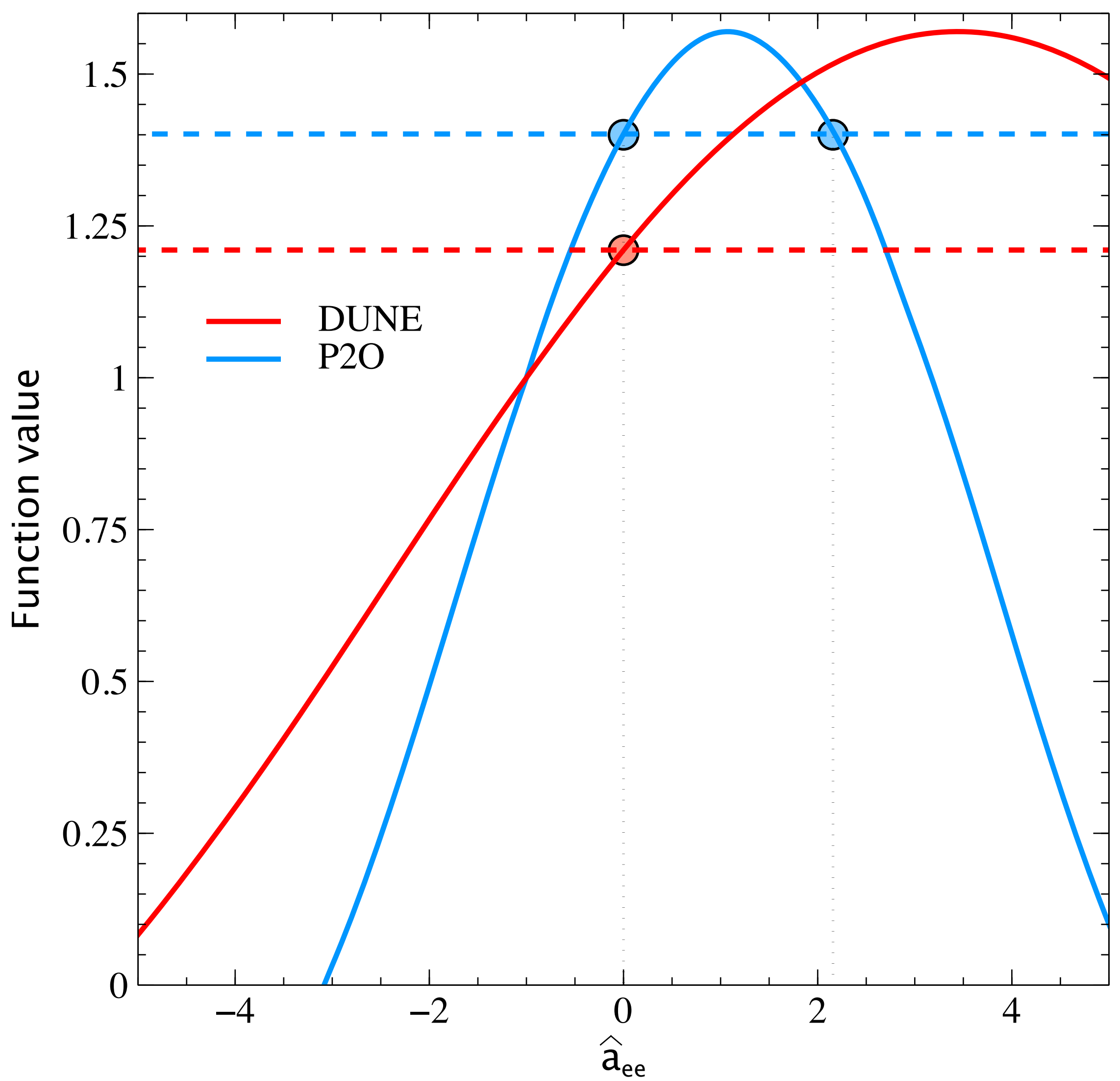
$$I_- = \left[\frac{\sin[1 - \hat{A}(1+\hat{a}_{ee})]\Delta}{1 - \hat{A}(1+\hat{a}_{ee})} - \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}} \right]$$

