Neutrino's Non-Standard Interactions; another eel under a willow?

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Second eel (loach) under a willow?

- = more new physics from neutrinos?

What is the natural time scale for discovery of new ν interactions?; caution

- Meitner-Hahn (1911) – discovery of Neutral current (1973)
- Discovery of neutrino (1953) – discovery of neutrino mass (1998)

→ ~ 50 years

ν's Non-standard interactions (NSI)

- If there exists NEW PHYSICS at TeV scale there might be NSI of ν's expressed by higher dimensional operators

$$\mathcal{L}_{\rm eff}^{\rm NSI} = -2\sqrt{2}\,\varepsilon_{\alpha\beta}^{fP} G_F (\overline{\nu}_\alpha \gamma_\mu P_L \nu_\beta)\,(\overline{f}\gamma^\mu P f),$$

$$P_L \equiv \tfrac{1}{2}(1-\gamma_5) \text{ or } P_R \equiv \tfrac{1}{2}(1+\gamma_5).$$

Wolfenstein, Grossman, Berezhiani-Rossi, Davidson et al. … many people

- But coefficient ε may be small ➡ on dimensional ground, ε~order $(M_W/M_{NP})^2$

➡ $(M_W/M_{NP})^2 = 0.01$ (0.0001) if $M_{NP} = 1$ (10) TeV

I report the progress in the last one year !

NSI theory; Some recent progress

Some relevant references

Z. Berezhiani and A. Rossi, Phys. Lett. **B535**, 207 (2002), hep-ph/0111137.

S. Davidson, C. Pena-Garay, N. Rius and A. Santamaria, JHEP **03**, 011 (2003), hep-ph/0302093.

S. Antusch, J. P. Baumann and E. Fernandez-Martinez, Nucl. Phys. B **810**, 369 (2009), 0807.1003.

M. B. Gavela, D. Hernandez, T. Ota and W. Winter, Phys. Rev. D **79**, 013007 (2009), 0809.3451.

C. Biggio, M. Blennow and E. Fernandez-Martinez, arXiv:0902.0607 [hep-ph].

Note; many original references omitted, sorry!

Gauge invariance and NSI

- At high scale where NSI are originated, there exists SU(2) x U(1) gauge invariance
- Therefore, if there is a d=6 operator

$$\frac{1}{\Lambda^2}(\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{\ell}_\gamma \gamma_\rho \ell_\delta).$$

$\varepsilon_{e\mu}^{ee}$

→ it must exists as a part of the gauge invariant operator

$$\frac{1}{\Lambda^2}(\bar{L}_\alpha \gamma^\rho L_\beta)(\bar{L}_\gamma \gamma_\rho L_\delta),$$

- But it involves 4 charged lepton operators

→ severe constraints from experiments

$\varepsilon_{e\mu}^{ee} < 10^{-6}$ ← $Br(\mu\text{->}eee) < 10^{-12}$

Smart way to avoid constraints from 4 lepton processes

- Anti-symmetrization; dim 6

Unique; Gavela et al. 08

$$\mathcal{O}_6^a = (\bar{L}_\gamma i\tau_2 L_\alpha^c)(\overline{L_\beta^c} i\tau_2 L_\delta)$$

$$= (\bar{\ell}_\alpha \gamma^\mu \ell_\beta)(\bar{\nu}_\gamma \gamma_\mu \nu_\delta) + (\bar{\ell}_\gamma \gamma^\mu \ell_\delta)(\bar{\nu}_\alpha \gamma_\mu \nu_\beta) - (\bar{\ell}_\alpha \gamma^\mu \ell_\delta)(\bar{\nu}_\gamma \gamma_\mu \nu_\beta) - (\bar{\ell}_\gamma \gamma^\mu \ell_\beta)(\bar{\nu}_\alpha \gamma_\mu \nu_\delta)$$

- Higgs projection; dim 8

$$2(\bar{L}_\beta \tilde{H})\gamma^\rho(\tilde{H}^\dagger L_\alpha)(\bar{L}_\delta \gamma_\rho L_\gamma)$$

- Now, are we free from any constraints from 4 lepton processes?

NO!

Constraints from loops

- Dressing by SM particles gives you the bound!; loop level constraint

Davidson et al. 03

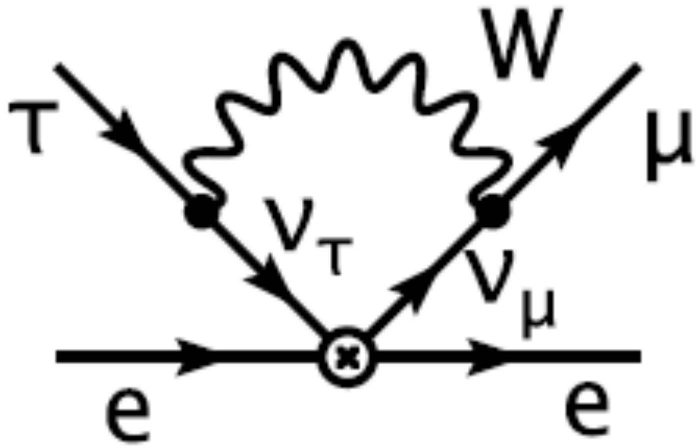


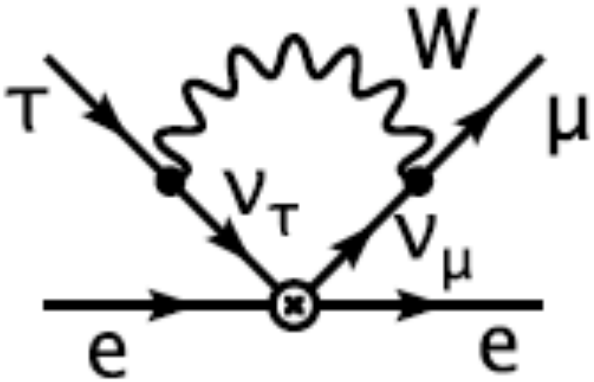
Figure 4: One-loop contributions to four-fermion interactions in the effective theory.

