Investigating Lorentz Invariance Violation with DUNE and P2O

Mehedi Masud
IBS-CTPU

NuFACT2023, Aug, 2023
Seoul National University, Korea

Based on JHEP01(2023), 076
with
N.R. Khan Chowdhury & N.Fiza

Plan of the talk

- Basic theory and motivation
- Impact of LIV on probability
- $\Delta\chi^2$ correlations and various degeneracies
- Improving constraints with DUNE+P2O
- Summary

Lorentz Invariance Violation (LIV)

Kostelecky et al. (2012), Mavromatos et al.

- Introduce Lorentz violation effectively in form of the Standard model extension (SME)
- In the SME the neutrino sector is described by

$$\mathcal{L} = \frac{1}{2}\overline{\Psi}(i\gamma^\alpha \partial_\alpha - M + \mathcal{Q})\Psi$$

Lorentz violating operator

with $\Psi = (\nu_e, \nu_\mu, \nu_\tau, \nu_e^C, \nu_\mu^C, \nu_\tau^C)^T$

- Lorentz violating part can be decomposed into:

$$\mathcal{L}_{\text{LIV}} \supset -\frac{1}{2}\left[a^\mu_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\psi_\beta + b^\mu_{\alpha\beta}\bar{\psi}_\alpha\gamma_5\gamma_\mu\psi_\beta\right]$$

- The observable effect on LH neutrinos are controlled by $(a_L)^\mu_{\alpha\beta} = (a+b)^\mu_{\alpha\beta}$

LIV:Theory background

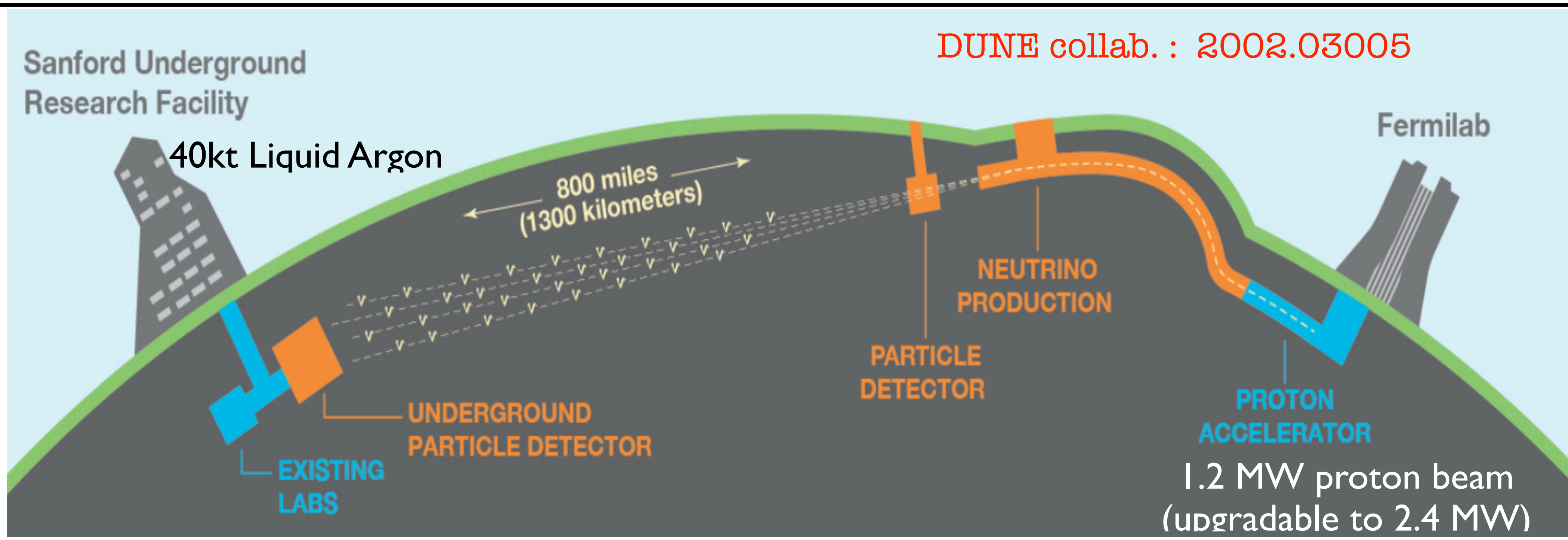
Kostelecky et al. (2012), Mavromatos et al.

- $H = H_{\rm vac} + H_{\rm mat} + H_{\rm LIV},$
- $H_{\rm vac} = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger, \quad H_{\rm mat} = A \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
- $H_{\rm LIV} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix}$

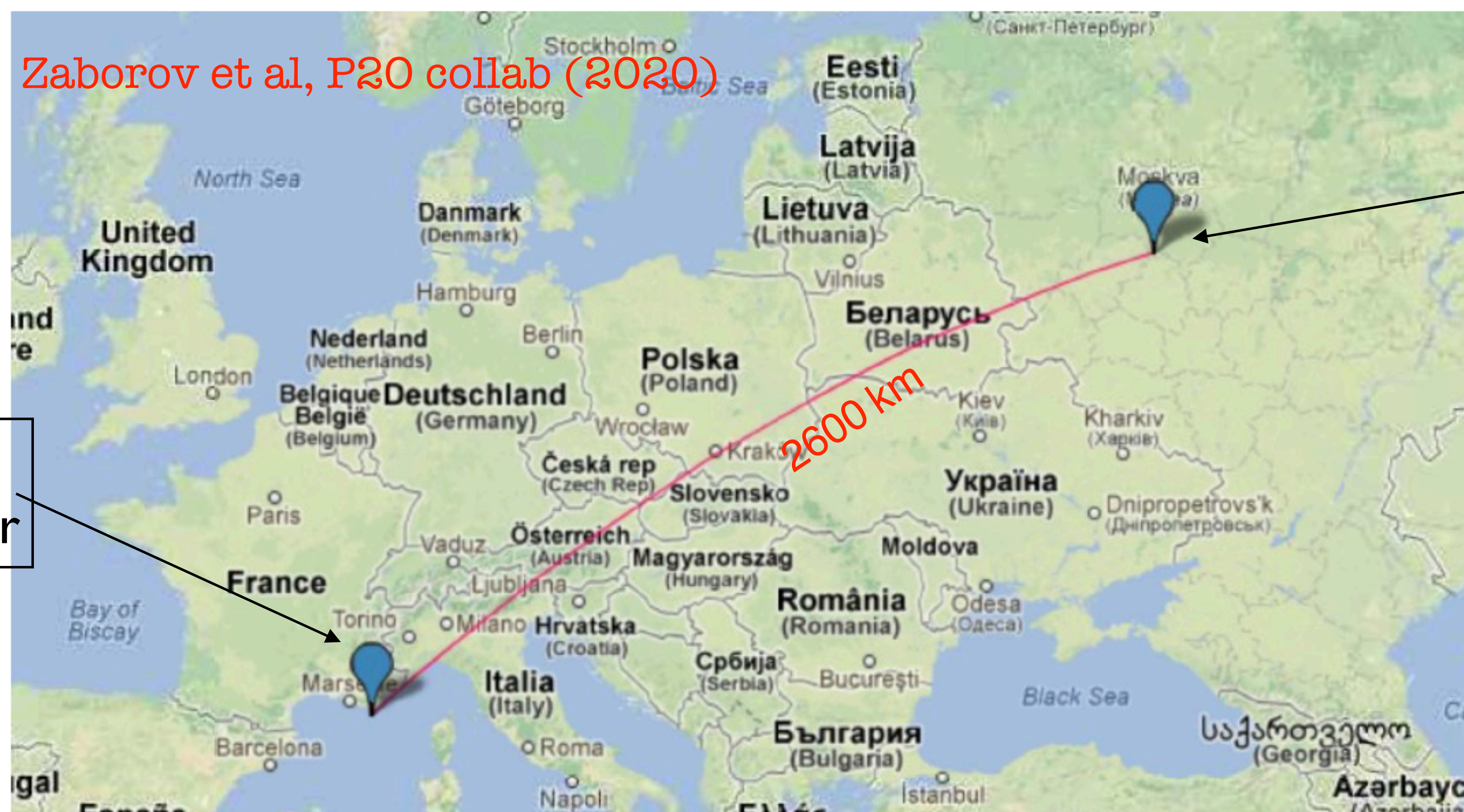
$(A = 2\sqrt{2} G_F N_e E)$

CPTV/ LIV are also probed in collider sectors: neutral meson mixing, $t\bar{t}$ production….