$$\hat{A} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

$$\simeq 0.03 \times \rho[g/cm^3] \times E[GeV]$$

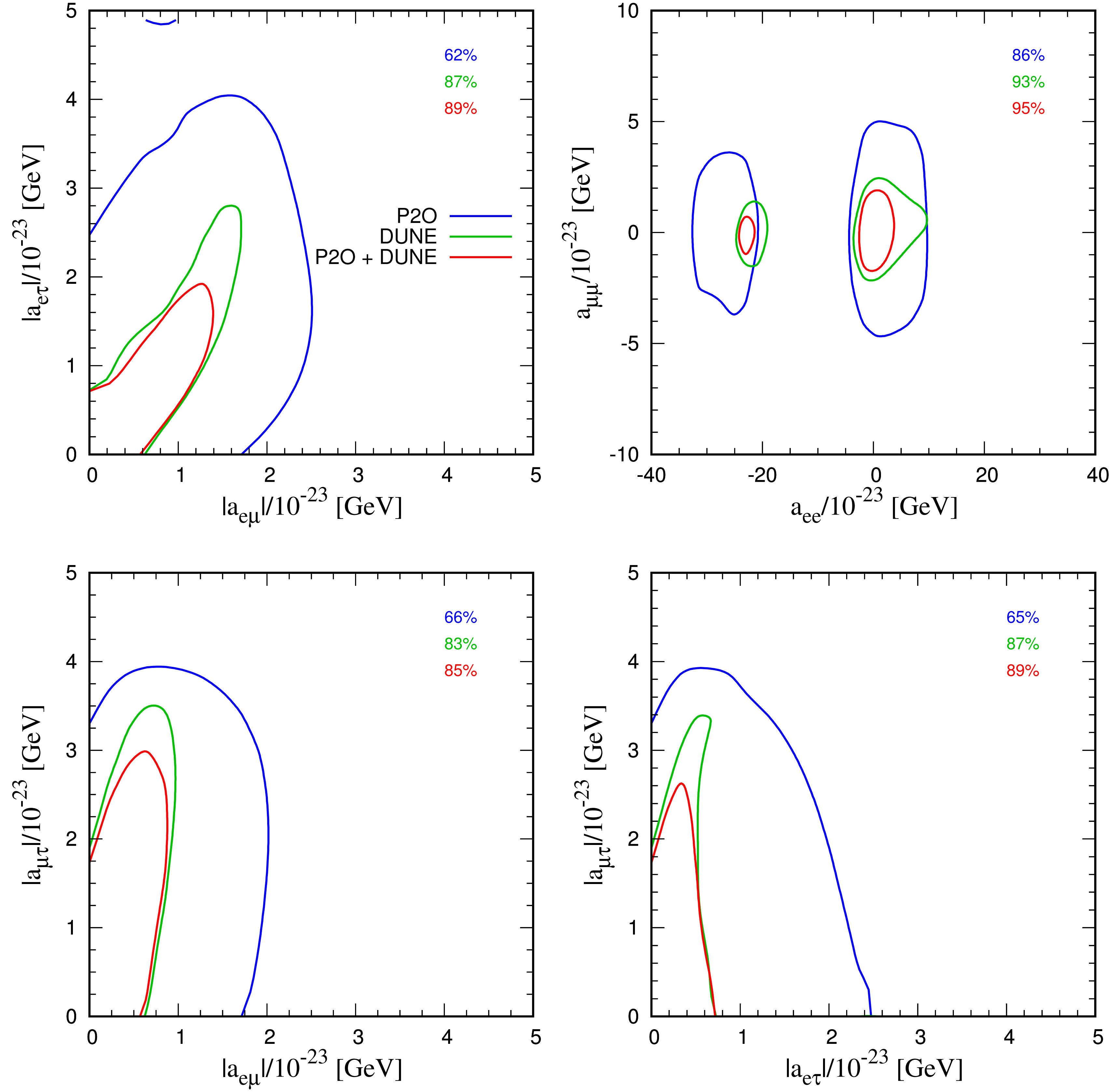
$\simeq 0.225$ for DUNE $[\rho = 3,\ E = 2.5]$

$\simeq 0.448$ for P2O $[\rho = 3.2,\ E = 5]$



The two terms in I_- are plotted for both DUNE (red) and P2O (blue) as functions of the parameter $\hat{a}_{ee} = a_{ee}\sqrt{2}G_F N_e$. The solid curve is the first term $\left(\frac{\sin[1-\hat{A}(1+\hat{a}_{ee})]\Delta}{1-\hat{A}(1+\hat{a}_{ee})}\right)$, while the dashed curve is the second term $\left(\frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right)$. The small coloured circles show the locations of solutions where the two terms intersect.

Back-up



62%
87%
89%
P2O
DUNE
P2O + DUNE
$|a_{e\tau}|/10^{-23}$ [GeV]
$|a_{e\mu}|/10^{-23}$ [GeV]
86%
93%
95%
$a_{\mu\mu}/10^{-23}$ [GeV]
$a_{ee}/10^{-23}$ [GeV]
66%
83%
85%
$|a_{\mu\tau}|/10^{-23}$ [GeV]
$|a_{e\mu}|/10^{-23}$ [GeV]
65%
87%
89%
$|a_{\mu\tau}|/10^{-23}$ [GeV]
$|a_{e\tau}|/10^{-23}$ [GeV]