$(\bar{e}\gamma^\rho Pe)(\bar{\nu}_\tau\gamma_\rho L\nu_\mu)$	$\lvert\varepsilon^{eP}_{\tau\mu}\rvert < 1.2$ $(\tau \to \mu\bar{e}e)^{*)}$ $\lvert\varepsilon^{eP}_{\tau\mu}\rvert < 0.1$ CHARM II	$\lvert\varepsilon^{eL}_{\tau\mu}\rvert < 0.04, \lvert\varepsilon^{eR}_{\tau\mu}\rvert < 0.02$ leptonic s^2_W at nufact

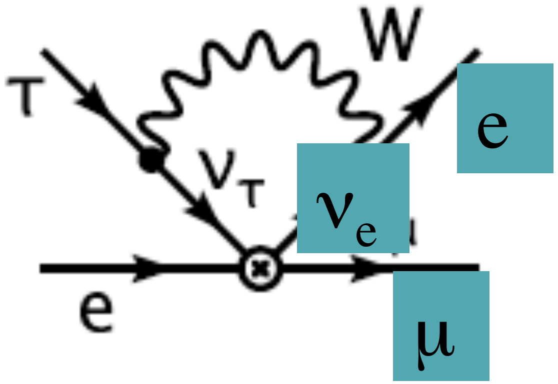
Constraints from loops

- Dressing by SM particles gives you the bound!; loop level constraint

Biggio, Blennow and Fernandez-Martinez (arXiv: 0902.0607)



+ 3 other diagrams with anti-symmetry such as =>

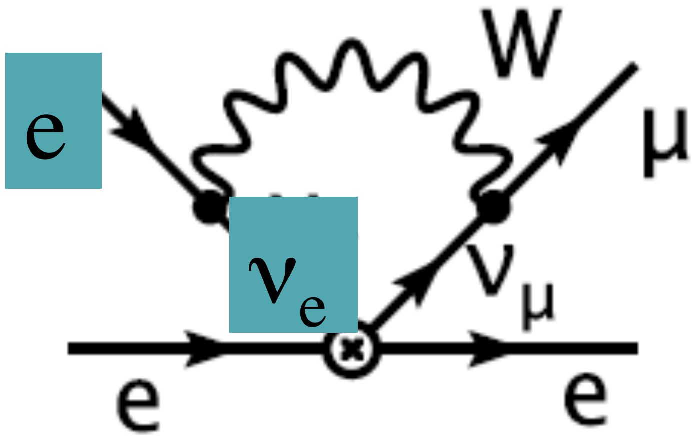


$(\bar{e}\gamma^\rho P_e)(\bar{\nu}_\tau\gamma_\rho L\nu_\mu)$	[illegible]	.02 ct

Bound is loosened by factor ~10^3

Bound on $\varepsilon^{matter}_{e\mu}$ is gone

- Used to be the most stringent loop level constraint
- But now, due to anti-symmetry, there is no such diagram as:



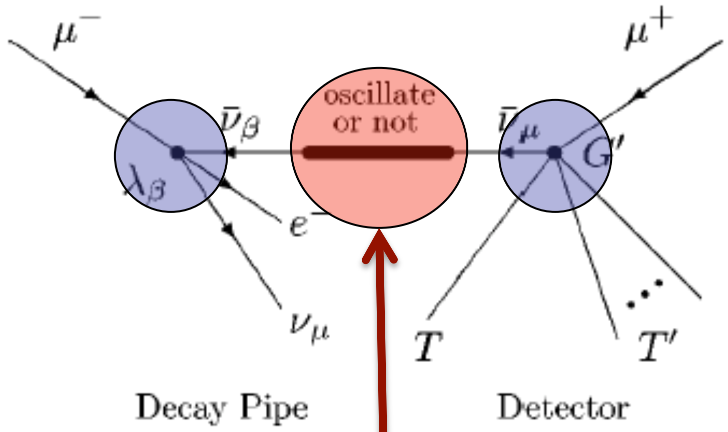
Biggio, Blennow and Fernandez-Martinez (0902.0607)

$(\bar{e}\gamma^\rho P e)(\bar{\nu}_\mu \gamma_\rho L \nu_e)$		GONE!

ν

oscillation with NSI

Non Standard Interaction (NSI)



- It comes in into 3 places, production, propagation, & detection

Grossmann, Ota-Sato-Yamashita, Huber et al. …

I this talk, I concentrate on effects of NSI in ν propagation in matter governed by evolution eq.

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

ν oscillation with NSI

- Given the structure

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

→ the system is highly nontrivial

- Note: when the new physics at TeV scale is identified, it will give us a few parameters
- all $\varepsilon_{\alpha\beta}$ are related, but likely to be present with similar magnitudes
- But, nobody seems to know how large is $\varepsilon_{\alpha\beta}$ effect in $P_{\gamma\delta}$ → perturbation theory of ν oscillation with NSI

Formulating perturbation theory of ν oscillation

- We have no definite recipe because we still do not know how large is θ_{13}
- Only known small parameter is $\Delta m^2_{solar}/\Delta m^2_{atm} = r_\Delta \sim 0.03$ → various possibilities (Note; $\sin(\pi/4-\theta_{23}) < 0.14$)

$$s_{13} \sim \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \simeq 0.03 \quad \rightarrow \quad \sin^2 2\theta_{13} \simeq 3.6 \times 10^{-3}$$

$$s_{13} \sim \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^{0.85} \simeq 0.05 \quad \rightarrow \quad \sin^2 2\theta_{13} \simeq 0.01$$

$$s_{13} \sim \sqrt{\frac{\Delta m^2_{21}}{\Delta m^2_{31}}} \simeq 0.17 \quad \rightarrow \quad \sin^2 2\theta_{13} \simeq 0.12$$

