Probing new physics with high energy appearance events @ NOvA

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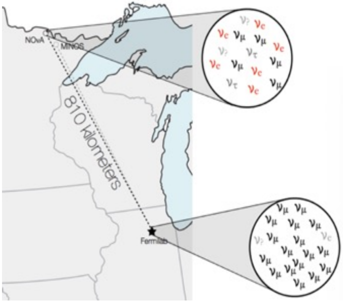
Indian Institute of Technology Hyderabad

Plan

1. Non-standard interactions (NSIs).
2. Constraining matter NSI paremeters with NOvA HE events.
3. Environmental neutrino decoherence.
4. Constraining decoherence params with NOvA HE events.
5. Conclusions

NOvA experiment

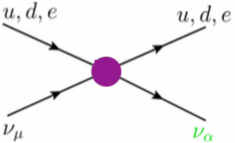
- NOvA : NuMI Off-axis ν_e Appearance Experiment with a baseline of 810 km.
- ν_μ beam produced : Fermilab's NuMI beam facility directed at an off-axis angle : 14.6 milli radians.
- Two identical liquid scintillator detectors.
- Primary Objective : To determine three-flavour neutrino oscillation parameters.
- NOvA uses $1 < E_\nu < 4$ GeV ν_e events to achieve this goal.



In this work, we consider $4 < E_\nu < 20$ GeV ν_e events (NOvA side band events) to study the sub-leading effects.

Non-standard interactions (NSIs)

Non-standard interactions (NSIs)

- NSI speculated by L. Wolfenstein, in his seminal paper [Phys. Rev. D17, 2369 (1978)], before the discovery of neutrino oscillations.
- 

  - Standard NC interaction : $\nu_\alpha + f \to \nu_\alpha + f$
  - Non-Standard NC interaction : $\nu_\alpha + f \to \nu_\beta + f$
- The effective four fermion Lagrangian density

$$\mathcal{L}^{NC}_{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{fC}_{\alpha\beta}(\overline{\nu}_\alpha\gamma^\rho P_L\nu_\beta)(\bar{f}\gamma_\rho P_C f) + \text{h.c.} \tag{1}$$

- The effective Hamiltonian

$$H_{eff} \simeq \frac{1}{2E}U\,\text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U^\dagger + V\,. \tag{2}$$

- The matter potential V

$$V = 2\sqrt{2}G_F N_e(r)E \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}, \tag{3}$$

Modified Appearance probability $P_{\mu e}$

- The Appearance probability for (NH) : expressed in terms of s_{13}, $r = \Delta m^2_{21}/\Delta m^2_{31}$ and $\epsilon_{e\tau}$ (small parameters), ϵ_{ee} :

$$\begin{aligned} P_{\mu e} &= x^2 f^2 + 2xyfg\cos(\Delta + \delta_{CP}) + y^2 g^2 + \\ &+ 4\hat{A}\epsilon_{e\tau} s_{23}c_{23}(xf[f\cos(\phi_{e\tau}+\delta) - g\cos(\Delta+\delta+\phi_{e\tau})] \\ &- yg[g\cos\phi_{e\tau} - f\cos(\Delta - \phi_{e\tau})]) \\ &+ \mathcal{O}(s^2_{13}\epsilon_{e\tau}, s_{13}\epsilon^2_{e\tau}, \epsilon^3_{e\tau}) + \mathcal{O}(\epsilon_{e\mu}) + h.o. \end{aligned} \tag{4}$$

