On the role of leptonic CPV phases in cLFV observables

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Based on: `arXiv:2107.06313` with A. Abada and A. M. Teixeira

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Motivation

Neutrino oscillations first laboratory evidence for **new physics**

$\Rightarrow$ (Neutral) lepton flavour is **violated**, neutrinos are **massive**

$\Rightarrow$ Massive neutrinos open the door to **cLFV** and new sources of **CP violation**

- Minimal $\mathbf{SM}_{m_\nu}$: massive **Dirac** neutrinos via Higgs mechanism
  $\Rightarrow$ accommodate **oscillation data**; **cLFV** unobservable, naturalness problem

NuFIT 5.0 (2020)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

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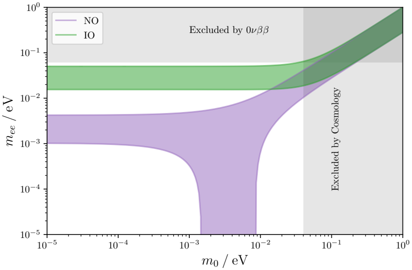
⇒ accommodate **oscillation data**; **cLFV** unobservable, naturalness problem
- (Low-scale) **seesaw mechanism**: heavy neutral leptons (**HNL**)
- **HNL**: e.g. massive **Majorana** neutrinos
⇒ **LNV** and **cLFV**
- **LNV** observables crucially depend on **CPV phases**



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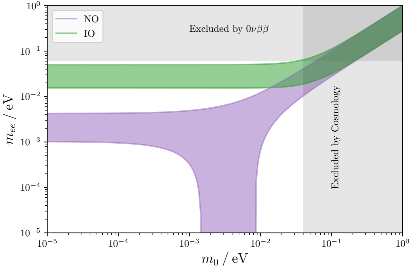


Vast model landscape feat. at least 2 **HNL**, at high and low scales

⇒ **TeV**-scale **HNL** offer rich **cLFV** phenomenology; potentially within collider reach

⇒ take effective "3+2 model"; analyse effects of **CPV phases** on **cLFV observables**

"3+2" toy model

Ignore precise origin of m_ν, assume 2 (heavy) Majorana neutrinos $N_{4,5}$ present
⇒ physical neutrino spectrum comprises 5 states (3 light, **2 heavy**)

Mixing parametrised via 10 mixing angles $\theta_{\alpha j}$, 6 Dirac $\delta_{\alpha j}$ and 4 Majorana phases φ_j
⇒ accommodate osc. data in (enlarged) PMNS mixing matrix

"Heavy-light" mixing given by (for $\cos\theta_{\alpha 4,5} \approx 1$):

$$\mathcal{U}_{\ell N} \approx \begin{pmatrix} \sin\theta_{14} e^{-i(\delta_{14}-\varphi_4)} & \sin\theta_{15} e^{-i(\delta_{15}-\varphi_5)} \\ \sin\theta_{24} e^{-i(\delta_{24}-\varphi_4)} & \sin\theta_{25} e^{-i(\delta_{25}-\varphi_5)} \\ \sin\theta_{34} e^{-i(\delta_{34}-\varphi_4)} & \sin\theta_{35} e^{-i(\delta_{35}-\varphi_5)} \end{pmatrix}$$

⇒ SM-like (3×3) block no longer unitary, leptonic W and Z vertices modified

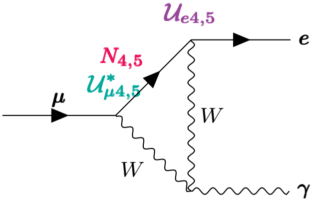
Take sterile masses $m_{4,5}$ at **TeV**-scale
⇒ sizeable **cLFV** rates @ 1 loop-level, what is the effect of **CPV phases**?

Example: $\mu \to e\gamma$

cLFV process mediated by $N_{4,5}$ @ 1 loop-level

$\mathbf{BR}(\mu \to e\gamma) \propto |G_\gamma^{\mu e}|^2$ **cLFV** form factor including mixing and loop function:

$$G_\gamma^{\mu e} = \sum_{i=4,5} \mathcal{U}_{ei}\,\mathcal{U}_{\mu i}^*\,G_\gamma\left(\frac{m_{N_i}^2}{m_W^2}\right)$$