ε perturbation theory

- I take the assumption

$$s_{13} \sim \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \simeq 0.03 \qquad \rightarrow \qquad \sin^2 2\theta_{13} \simeq 3.6 \times 10^{-3}$$

- I assume $a/\Delta m^2_{atm} \sim \Delta m^2_{atm}$ L / E ~ O(1)
- most natural perturbation theory of ν oscillation → $P_{e\mu}$ consists only of order ε^2 terms → widely used Cervera et al. formula (golden measurement paper)
- (If θ_{13} large, one may try $(s_{13})^2 \sim r_\Delta = \varepsilon$ → δ term ~ $\varepsilon^{3/2}$ → $(s_{13})^3$ term required)

ε perturbation theory with NSI

- We include NSI by assuming

$$\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim s_{13} \sim \varepsilon_{\alpha\beta} \sim \epsilon \quad (\alpha, \beta = e, \mu, \tau).$$

➡ and expand to ε^2; NSI 2nd order formula

- If dimension 8, 1st order formula would be enough

but, 2nd order formula is simpler !

- Are you happy with $\sin^2 2\theta_{13} \sim 0.004$?
- Well, in fact I argue sometimes that θ_{13} is large, e.g., reactor range
- Are you schizophrenia? ➡ Yes!

SI formula -> NSI 2nd order formula

$$P(\nu_e \to \nu_\mu) = 4c_{23}^2 \left| c_{12}s_{12}\,(\Delta m^2_{21} / a) \right|^2 \sin^2\frac{aL}{4E}$$

$$+\ 4s_{23}^2 \left| s_{13}\, e^{-i\delta}\,(\Delta m^2_{31}/a) \right|^2 \left(\frac{a}{\Delta m^2_{31}-a}\right)^2 \sin^2\frac{\Delta m^2_{31}-a}{4E}L$$

$$+\ 8c_{23}s_{23}\,\mathrm{Re}\left[\left(c_{12}s_{12}\,(\Delta m^2_{21} / a)\right)\left(s_{13}\, e^{-i\delta}\,(\Delta m^2_{31}/a)\right) \right]$$

$$\times \frac{a}{\Delta m^2_{31}-a}\sin\frac{aL}{4E}\cos\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{31}-a}{4E}L$$

$$+\ 8c_{23}s_{23}\,\mathrm{Im}\left[\left(c_{12}s_{12}\,(\Delta m^2_{21} / a)\right)\left(s_{13}\, e^{-i\delta}\,(\Delta m^2_{31}/a)\right) \right]$$

$$\times \frac{a}{\Delta m^2_{31}-a}\sin\frac{aL}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{31}-a}{4E}L$$

Cervera et al , hep-ph/0002108

SI formula -> NSI 2nd order formula

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) &= 4c_{23}^2 \left| c_{12}s_{12}\frac{\Delta m_{21}^2}{a} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau} \right|^2 \sin^2 \frac{aL}{4E} \\
&+ 4s_{23}^2 \left| s_{13}e^{-i\delta}\frac{\Delta m_{31}^2}{a} + s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau} \right|^2 \left(\frac{a}{\Delta m_{31}^2 - a} \right)^2 \sin^2 \frac{\Delta m_{31}^2 - a}{4E}L \\
&+ 8c_{23}s_{23}\, \mathrm{Re} \left[\left(c_{12}s_{12}\frac{\Delta m_{21}^2}{a} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau} \right) \left(s_{13}e^{i\delta}\frac{\Delta m_{31}^2}{a} + s_{23}\varepsilon_{e\mu}^* + c_{23}\varepsilon_{e\tau}^* \right) \right] \\
&\qquad \times \frac{a}{\Delta m_{31}^2 - a} \sin \frac{aL}{4E} \cos \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{31}^2 - a}{4E}L \\
&+ 8c_{23}s_{23}\, \mathrm{Im} \left[\left(c_{12}s_{12}\frac{\Delta m_{21}^2}{a} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau} \right) \left(s_{13}e^{i\delta}\frac{\Delta m_{31}^2}{a} + s_{23}\varepsilon_{e\mu}^* + c_{23}\varepsilon_{e\tau}^* \right) \right] \\
&\qquad \times \frac{a}{\Delta m_{31}^2 - a} \sin \frac{aL}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{31}^2 - a}{4E}L
\end{aligned}
$$

T. Kikuchi, H.M., S. Uchinami, arXiv:0809.3312 => JHEP

Generalized atmospheric and solar variables

SI-NSI confusion !

$$\Theta_\pm \equiv s_{13}\frac{\Delta m^2_{31}}{a} + \left(s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau}\right)e^{i\delta}$$

$$\Xi \equiv \left(c_{12}s_{12}\frac{\Delta m^2_{21}}{a} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau}\right)e^{i\delta}$$

"θ_{12}"