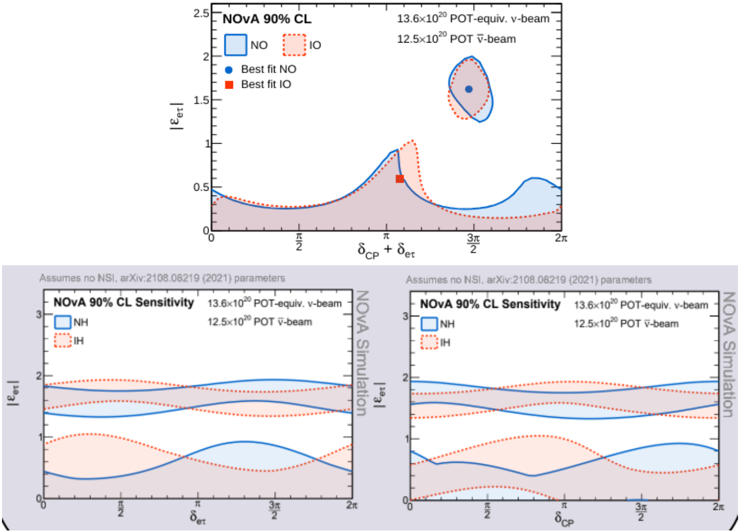
$$x = 2s_{13}s_{23},\ \ y = rc_{23}\sin 2\theta_{12},\ \ \Delta = \frac{\Delta m^2_{31}L}{4E},\ \ \hat{A} = \frac{A}{\Delta m^2_{31}},$$

$$f, \bar{f} = \frac{\sin[\Delta(1 \mp \hat{A}(1+\epsilon_{ee}))]}{(1 \mp \hat{A}(1+\epsilon_{ee}))}\,,\ \ g = \frac{\sin[\hat{A}(1+\epsilon_{ee})\Delta]}{\hat{A}(1+\epsilon_{ee})}$$

[Liao, Marfatia, Whisnant, Phys. Rev. D 93, 093016]

- For IH : $\Delta \to -\Delta$ and $\hat{A} \to -\hat{A}$

NOvA collaboration results (arXiv: 2403.07266)



NOvA Collaboration: fig. 4 in ref. *arxiv:2403.07266* (upper). On behalf of the NOvA collaboration: figure from ref. *FERMILAB-POSTER-22-033-ND* (lower).

Our work

Constraining NSI parameters using NOvA HE events

Parameters

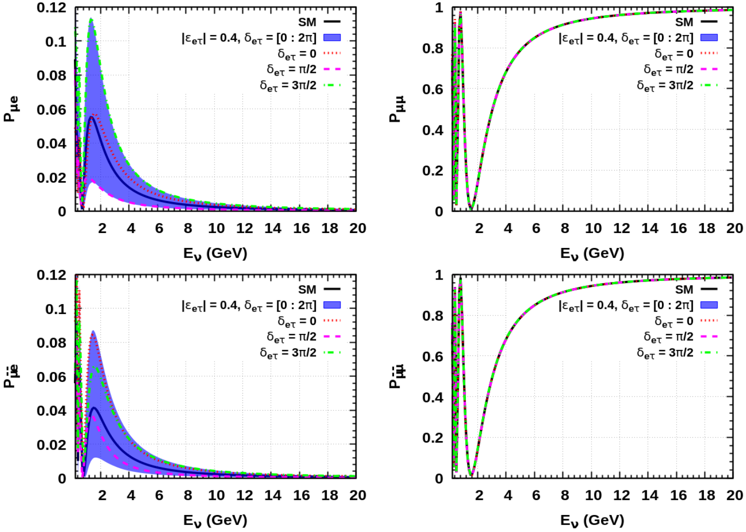
- Simulation details and oscillation parameters are taken from ref. *Phys. Rev. D 106 (3) (2022) 032004.*
  - Run time : 6 years for ν and 3 years for $\bar{\nu}$.
  - Exposure : 13.6×10^{20} POT for ν and 12.5×10^{20} POT for $\bar{\nu}$.
  - Target volume (FD) : 14 kton.
  - Baseline : 810 km.
  - Earth's crust density : 2.84 gm/cm^3 .