Schematics of DUNE & P2O



E ~ 2.5 GeV

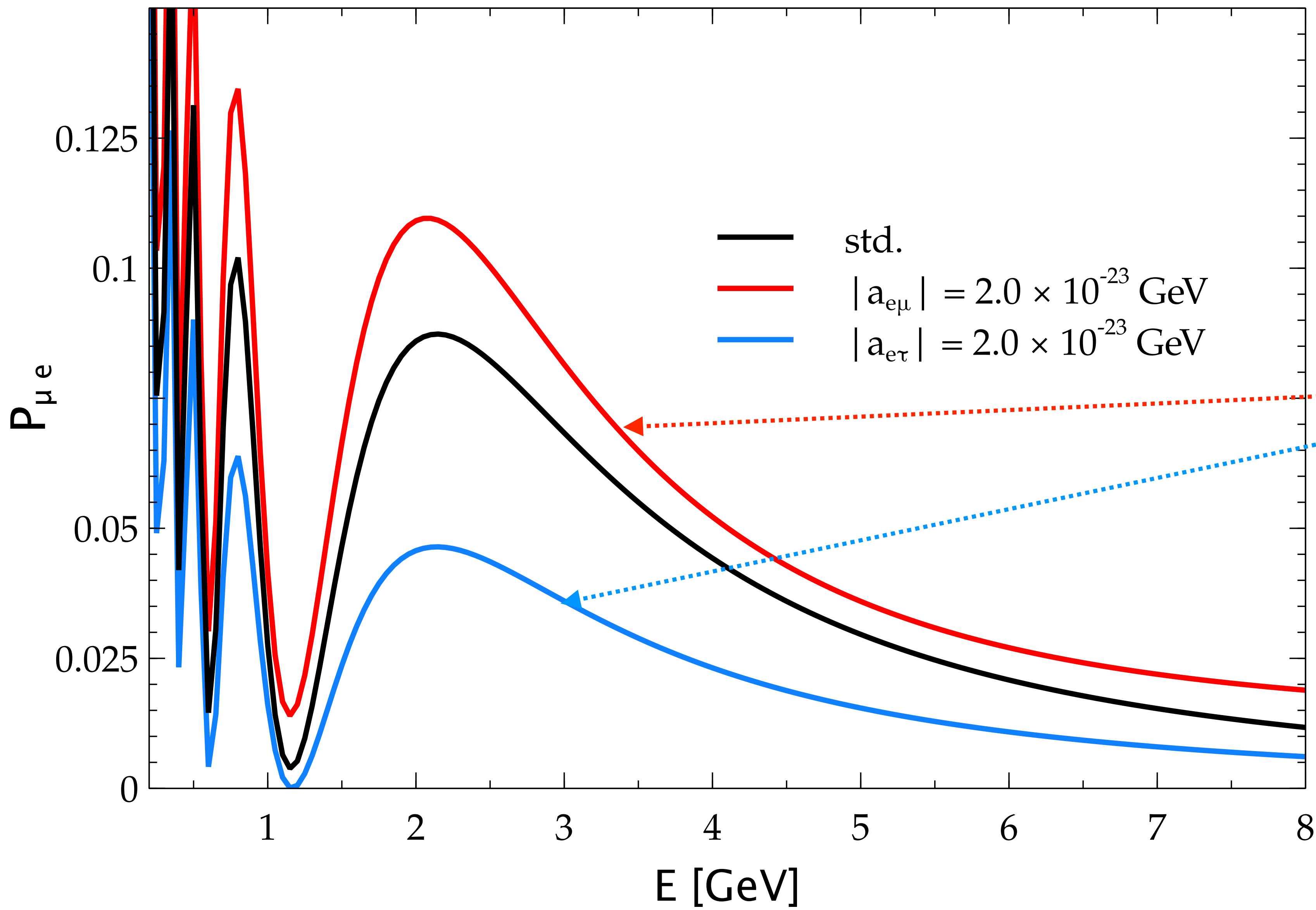


Protvino
accelerator
complex
90 kW beam

ORCA/KM3NET:
6 Mt cerencov detector

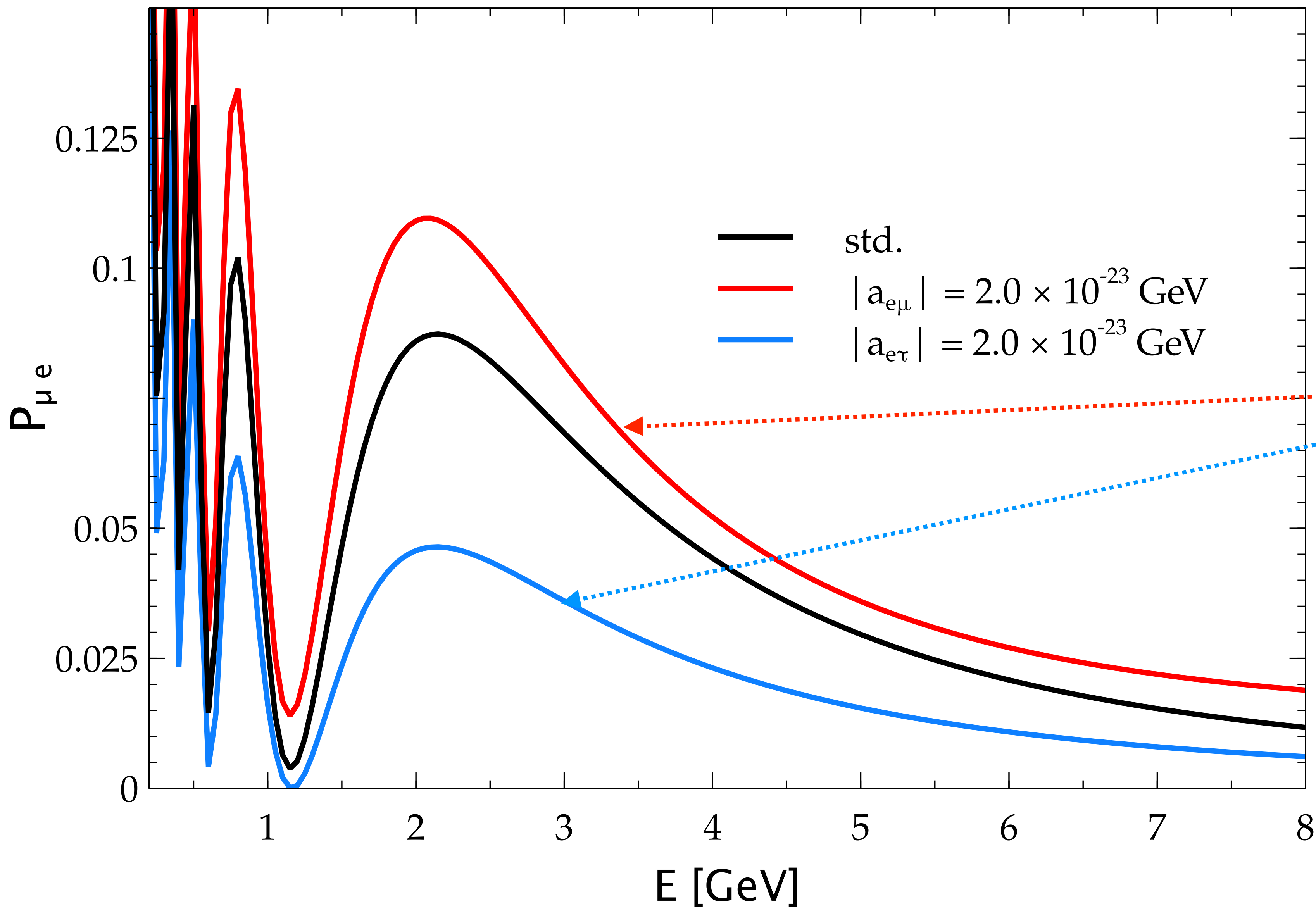
E ~ 5 GeV

Impact of LIV parameters at probability



$a_{e\mu}$ & $a_{e\tau}$ change in opposite directions

Impact of LIV parameters at probability



$a_{e\mu}$ & $a_{e\tau}$ change in opposite directions

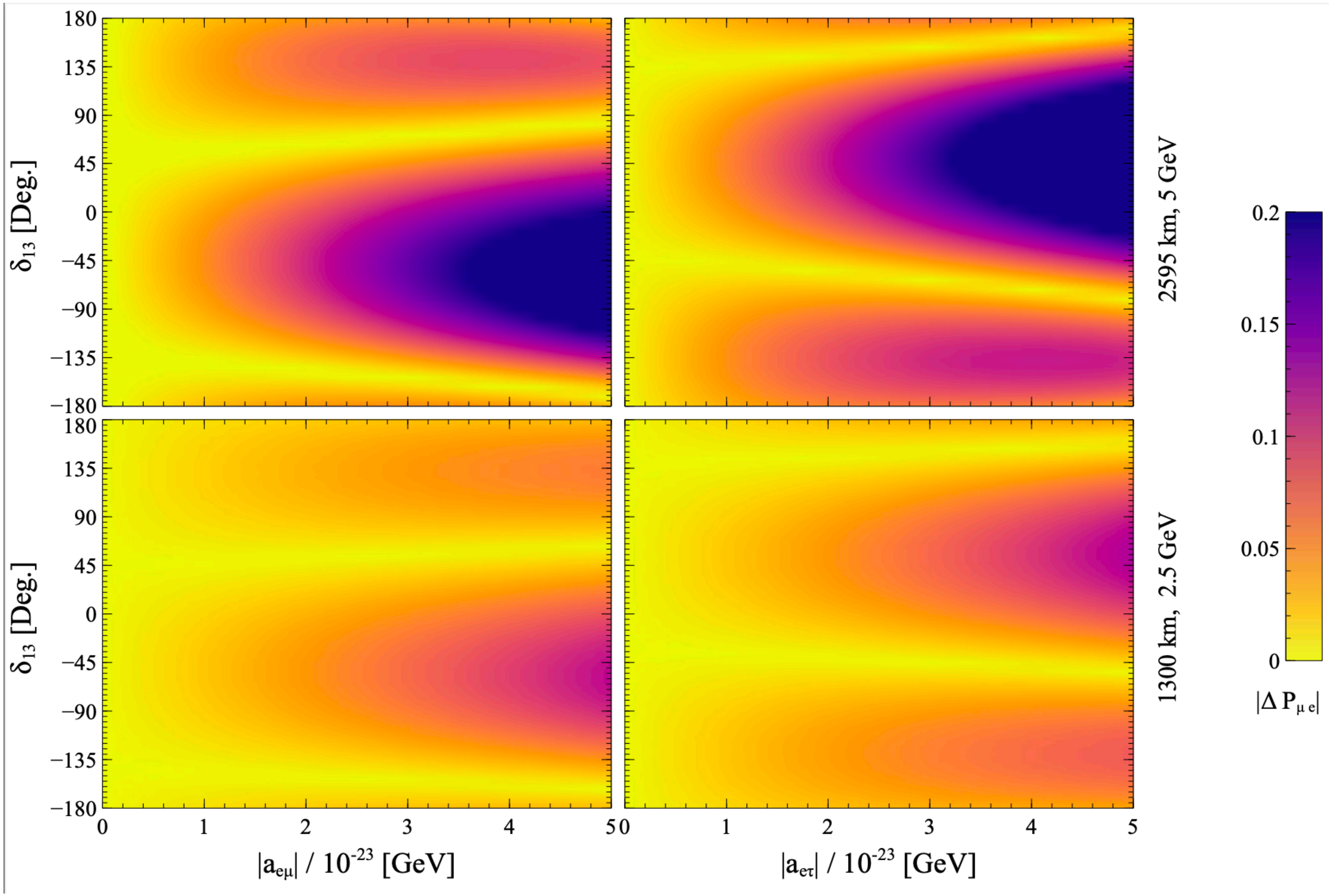
$\delta_{13} \simeq -122.4°$