"θ_{13}"

$$\tilde{H}^{\rm NSI} = U_{23}^\dagger \begin{bmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix} U_{23} \equiv \begin{bmatrix} \tilde\varepsilon_{ee} & \tilde\varepsilon_{e\mu} & \tilde\varepsilon_{e\tau} \\ \tilde\varepsilon^*_{e\mu} & \tilde\varepsilon_{\mu\mu} & \tilde\varepsilon_{\mu\tau} \\ \tilde\varepsilon^*_{e\tau} & \tilde\varepsilon^*_{\mu\tau} & \tilde\varepsilon_{\tau\tau} \end{bmatrix}$$

$$= \begin{bmatrix} \varepsilon_{ee} & c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau} & s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau} \\ c_{23}\varepsilon^*_{e\mu} - s_{23}\varepsilon^*_{e\tau} & c^2_{23}\varepsilon_{\mu\mu} + s^2_{23}\varepsilon_{\tau\tau} - c_{23}s_{23}(\varepsilon_{\mu\tau} + \varepsilon^*_{\mu\tau}) & c^2_{23}\varepsilon_{\mu\tau} - s^2_{23}\varepsilon^*_{\mu\tau} + c_{23}s_{23}(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}) \\ s_{23}\varepsilon^*_{e\mu} + c_{23}\varepsilon^*_{e\tau} & c^2_{23}\varepsilon^*_{\mu\tau} - s^2_{23}\varepsilon_{\mu\tau} + c_{23}s_{23}(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}) & s^2_{23}\varepsilon_{\mu\mu} + c^2_{23}\varepsilon_{\tau\tau} + c_{23}s_{23}(\varepsilon_{\mu\tau} + \varepsilon^*_{\mu\tau}) \end{bmatrix}$$

How big is the contribution of $\varepsilon_{\alpha\beta}$? Bird-eye view

Channel	ϵ_{ee}	$\epsilon_{e\mu}$	$\epsilon_{e\tau}$	$\epsilon_{\mu\tau}$	$\epsilon_{\mu\mu}$	$\epsilon_{\tau\tau}$	a dep. (NSI)	a dep. (SI)
$P(\nu_e \to \nu_\alpha)$: $\alpha = e, \mu, \tau$	ϵ^3	ϵ^2	ϵ^2	ϵ^3	ϵ^3	ϵ^3	ϵ^2	ϵ^2
$P(\nu_\alpha \to \nu_\beta)$: $\alpha, \beta = \mu, \tau$	ϵ^3	ϵ^2	ϵ^2	ϵ^1	$\epsilon^1(\epsilon^2)$	$\epsilon^1(\epsilon^2)$	ϵ^1	ϵ^2

Matter hesitation   Direct transition by NSI   If θ_{23} is maximal

- decoupling of $\varepsilon_{\alpha\beta}$ in $\mu-\tau$ sector to $P(\nu_e \to \nu_\mu)$ and $P(\nu_e \to \nu_\tau)$ to ε^2
- Simplify NSI measurement strategy

⇒ Determine $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ from $P(\nu_e \to \nu_\mu)$

⇒ then, one can go to $\mu-\tau$ sector

However, in $\mu-\tau$ sector,

- $\varepsilon_{\alpha\beta}$ (in $\mu-\tau$ sector) dependent term is common to all $P(\nu_\mu \to \nu_\tau)$, $P(\nu_\mu \to \nu_\mu)$ and $P(\nu_\tau \to \nu_\tau)$ ➡ impossible to determine 3 parameters, $\varepsilon_{\mu\tau} = |\varepsilon_{\mu\tau}| e^{i\varphi}$ and $(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau})$, by rate only analysis

Symmetry in $P(\nu_\alpha \to \nu_\beta)$ with NSI !

- $P(\nu_e \to \nu_\tau)$ can be obtained from $P(\nu_e \to \nu_\mu)$ by transformation

$$c_{23} \longrightarrow -s_{23}, \qquad s_{23} \longrightarrow c_{23}$$

- and undoing any transformation in the generalized solar and atmospheric variables

Parameter degeneracy

Parameter degeneracy 1

- Intrinsic, sign-Δm^2, θ_{23} octant degeneracy prevails in a generalized form which include NSI parameters
- In matter perturbative regime, for example, $P_{e\mu}$ is approx. invariant under

$$\Delta m^2_{31} \rightarrow -\Delta m^2_{31},\quad \delta \rightarrow \pi - \delta,\quad \phi_{e\alpha} \rightarrow 2\pi - \phi_{e\alpha}.$$

← sign-Δm^2

SI version: HM-Nunokawa 01

$$c_{23} \rightarrow s_{23},\quad s_{23} \rightarrow c_{23},\quad (\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}) \rightarrow -(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}).$$

← θ_{23} octant

Fogli-Lisi 96

Parameter degeneracy 2

- A completely new type of degeneracy also exist → solar – atmospheric variable exchange degeneracy

$$|\Theta_{\pm}^{(2)}| = \sqrt{\frac{Z}{X_{\pm}}}|\Xi^{(1)}| \text{ and } |\Xi^{(2)}| = \sqrt{\frac{X_{\pm}}{Z}}|\Theta_{\pm}^{(1)}|$$

$$X_{\pm} \equiv \left(\frac{a}{\delta m_{31}^2 \mp a}\right)^2 \sin^2 \frac{\delta m_{31}^2 \mp a}{4E} L,$$

$$Y_{\pm} \equiv \left(\frac{a}{\delta m_{31}^2 \mp a}\right) \sin \frac{aL}{4E} \sin \frac{\delta m_{31}^2 \mp a}{4E} L,$$