Parameters	True values	3σ ranges
$\sin^2\theta_{12}$	0.307	Fixed
$\sin^2\theta_{13}$	0.021	[0.02 : 0.02405]
$\sin^2\theta_{23}$ NH (IH)	0.57 (0.56)	[0.38 : 0.64]
δ_{CP} NH (IH)	0.82π (1.52π)	$[0 : 2\pi]$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	7.53	Fixed
$\frac{\Delta m^2_{32}}{10^{-3}\ eV^2}$ NH (IH)	2.41 (−2.45)	[±2.29 : ±2.54]

Table: Standard oscillation parameters

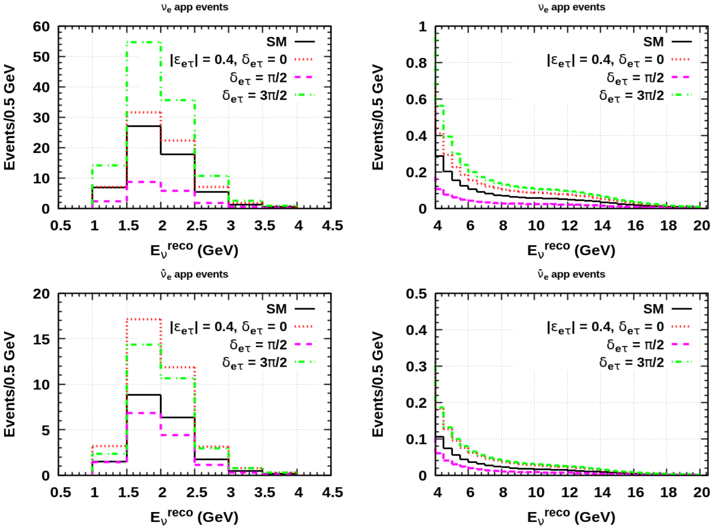
- NSI bounds : $|\epsilon_{e\tau}| \leq 0.4$ and $|\epsilon_{e\mu}| \leq 0.3$ (arxiv:2403.07266)

Oscillation probability in the presence of NSI (non-zero $\epsilon_{e\tau}$)



Oscillation probability when only $|\epsilon_{e\tau}|e^{i\phi_{e\tau}}$ is non zero.

Corresponding Event rates



Number of events when only $|\epsilon_{e\tau}|e^{i\phi_{e\tau}}$ is non zero.

Events rate

- NSI

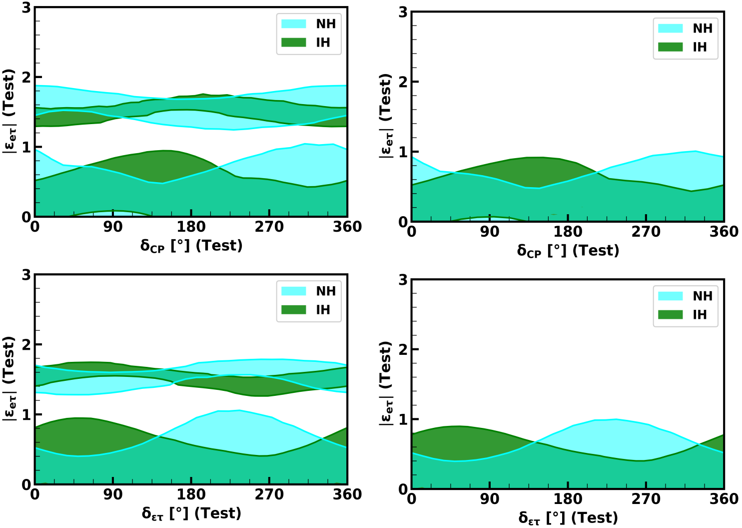
Cases		ν_e-app events			$\bar{\nu}_e$-app events		
		1 - 4 GeV	1 - 20 GeV	Excess	1 - 4 GeV	1 - 20 GeV	Excess
SM		59.0	61.0	2.0	19.0	19.6	0.6
$\lvert\epsilon_{e\tau}\rvert = 0.4$	$\delta_{e\tau} = 0$	70.0	73	3.0	36.3	37.4	1.1
	$\delta_{e\tau} = \pi/2$	19.0	20.0	1.0	14.1	14.4	0.3
	$\delta_{e\tau} = 3\pi/2$	118.3	122.3	4.0	31.3	32.4	1.1

Table: Excess events at HE considering $\epsilon_{e\tau} \neq 0$.