$\Delta P = P(Std.+LIV) - P(Std.)$

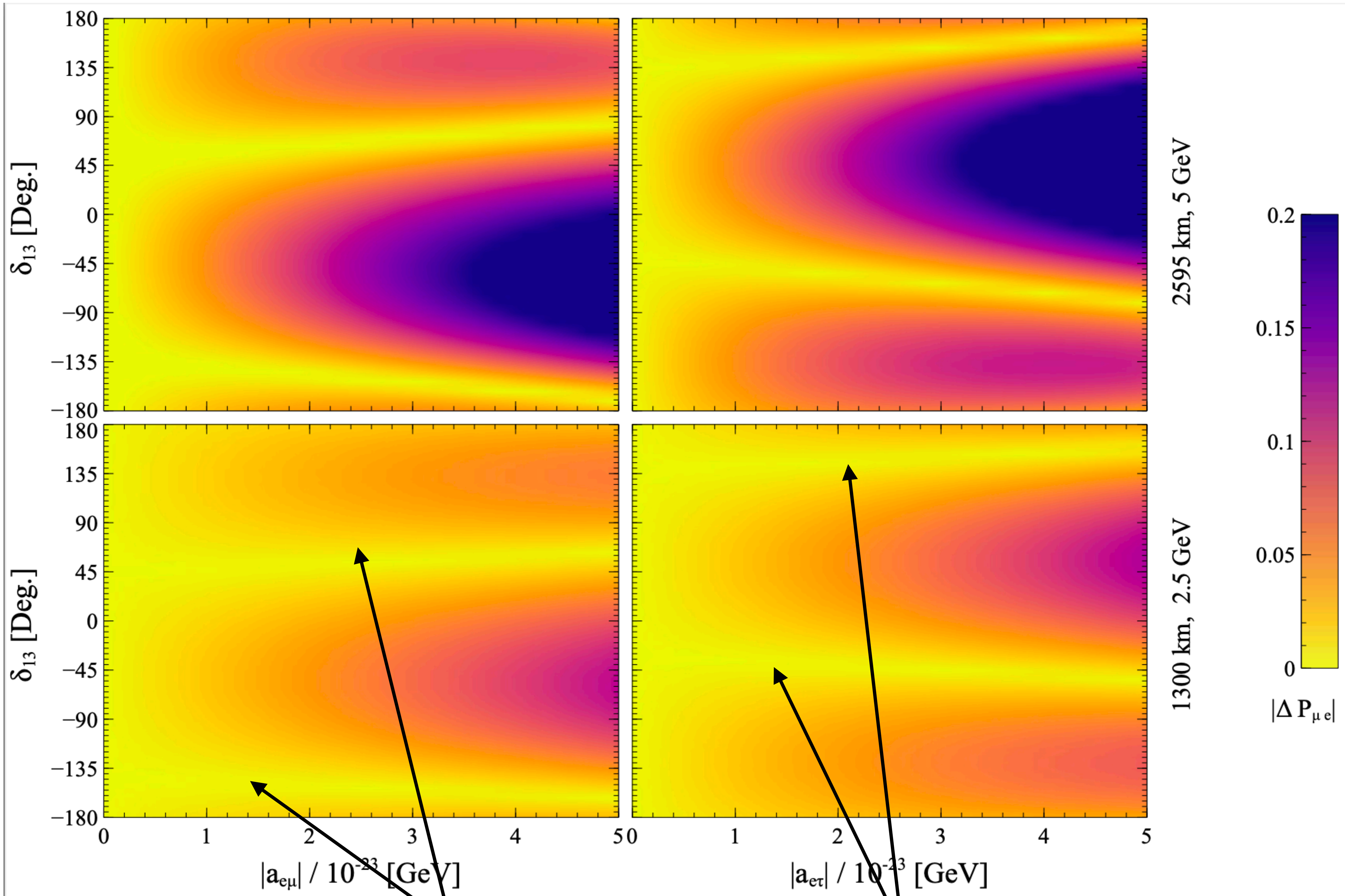
$$\Delta P_{\mu e}(|a_{e\mu}|) \simeq 8|a_{e\mu}|\frac{\pi}{2}E s_{13}\sin 2\theta_{23}c_{23}\left[-\sin\delta_{13} + \frac{2}{\pi}\frac{s_{23}^2}{c_{23}^2}\cos\delta_{13}\right], \quad +ve$$

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

$\Delta P_{\mu e}$ heatplots in $(\delta_{13} - a_{\alpha\beta})$ plane



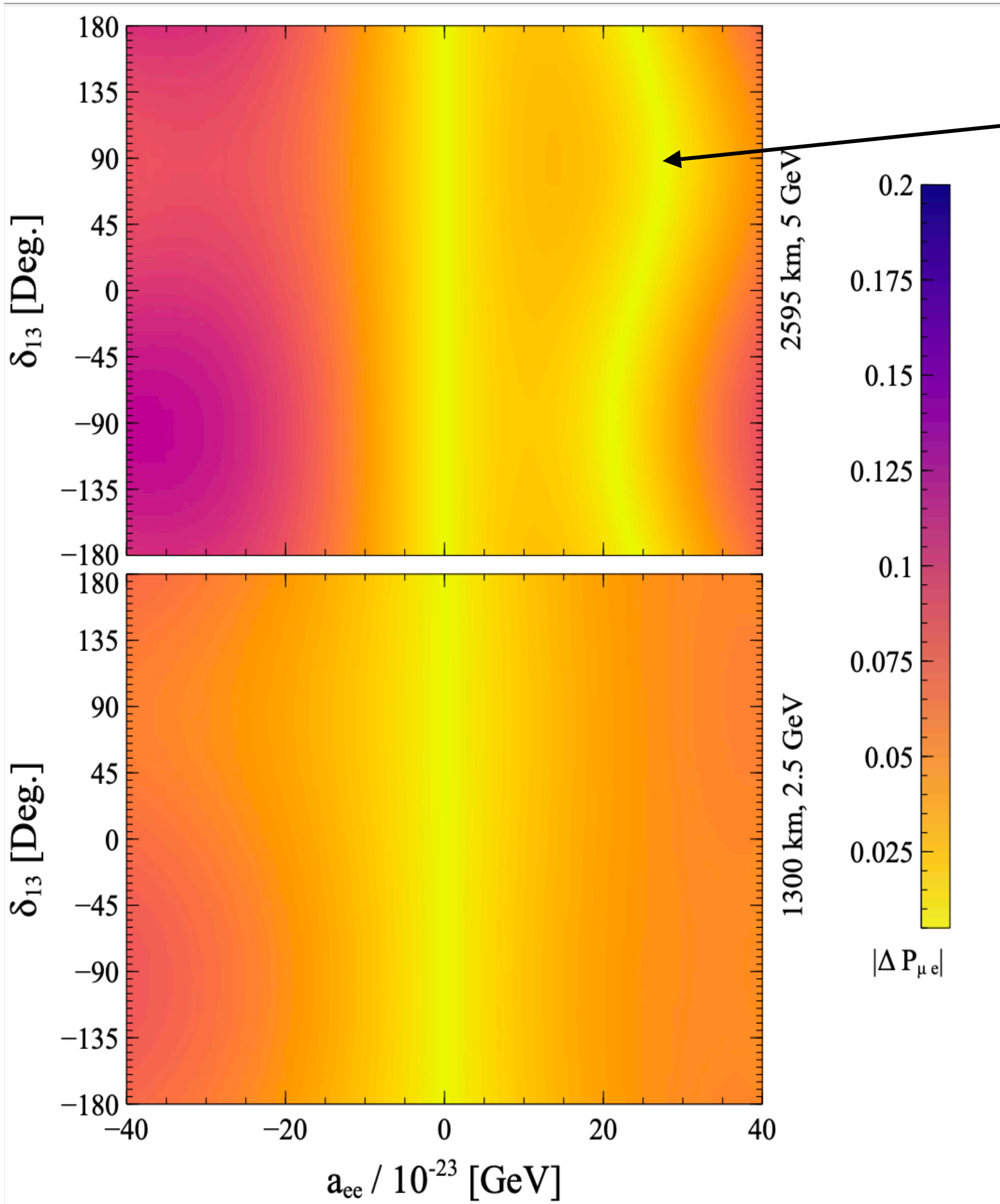
$\Delta P_{\mu e}$ heatplots in $(\delta_{13} - a_{\alpha\beta})$ plane