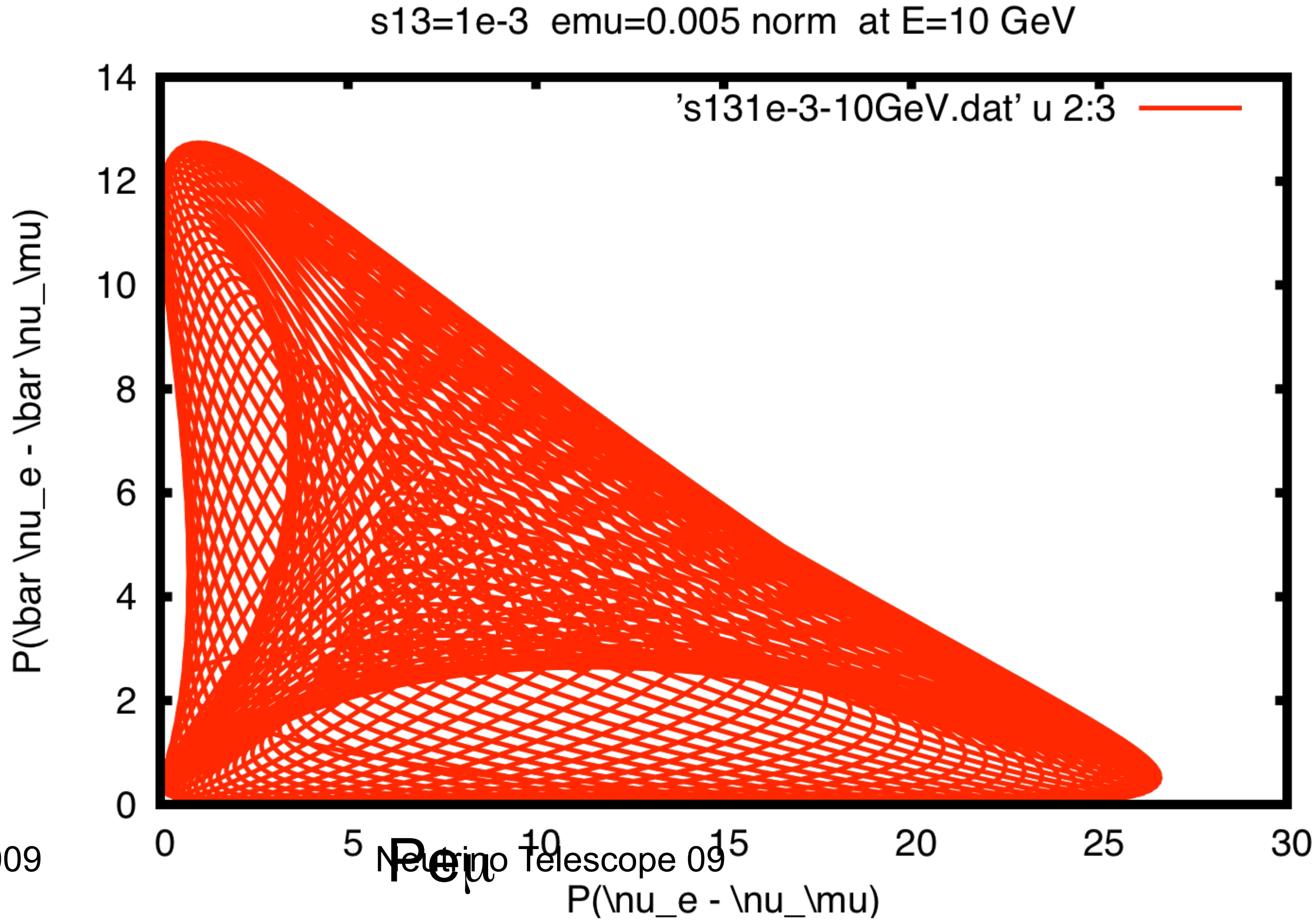
$$Z \equiv \sin^2 \frac{aL}{4E}.$$

NSI perturbation theory; temporary summary

- Structure of ν oscillation with NSI is in fact very simple within ε perturbation theory
- But in real life, it is complicated even with single $\varepsilon_{\alpha\beta}$ because the system is enriched with 2 phases → lepton KM phase + NSI phase (see next page)

ν oscillation with NSI is already complicated phenomenon even with single $\varepsilon_{\alpha\beta}$ (example with $\varepsilon_{e\mu}$)

P-bar eμ



Peμ

Solving the 2 phase confusion with 2-detector setting

SI-NSI confusion

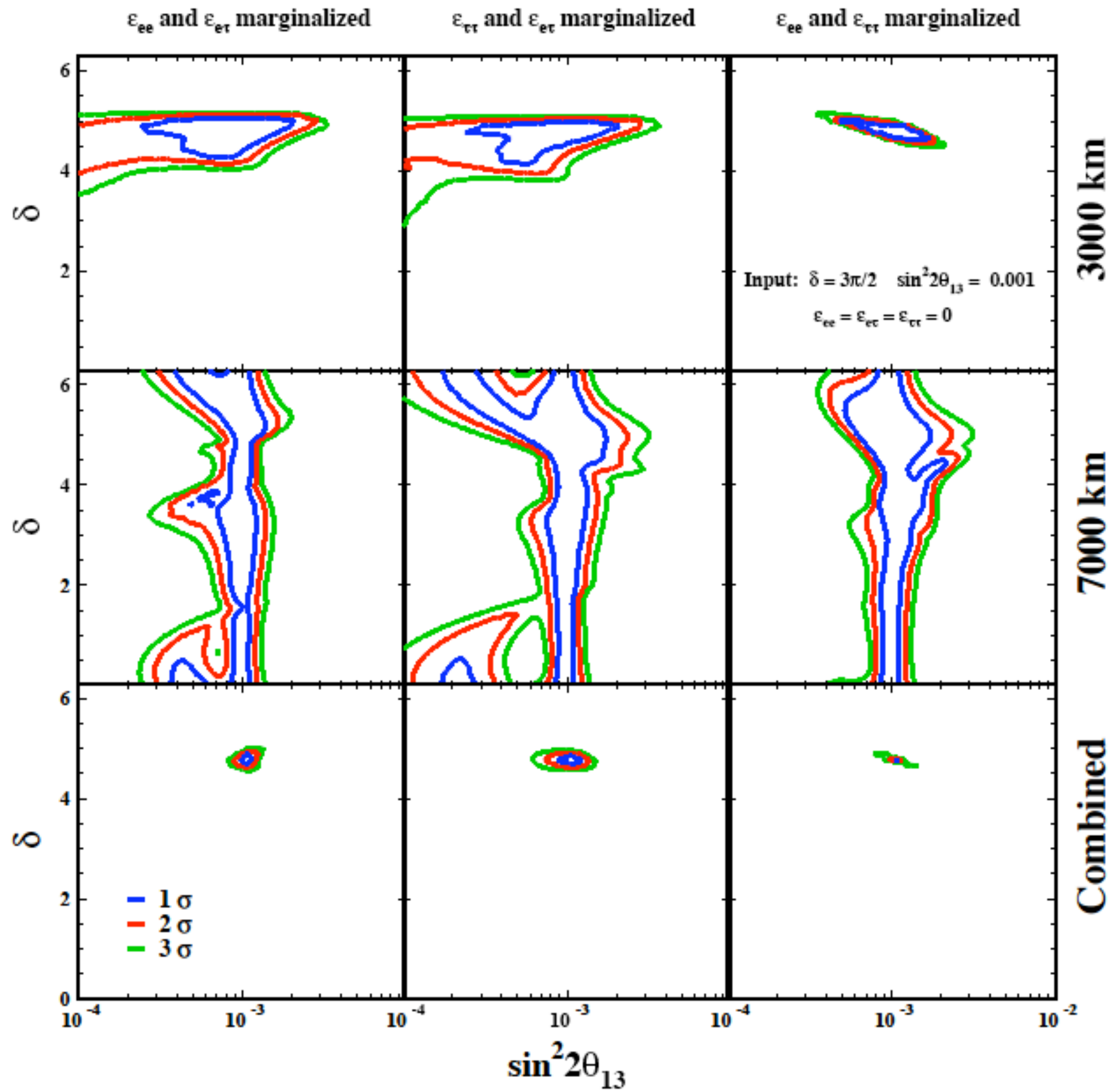
- We saw that SI and NSI parameters come together: → SI-NSI confusion