2D sensitivity of $\epsilon_{e\tau}$ versus δ_{CP} and $\delta_{e\tau}$ (95% CL)

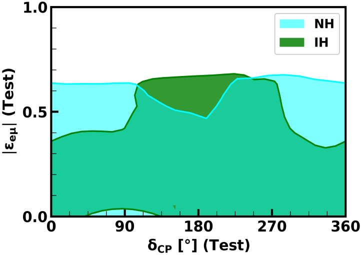
Including 1-5 GeV events

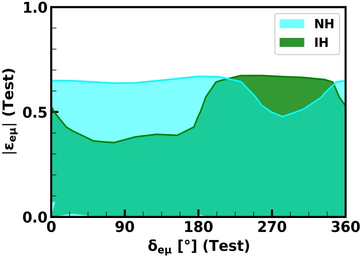
High energy events(1-20 GeV)



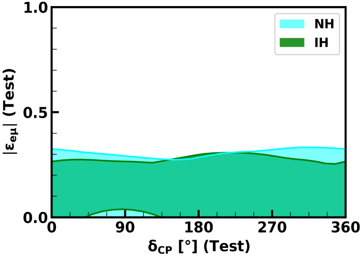
2D sensitivity of $\epsilon_{e\mu}$ versus δ_{CP} (95% CL)

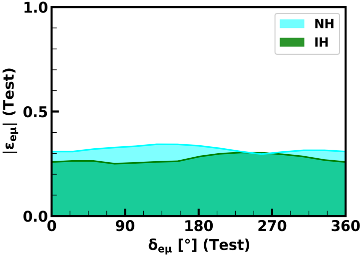
Including 1-5 GeV events





High energy events(1-20 GeV)





Conclusions

- The degenerate band observed around higher values of $\epsilon_{e\tau} > 1$ in the left side plot disappears when we consider the high energy events (1-20 GeV).
- Same conclusion can be drawn when the true hierarchy is assumed to be inverted hierarchy.
- Our conclusions agree with the conclusion drawn in the recent NOvA NSI paper (arXiv: 2403.07266) where the authors mention *"Analyzing a* ***wider range of neutrino energies****, and possibly combining with measurements from other experiments, is being explored to increase sensitivity to the upper contour in the future."*

Effect of environmental decoherence
@
NOvA HE

Environmental decoherence

- Neutrino system interacts with the stochastic environment.
- $\frac{d\tilde{\rho}_m(t)}{dt} = -i\left[H, \tilde{\rho}_m(t)\right] + \mathcal{D}\left[\tilde{\rho}_m(t)\right]$.
- **Assumptions:**
  (a) complete positivity,
  (b) trace preserving conditions,
  (c) increasing von Neumann entropy,
  (d) energy conservation of the neutrino system.

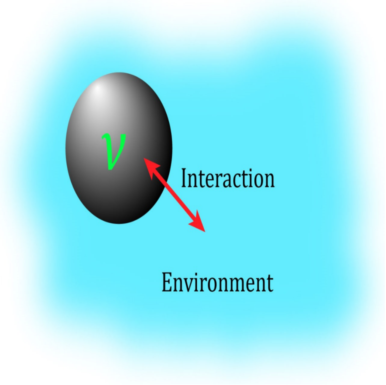


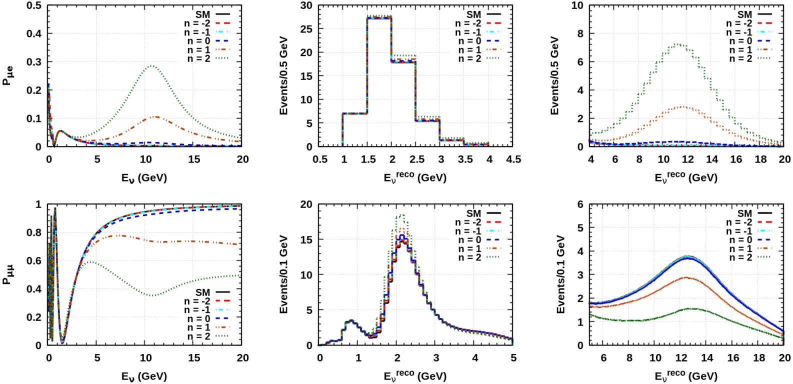
Fig 2. Neutrino system as an open quantum system.