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

$$\sin \delta_{13} = -\frac{2}{\pi} \cos \delta_{13}$$

$\Delta P_{\mu e}$ heatplots in $(\delta_{13} - a_{ee})$ plane



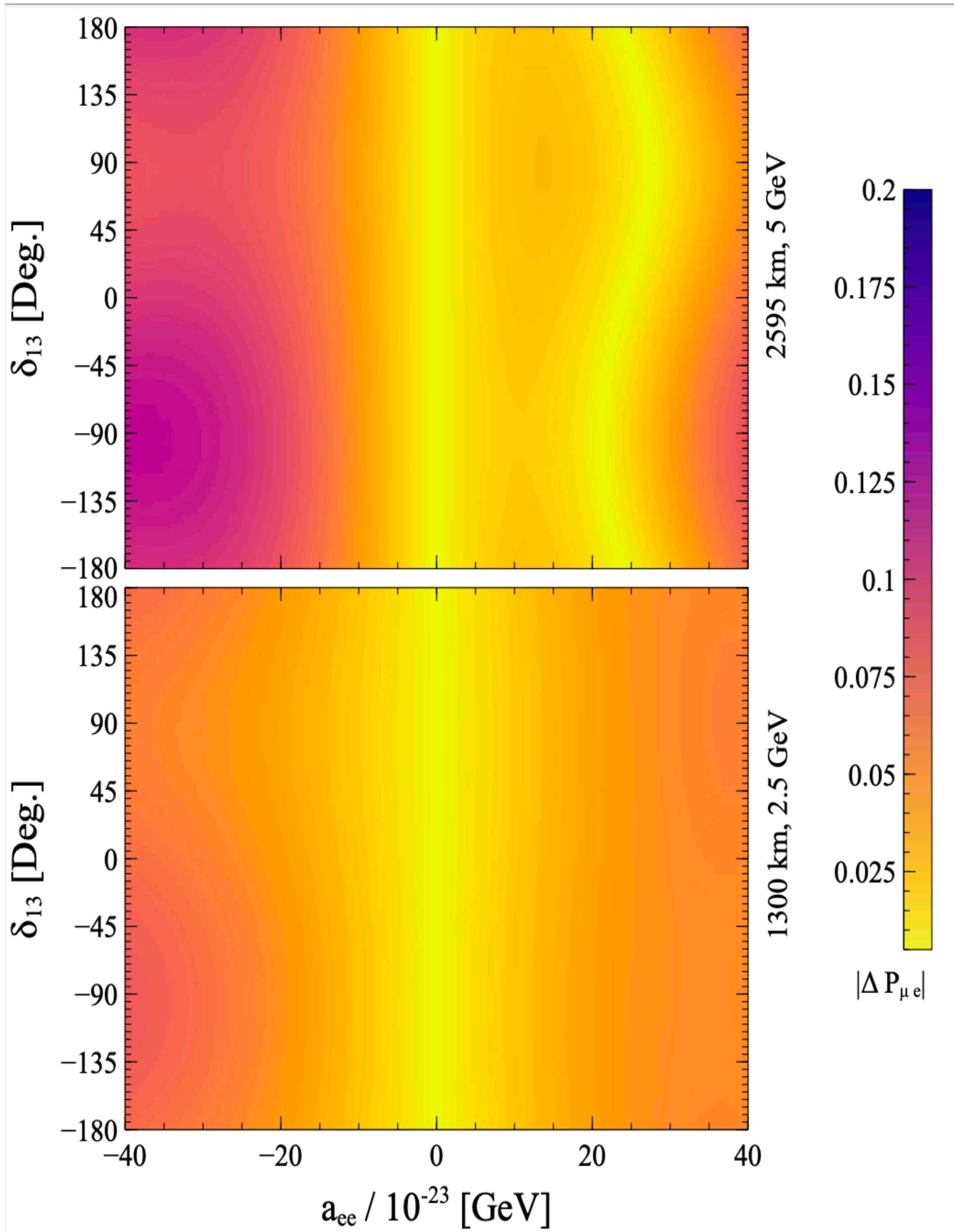
Additional degeneracy at
$\varepsilon_{ee} \simeq 20 \times 10^{-23}$ GeV

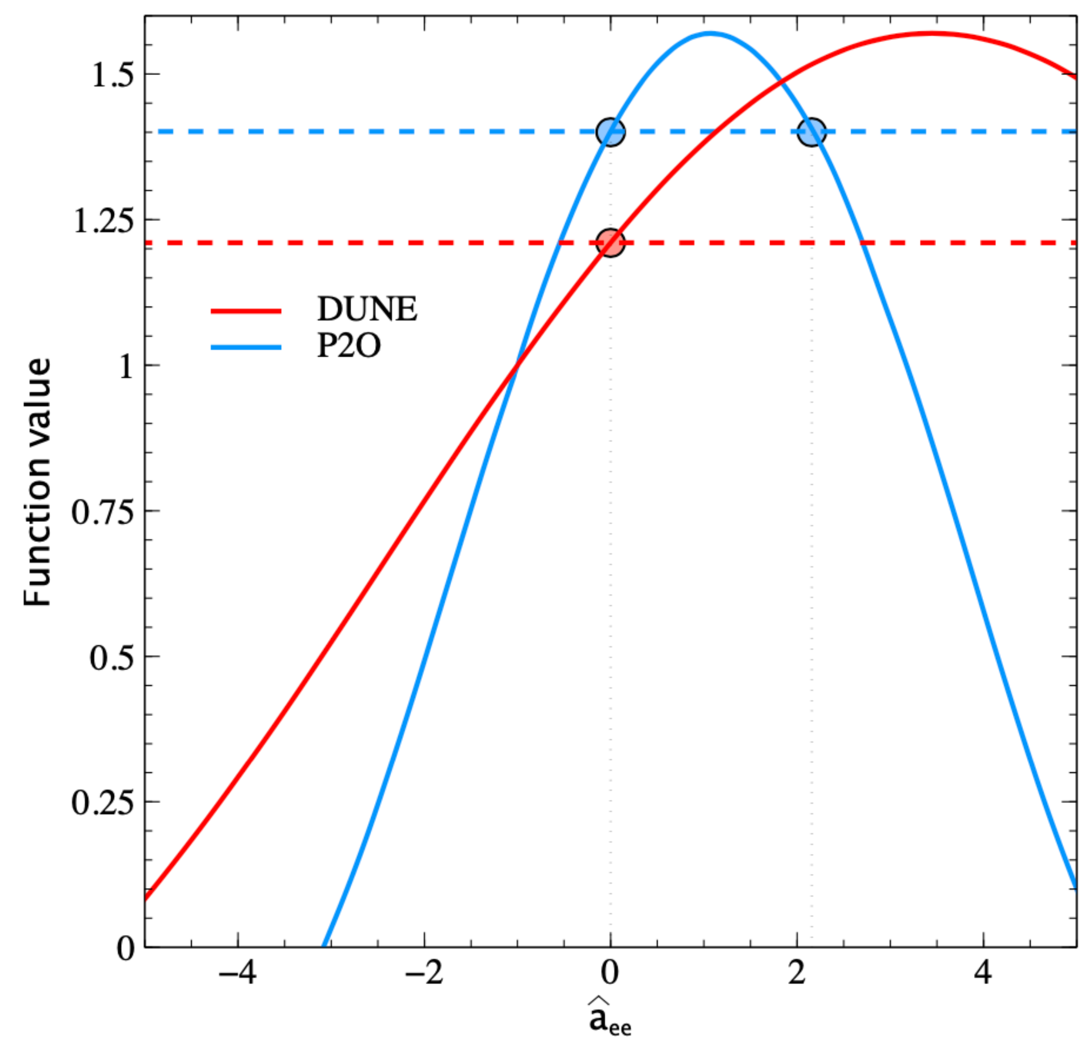
$\Delta P_{\mu e}$ heatplots in $(\delta_{13} - a_{\alpha\beta})$ plane

$$\hat{A} \to \hat{A}[1 + a_{ee}/\sqrt{2}G_F N_e] = 2\sqrt{2}G_F N_e E[1 + a_{ee}/\sqrt{2}G_F N_e] = \hat{A}[1 + \hat{a}_{ee}]$$

(Define $\hat{a}_{ee} = a_{ee}/\sqrt{2}G_F N_e$)