$$\Theta_{\pm} \equiv s_{13}\frac{\Delta m^2_{31}}{a} + (s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau})e^{i\delta}$$

$$\Xi \equiv \left(c_{12}s_{12}\frac{\Delta m^2_{21}}{a} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau}\right)e^{i\delta}$$

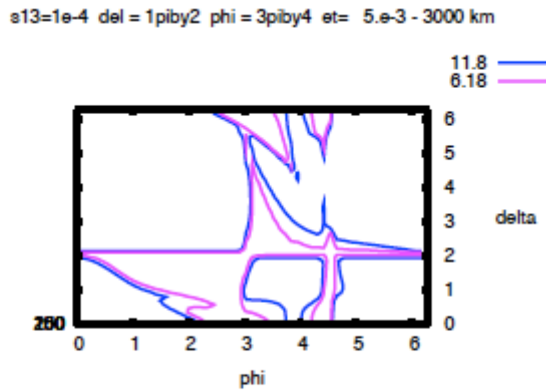
- Last year I have reported that 2 detector setting (3000 + 7000 km) in neutrino factory can resolve θ_{13}-$|\varepsilon_{e\mu}|$ (or $|\varepsilon_{e\tau}|$) confusion
- Today, I discuss 2 phase confusion; CPV phase of $\varepsilon_{\alpha\beta}$ can be confused with lepton KM phase δ → single $\varepsilon_{\alpha\beta}$ system

θ_{13} - NSI confusion can be solved: @NO-VE08



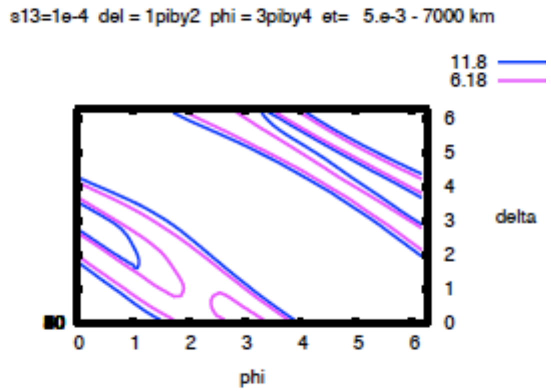
Set up: 10^{21} muons/year, 4+4 years of ν, ν–bar, two 50 kt iron detectors (Cipriani Ribeiro-HM-Nunokawa-Uchinami-Zukanovich Funchal, Arxiv: 0709.1980=>JHEP 07)