Oscillation probability in the presence of decoherence

- $P_{\alpha\beta}(t) = Tr[\tilde{\rho}_\alpha(t)\tilde{\rho}_\beta(0)]$.
- $$P_{\alpha\beta}(L) = \delta_{\alpha\beta} - 2\sum_{j>k} Re\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{V}^*_{\beta k}\right)$$
  $$+ 2\sum_{j>k} Re\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\beta k}\right)\exp(-\Gamma_{jk}L)\cos\left(\frac{\tilde{\Delta}m^2_{jk}}{2E}L\right)$$
  $$+ 2\sum_{j>k} Im\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\beta k}\right)\exp(-\Gamma_{jk}L)\sin\left(\frac{\tilde{\Delta}m^2_{jk}}{2E}L\right) .$$
- Damping of interference terms by a factor $e^{-\Gamma L}$ in the oscillation probability.
- Energy dependency on Γ :

$$\boxed{\Gamma_{jk}(E_\nu) = \Gamma_0\left(\frac{E_\nu}{GeV}\right)^n} \;;\; n = 0, \pm 1, \pm 2 \;.$$

Oscillation probability and event rate in the presence of decoherence



$\Gamma_{21} = \Gamma_{31} = \Gamma_{32} = 1.0 \times 10^{-23}\ GeV$. ν_e appearance probability and event rate (upper row). Disappearance probability and event rate (lower row).

Events

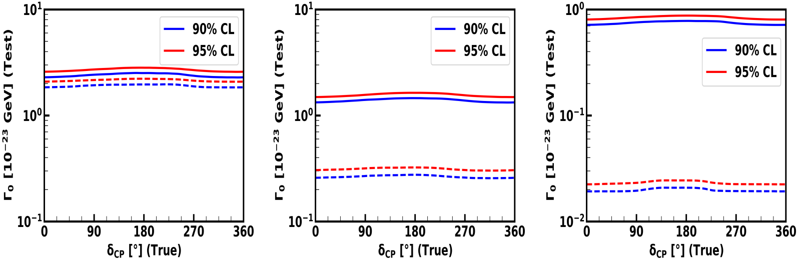
- Decoherence ($\Gamma_{21} = \Gamma_{31} = \Gamma_{32} = 1.0 \times 10^{-23}$ GeV)

	ν_e-app events			ν_μ-disapp events		
Cases	1 - 4 GeV	1 - 20 GeV	Excess events (4 - 20 GeV)	0 - 5 GeV	0 - 20 GeV	Excess events (5 - 20 GeV)
SM	59.0	61.0	2.0	215.0	589.8	374.8
$n = -2$	59.1	61.2	2.1	218.0	592.7	374.7
$n = -1$	59.3	61.7	2.4	220.8	594.9	374.1
$n = 0$	59.7	66.0	6.3	225.9	592.3	366.4
$n = 1$	60.7	101.0	40.3	234.8	529.8	295.0
$n = 2$	63.0	165.9	102.9	250.1	423.8	173.7

Table: Excess #events at HE considering $\Gamma_{ij} \neq 0$.

Constraining Γ for power law dependency $n \geq 0$

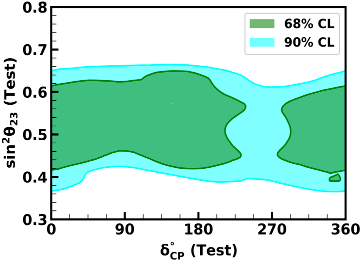
- Since $n \geq 0$ have significant contribution to modify probability and number of events, we analyse the upper bounds for $n \geq 0$.
- In all the three cases ($n = 0$ (left plot), $n = 1$ (middle plot) and $n = 2$ (right plot)), we see that the dashed lines corresponding to 1-20 GeV events impose tighter bounds on the decoherence parameter Γ.