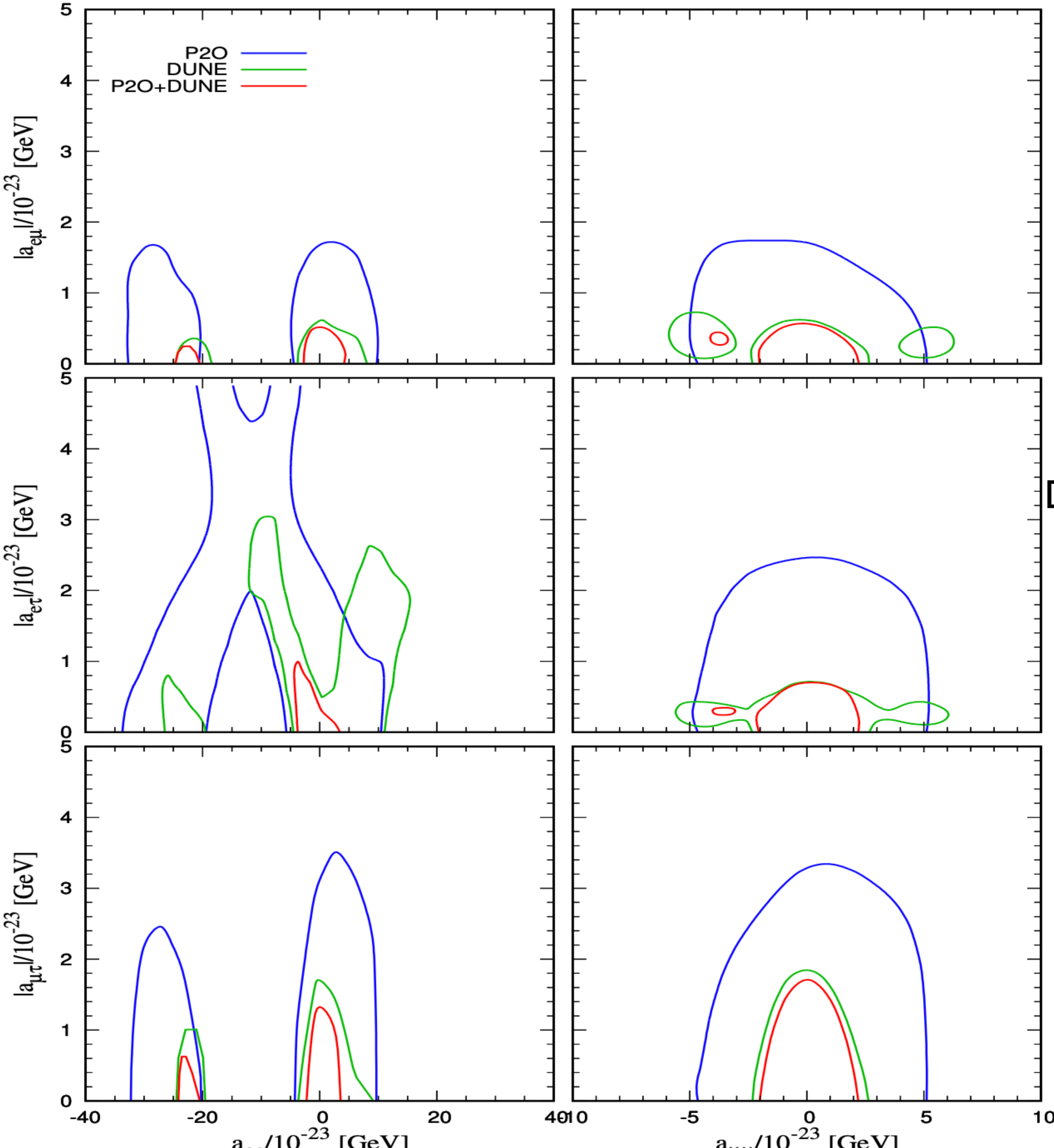
$$\Delta P_{\mu e}(a_{ee}) = 0 \implies \left[\frac{\sin[1-\hat{A}(1+\hat{a}_{ee})]\Delta}{1-\hat{A}(1+\hat{a}_{ee})} - \frac{\sin[1-\hat{A}]\Delta}{1-\hat{A}}\right] = 0$$





P2O has two solutions in this range

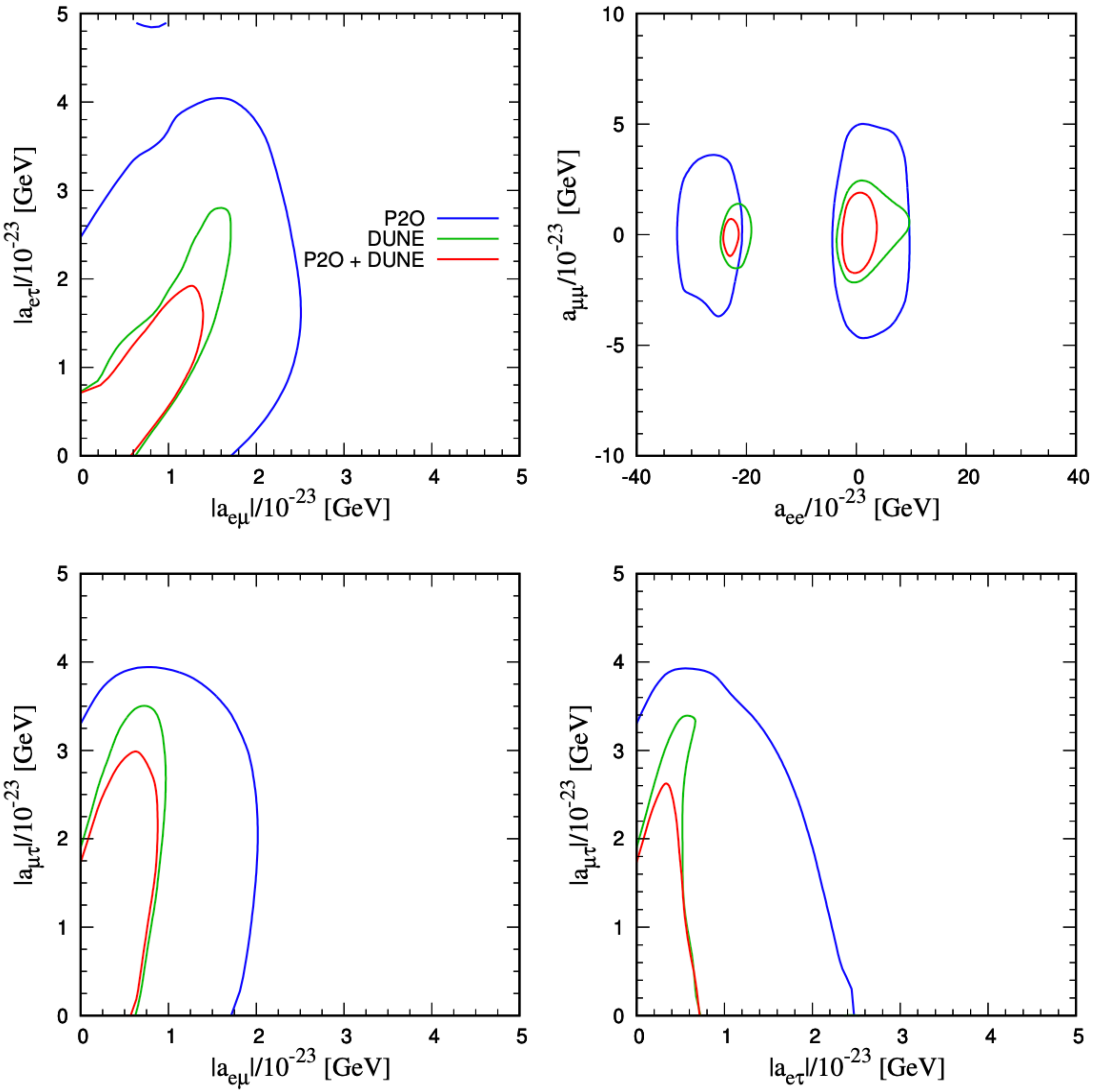
LIV-LIV parameter space ($a_{\alpha\beta} - a_{\gamma\gamma}$) at 95% C.L.



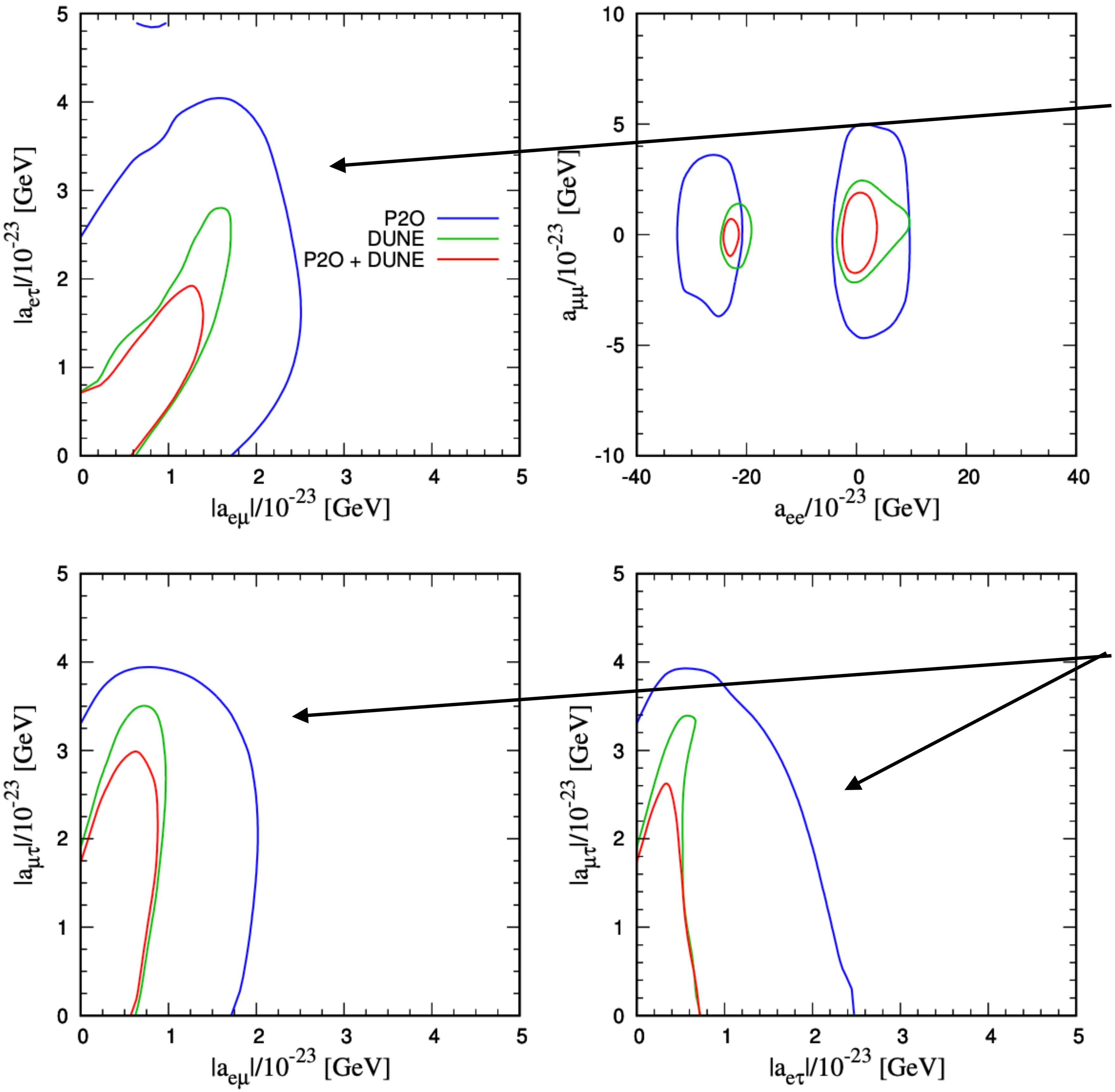
$\Delta\chi^2_{\text{min}}$ after marginalization over $\theta_{23}, \delta_{13}, \Delta m^2_{31}$ (sign, magnitude)