2 phase confusion can be resolved

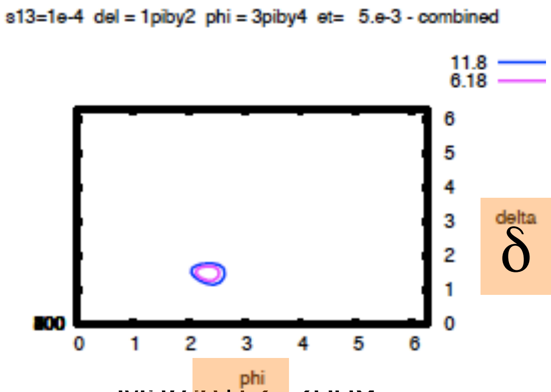


3000 km

$|\varepsilon_{e\tau}| = 5\times10^{-3}$



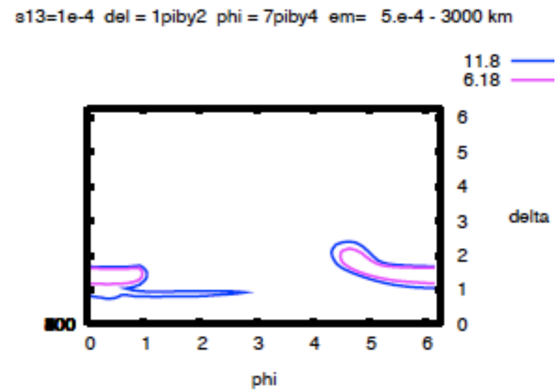
7000 km



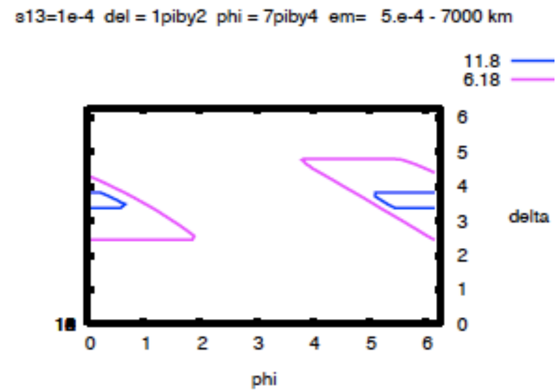
δ

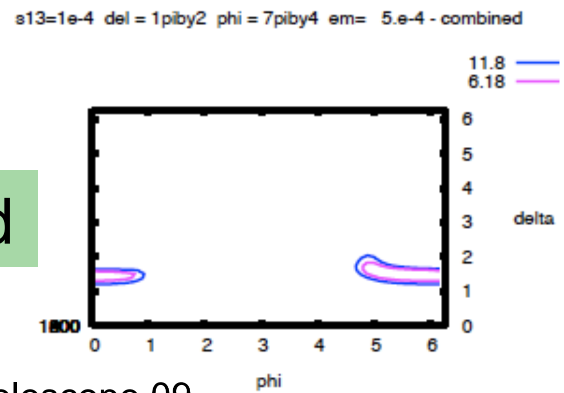
φ

combined



$|\varepsilon_{e\mu}| = 5\times10^{-4}$

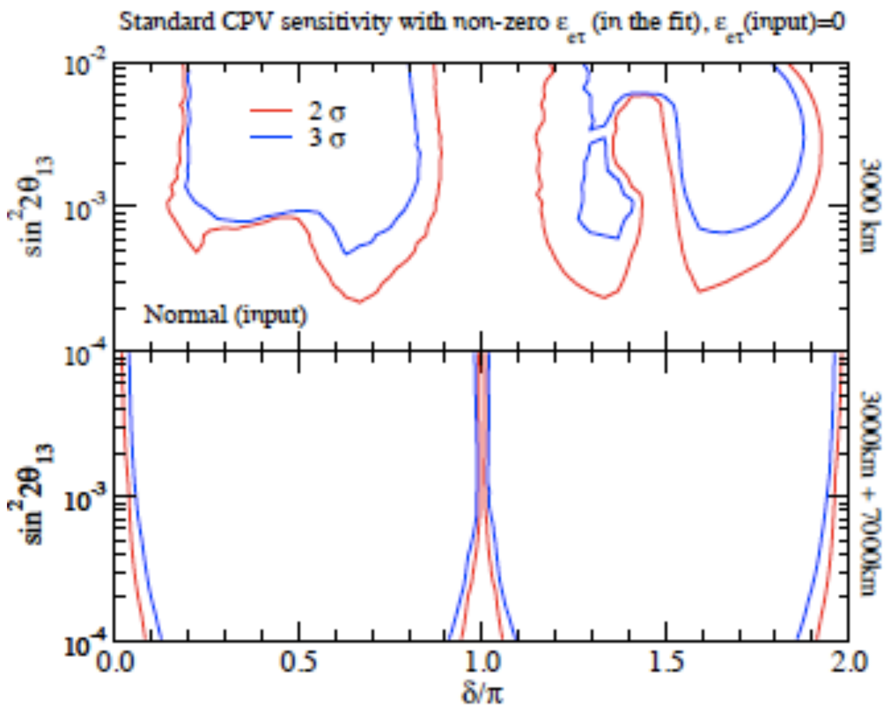




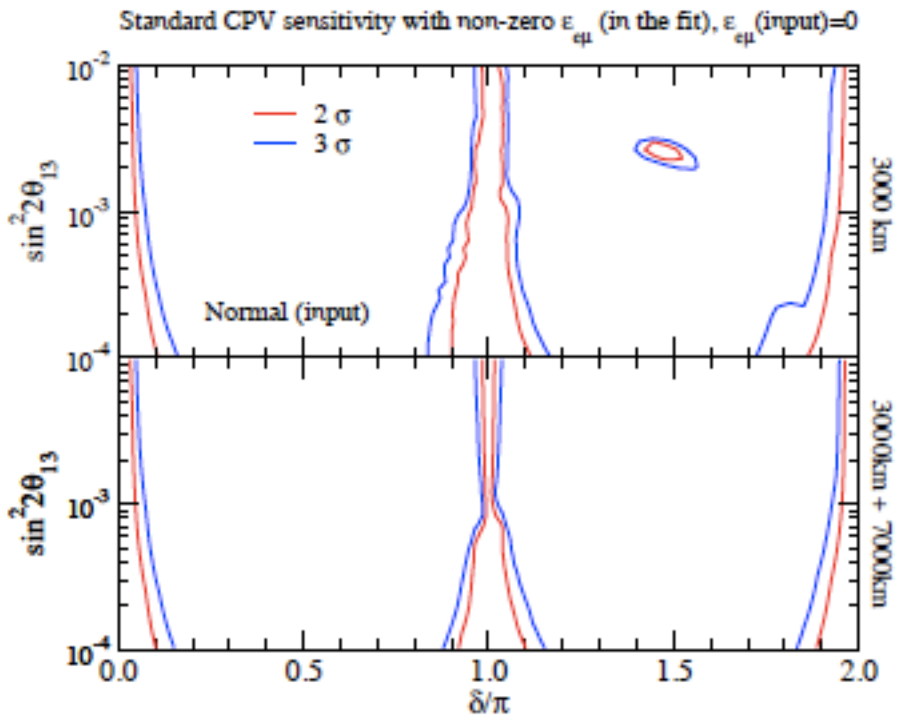
Cipriani Ribeiro et al. coming soon !