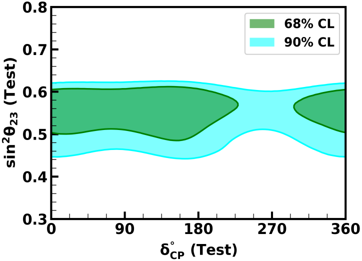
Constraining Γ for 1 - 5 GeV (solid lines) and 1- 20 GeV (dashed lines). In left for $n = 0$, middle $n = 1$ and right for $n = 2$. Marginalized over δ_{CP}, θ_{23}, Δm^2_{31}.

2D sensitivity of θ_{23} versus δ_{CP}

Standard NOvA framework.



Including high energy events (up to 20 GeV).



$\Gamma_{21} = \Gamma_{31} = \Gamma_{32} = 1.0 \times 10^{-23}\ GeV$ in true for $n = 2$. Marginalized over Δm^2_{31}, θ_{13} and Γ.

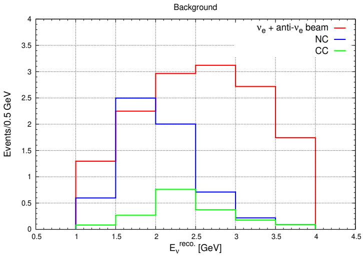
Conclusions

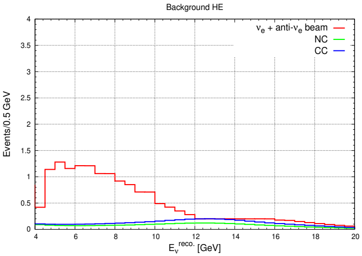
- Considering 1-20 GeV events has provided tighter bounds on decoherence parameter Γ.
- The 2D sensitivity of θ_{23} versus δ_{CP} shows, how the measurement of θ_{23} and δ_{CP} gets effected in the presence of non-zero decoherence in nature.

Thank you!

Back up!

Background events

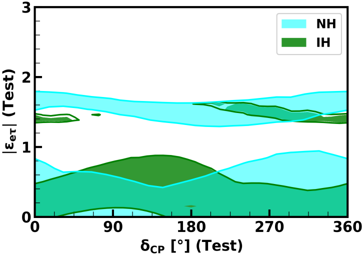




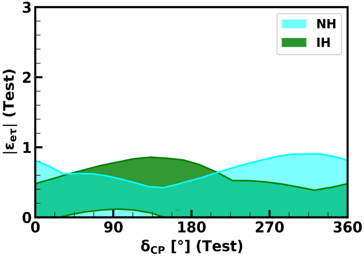
- Beam and NC backgrounds significant at 1-4 GeV.
- At high energy beam backgrounds are significant.

2D sensitivity of $\epsilon_{e\tau}$ versus δ_{CP} (90% CL)

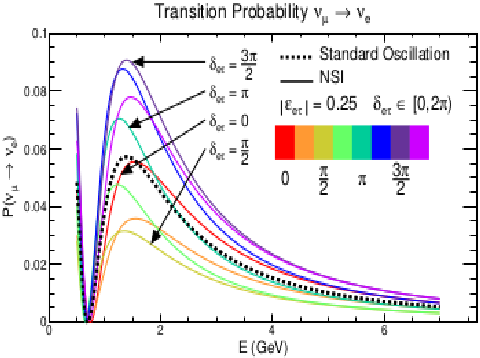
Including 1-5 GeV events



High energy events(1-20 GeV)



NOvA collaboration results (arXiv: 2403.07266)



NOvA Collaboration: fig. 1 in ref. *arxiv:2403.07266*

NSI Phenomenology

- The effective Hamiltonian

$$H_{eff} \simeq \frac{1}{2E} U \,\mathrm{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U^\dagger + V \,. \tag{5}$$

- The matter potential V

$$V = 2\sqrt{2} G_F N_e(r) E \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix} , \tag{6}$$