Degeneracy at $a_{ee} \simeq -20 \times 10^{-23}$ GeV (due to mass ordering marginalization)

LIV-LIV parameter space



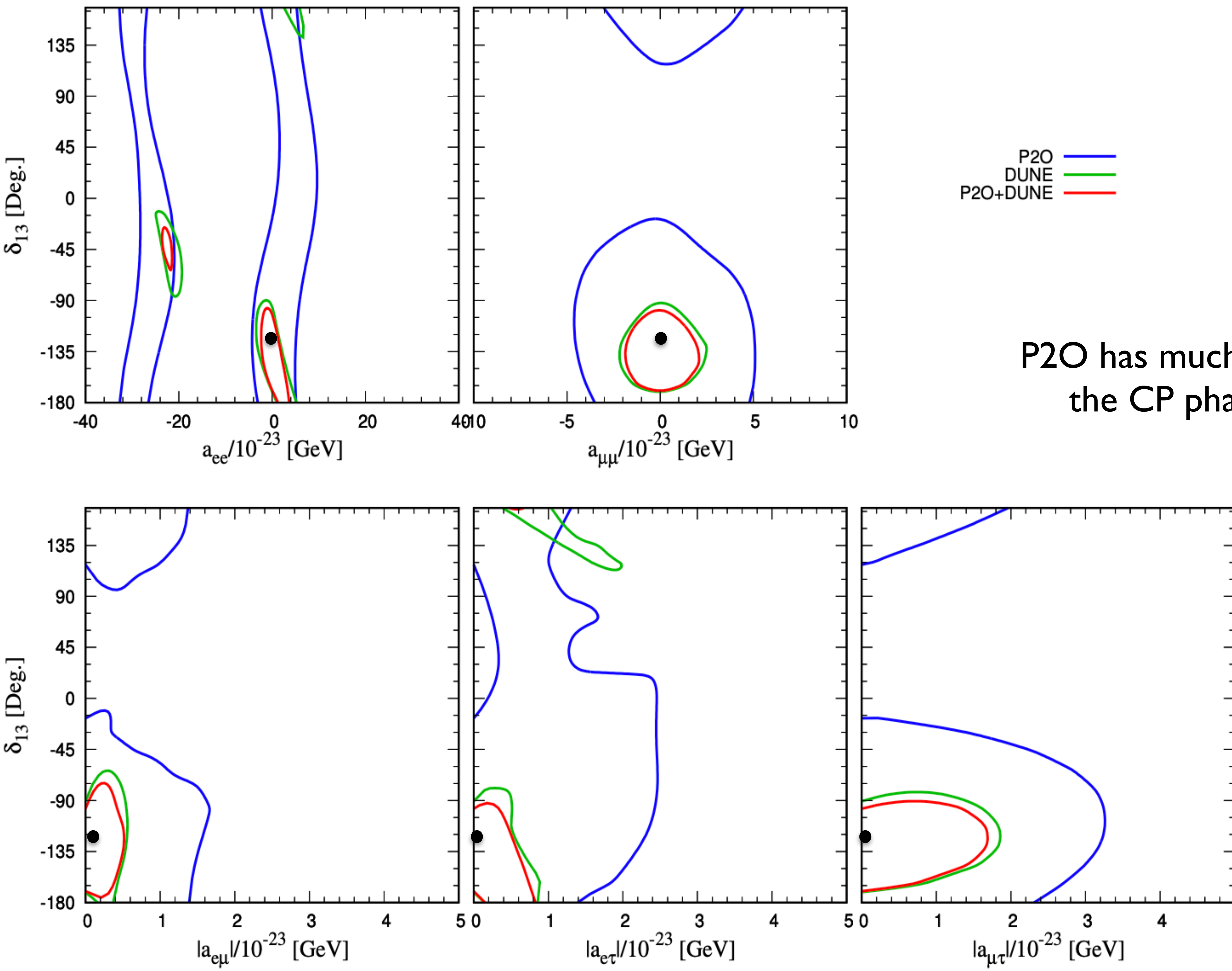
LIV-LIV parameter space



Similar impacts for $a_{e\mu}$ & $a_{e\tau}$

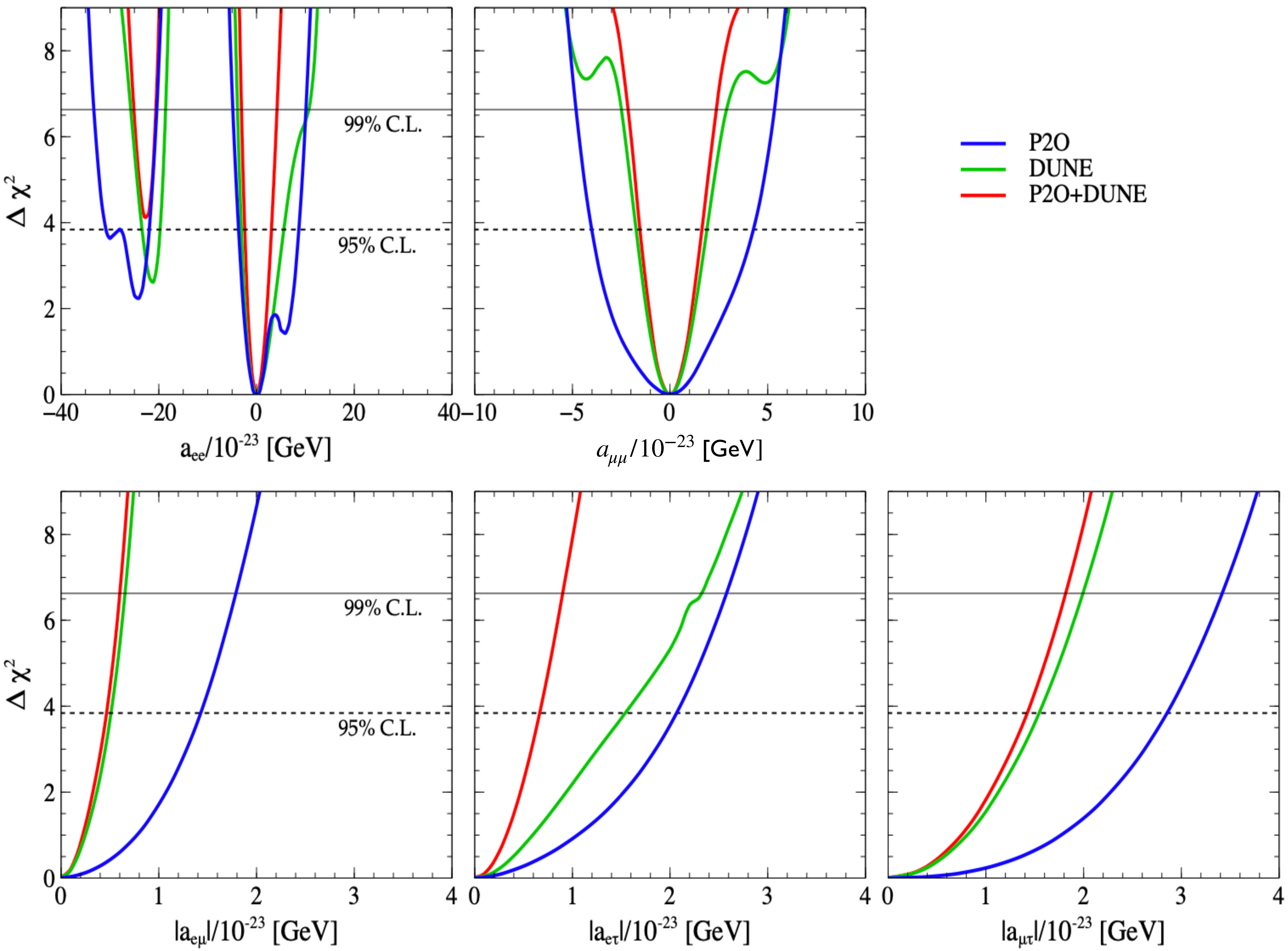
Not as effective in probing $a_{\mu\tau}$