Lepton KM CPV discovery potential

$\varepsilon_{e\tau}$



$\varepsilon_{e\mu}$



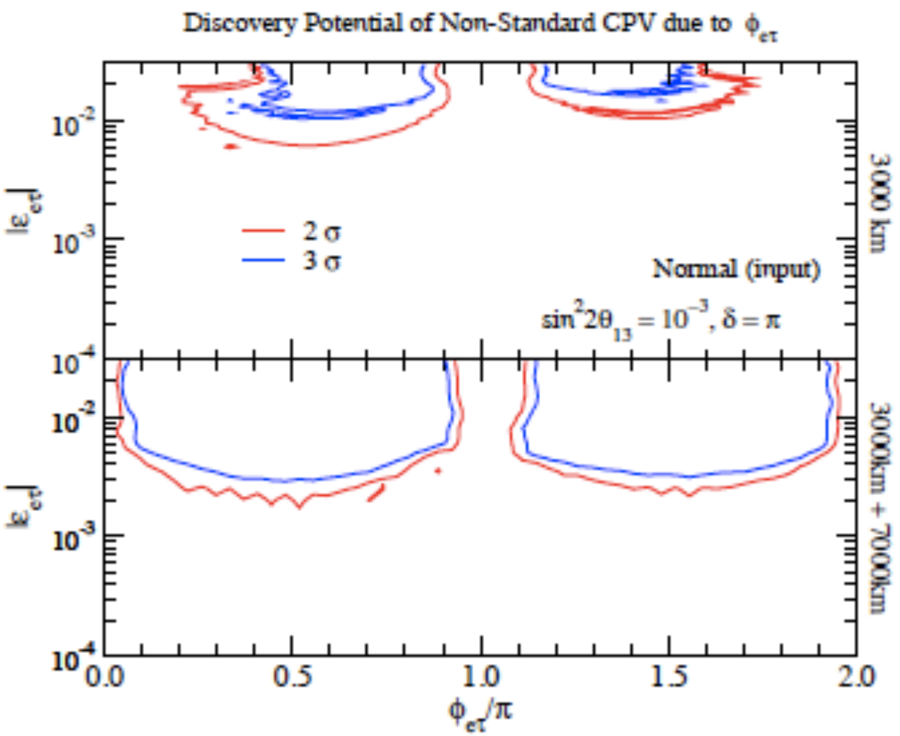
Upper 3000 km
lower combined

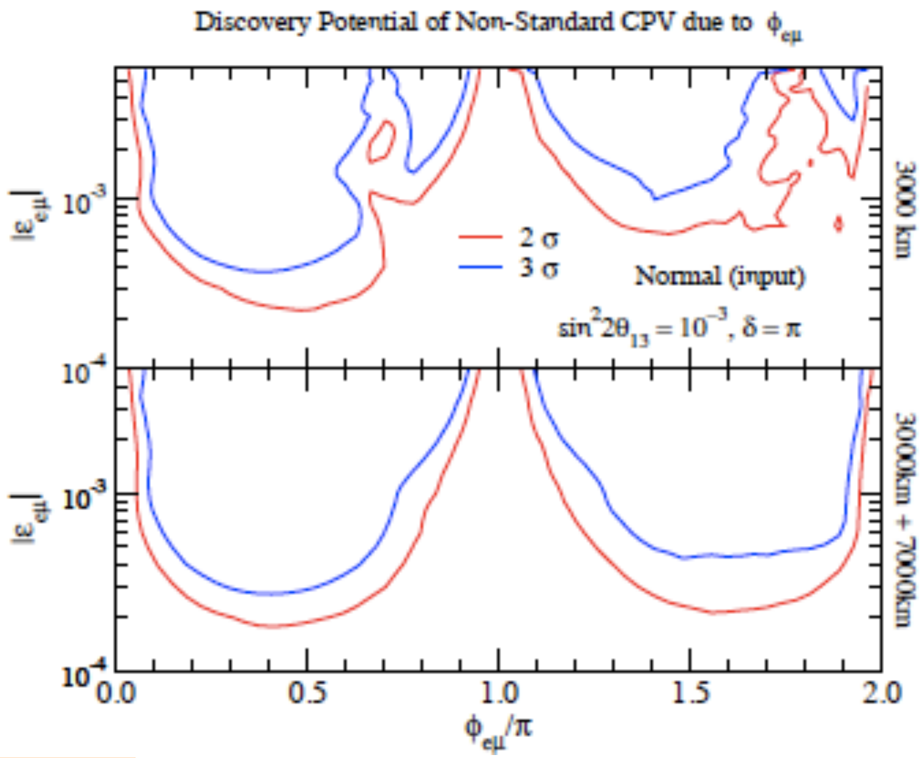
θ_{13}, $\varepsilon_{e\mu}$, etc.
marginalized

NSI phase CPV discovery potential

$\varepsilon_{e\tau}$

$\varepsilon_{e\mu}$





Upper 3000 km
lower combined

θ_{13}, δ, etc.
marginalized

Conclusion

- New consideration lead to loosing the bound on NSI by a factor of ~10^{-3}
- Global overview for ν oscillation with NSI is obtained by perturbative formulation
- problem of 2 phase confusion addressed with 2 detector setting 3000 + 7000 km in neutrino factory

→ synergy between 2 detectors seems strong enough to solve it with single $\varepsilon_{\alpha\beta}$

→ Can establish 2 new CPV!

Second loach can be BIG!