LIV-SI(δ_{13}) parameter space

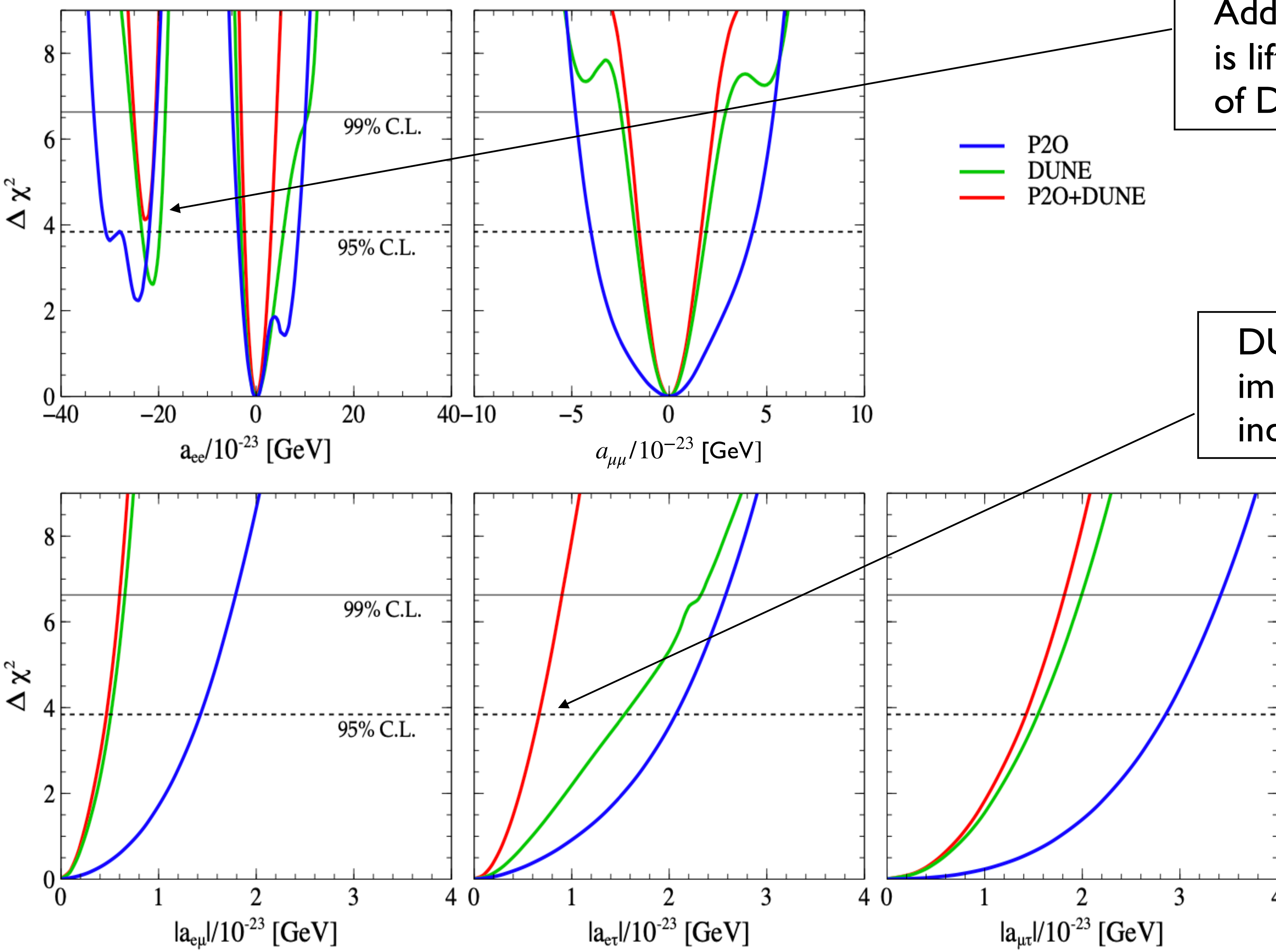


P2O has much less sensitivity to the CP phase than DUNE

Constraints on LIV parameters



Constraints on LIV parameters



Additional degeneracy for a_{ee} is lifted at 95% on combination of DUNE+P2O

DUNE+P2O shows marked improvement compared to individual bounds

Constraints on LIV parameters (95% C.L.)

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

Constraints on LIV parameters (95% C.L.)

Parameter	Bounds from DUNE $[10^{-23}\,\text{GeV}]$	Bounds from P2O $[10^{-23}\,\text{GeV}]$	Bounds from (P2O+DUNE) $[10^{-23}\,\text{GeV}]$
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

SK:

$$|a_{e\mu}| \lesssim 3.2 \times 10^{-23}\ \text{GeV};$$

$$|a_{e\tau}| \lesssim 5 \times 10^{-23}\ \text{GeV}.$$

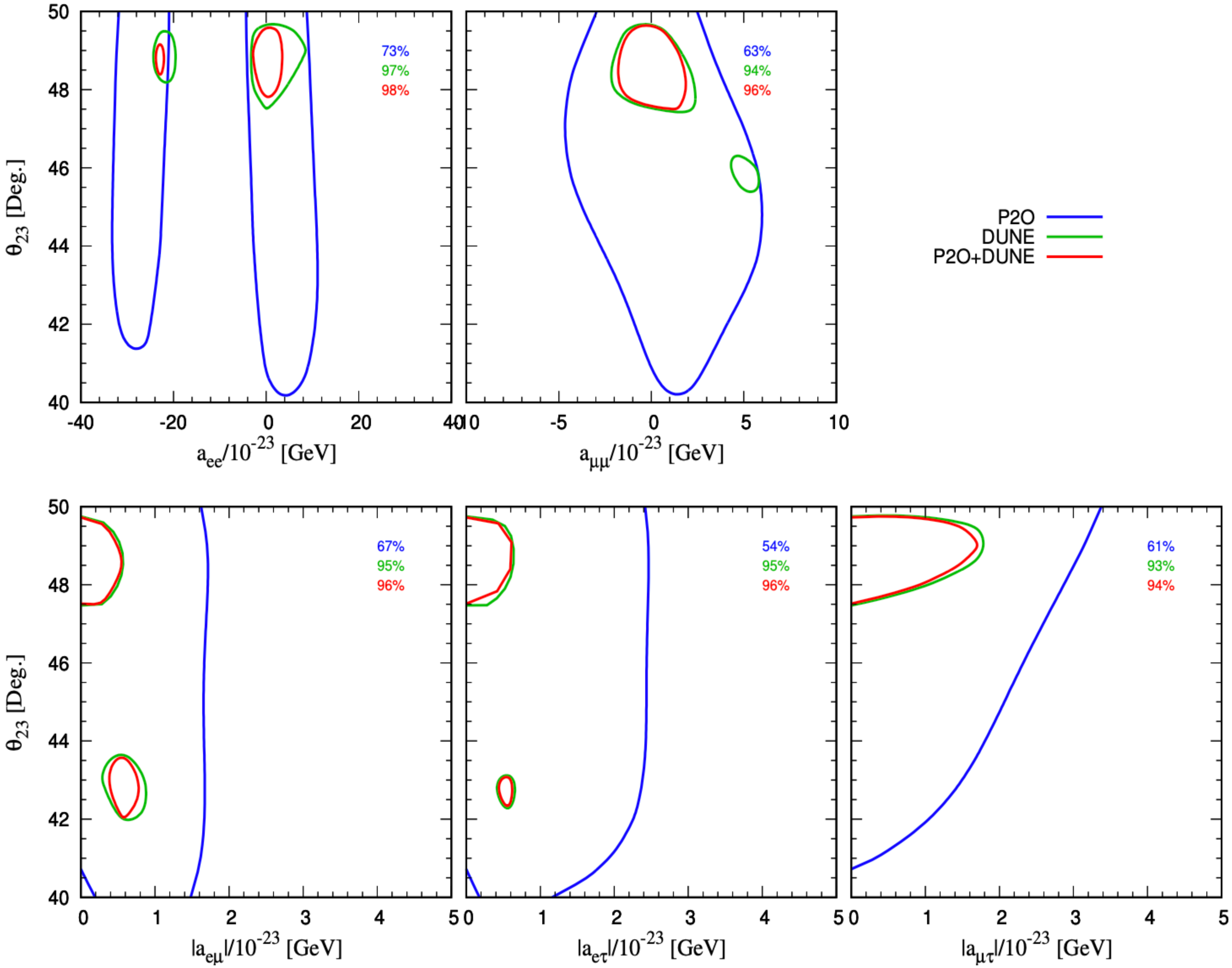
IceCube:

$$|a_{\mu\tau}| \lesssim 0.41 \times 10^{-23}\ \text{GeV}.$$

Summary

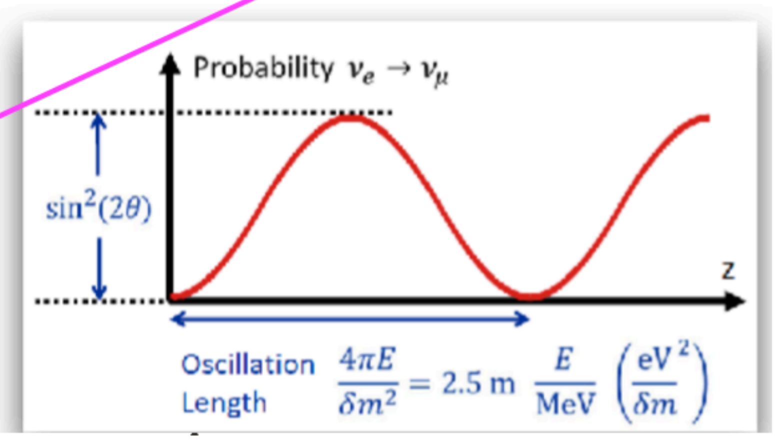
- LIV in $ee, e\mu, e\tau$ sector can be efficiently explored in LBL expts.
- Interesting degeneracies at different L,E: can be understood from probability analysis
- DUNE & P2O can help lift hard-to-remove degeneracies for LIV in ee sector
- Improvement of bounds by factors of 7-8 on $a_{e\mu}, a_{e\tau}$

LIV-SI(θ_{23}) parameter space



Backup

- Each ν_k propagates as e^{-iE_kL} with $E_k \simeq \sqrt{|\vec{p}|^2 + m_k^2} \simeq E + \frac{m_k^2}{2E}$ where $E \simeq |\vec{p}|$
- Oscillation arises due to the difference $\Delta m_{kj}^2 = m_k^2 - m_j^2$
- $P(\nu_\mu \to \nu_e) = |<\nu_e|\nu_\mu(L)>|^2$
  $= \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$



$\simeq 1.27 \times \frac{\delta m^2[eV^2]\,.\,L[km]}{E[GeV]} \simeq \pi/2$

(For maximal oscillation)

$\frac{L[km]}{E[GeV]} \sim (\delta m^2[eV^2])^{-1}$

Main Principle for Long-Baseline expts.

Leptonic CP violation?

Table: de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle: 2006.11237

Oscillation parameter	Best fit value	3σ range
$\theta_{12}/°$	34.3	[31.4, 37.4]
$\theta_{23}/°$	48.8	[41.6, 51.3]
$\theta_{13}/°$	8.6	[8.2, 8.9]
δ_{13}/π	-0.8	$[-1, 0] \cup [0.8, 1]$
$\Delta m^2_{21}/10^{-5}$ eV^2	7.5	[6.9, 8.1]
$\Delta m^2_{31}/10^{-3}$ eV^2	2.6	[2.5, 2.7]

Is the CP phase non-zero?
could help explain baryon asymmetry

$$
\begin{aligned}
P_{\mu e} &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(1-A)\Delta}{1-A} \\
&+ \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2 A\Delta}{A} \\
&+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta + \Delta)
\end{aligned}
$$

where,

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

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

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Backup

$$\Delta P_{\mu e}(a_{ee}) \simeq 4s_{13}^2c_{13}^2s_{23}^2\left\{\frac{\sin^2\left[1-\hat{A}(1+a_{ee}/\sqrt{2}G_FN_e)\right]\Delta}{\left[1-\hat{A}(1+a_{ee}/\sqrt{2}G_FN_e)\right]^2}-\frac{\sin^2\left[1-\hat{A}\right]\Delta}{\left[1-\hat{A}\right]^2}\right\}+\cos\delta_{13}\text{-term.}$$

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

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

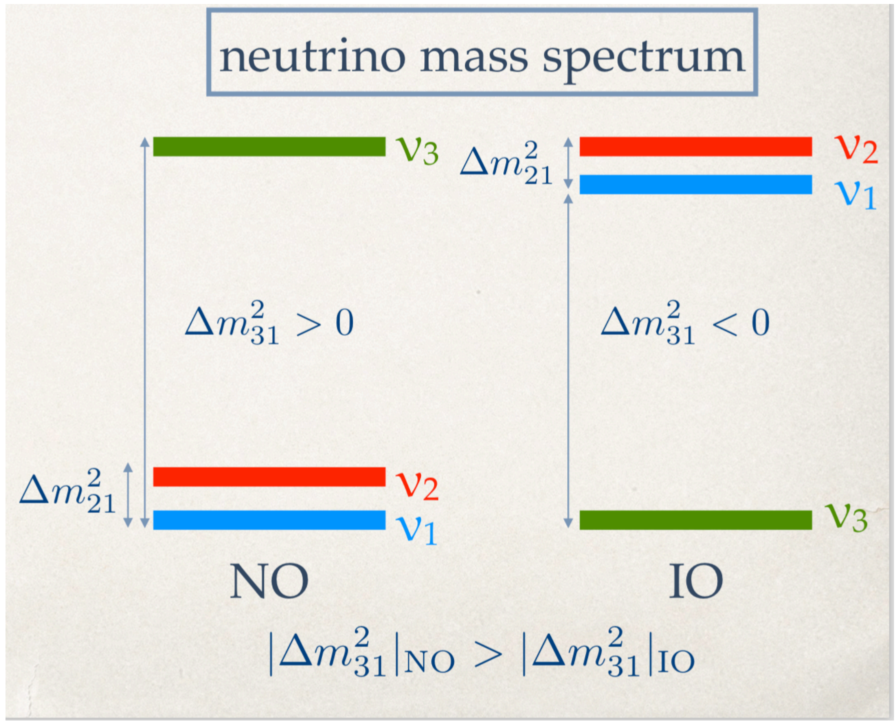
$$\sim\underbrace{\left[\frac{\sin\left[1-\hat{A}(1+\hat{a}_{ee})\right]\Delta}{1-\hat{A}(1+\hat{a}_{ee})}-\frac{\sin\left[1-\hat{A}\right]\Delta}{1-\hat{A}}\right]}_{\text{I}_-}\times\underbrace{\left[\frac{\sin\left[1-\hat{A}(1+\hat{a}_{ee})\right]\Delta}{1-\hat{A}(1+\hat{a}_{ee})}+\frac{\sin\left[1-\hat{A}\right]\Delta}{1-\hat{A}}\right]}_{\text{I}_+}.$$

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

Mass ordering ambiguity

Table: de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle: 2006.11237

Oscillation parameter	Best fit value	3σ range
$\theta_{12}/^\circ$	34.3	$[31.4, 37.4]$
$\theta_{23}/^\circ$	48.8	$[41.6, 51.3]$
$\theta_{13}/^\circ$	8.6	$[8.2, 8.9]$
δ_{13}/π	-0.8	$[-1, 0] \cup [0.8, 1]$
$\Delta m^2_{21}/10^{-5}$ eV^2	7.5	$[6.9, 8.1]$
$\Delta m^2_{31}/10^{-3}$ eV^2	2.6	$[2.5, 2.7]$



What is the sign of Δm^2_{31} ?

$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{1-A} + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A} + \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\delta + \Delta)$$

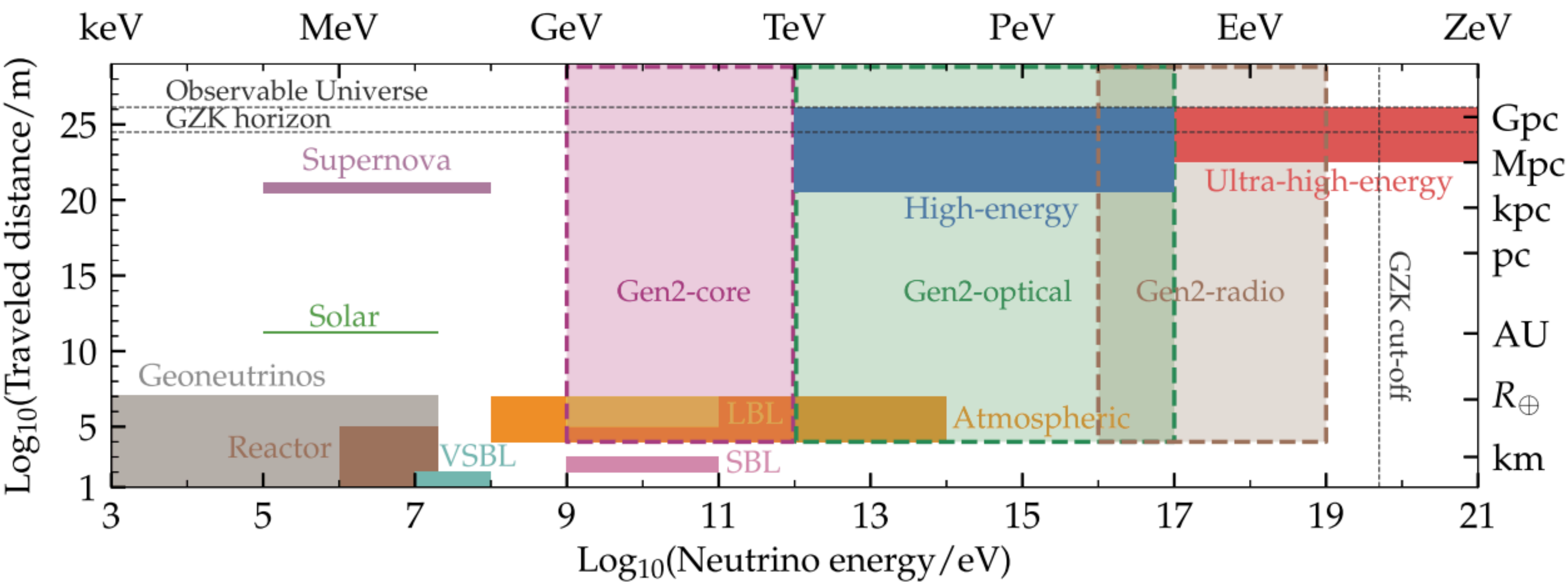
where,

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

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

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Icecube-Gen2



Artsen et al . 2021 (JPG)

Chisquare

$$\Delta\chi^2(p^{\text{true}}) = \underset{p^{\text{test}},\eta}{\text{Min}}\left[2\sum_{k}^{\text{mode}}\sum_{j}^{\text{channel}}\sum_{i}^{\text{bin}}\left\{N_{ijk}^{\text{test}}(p^{\text{test}};\eta) - N_{ijk}^{\text{true}}(p^{\text{true}}) + N_{ijk}^{\text{true}}(p^{\text{true}})\ln\frac{N_{ijk}^{\text{true}}(p^{\text{true}})}{N_{ijk}^{\text{test}}(p^{\text{test}};\eta)}\right\} + \sum_{l}\frac{(p_l^{\text{true}} - p_l^{\text{test}})^2}{\sigma_{p_l}^2} + \sum_{m}\frac{\eta_m^2}{\sigma_{\eta_m}^2}\right].$$