Assume $m_4 \approx m_5$ and $\sin\theta_{\alpha 4} \approx \sin\theta_{\alpha 5} \ll 1$:

$$|G_\gamma^{\mu e}|^2 \approx 4\, s_{14}^2 s_{24}^2 \cos^2\left(\frac{\delta_{14}+\delta_{25}-\delta_{15}-\delta_{24}}{2}\right) G_\gamma\left(\frac{m_{N_i}^2}{m_W^2}\right)$$

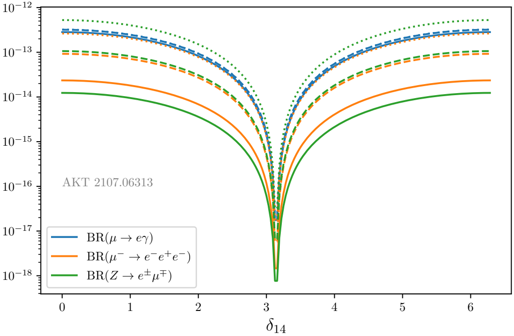
$\Rightarrow$ Rate depends on **Dirac phases**, full **cancellation** for $\delta_{14}+\delta_{25}-\delta_{15}-\delta_{24} = \pi$

Other form factors more complicated, Z-penguin and boxes also depend on $\varphi_{4,5}$

Effects of Dirac phases

Simplified approach on $\mu - e$ **flavour violating** observables
$\mu \to 3e$ additionally depends Z-penguins and box-diagrams

Take $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$ and $m_4 = m_5 = (1, 5, 10)\,\text{TeV}$, only $\delta_{14} \neq 0$:

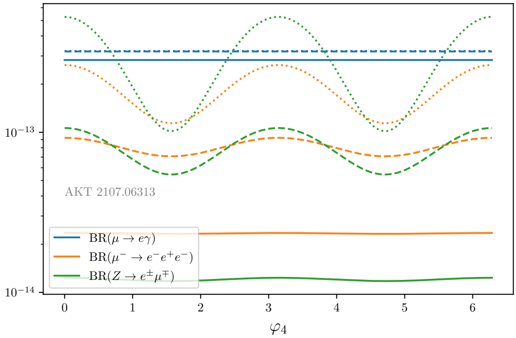


$\Rightarrow$ Strong cancellation for $\delta_{14} = \pi$ in all observables (similar results for $\delta_{24}, \delta_{15}, \delta_{25}$)

Effects of Majorana phases

Simplified approach on $\mu - e$ **flavour violating** observables

Take $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$ and $m_4 = m_5 = (1, 5, 10)$ TeV, only $\varphi_4 \neq 0$:



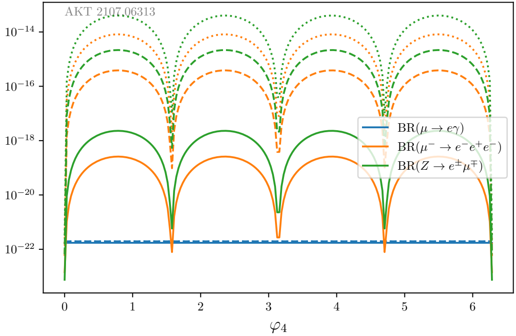
⇒ Variational behaviour amplified with increasing $m_{4,5}$

⇒ Photon penguin independent of φ_4 (analytically expected)

Joint behaviour of Dirac and Majorana CPV phases

Simplified approach on $\mu - e$ flavour violating observables

Take $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$ and $m_4 = m_5 = (1, 5, 10)\ \mathrm{TeV}$, vary φ_4, fix $\delta_{14} = \pi$:

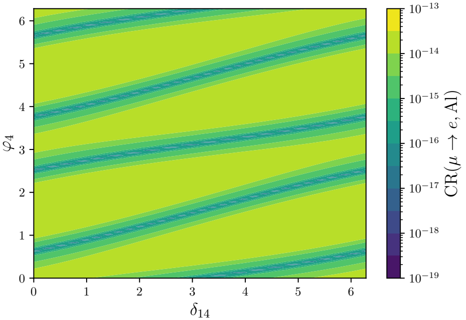


$\Rightarrow$ Cancel dipole contributions, presence of $\varphi_4 \neq 0$ enhances Z-penguin and boxes

Joint behaviour of Dirac and Majorana CPV phases (continued)

Neutrinoless $\mu - e$ conversion in nuclei, process depends on all topologies and phases

Take $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$ and $m_4 = m_5 = 1\,\mathrm{TeV}$, vary 2 phases at a time:



⇒ Varying only φ_4 can lead to strong cancellations as well, interference of contributions

Joint behaviour of Dirac and Majorana CPV phases (continued)

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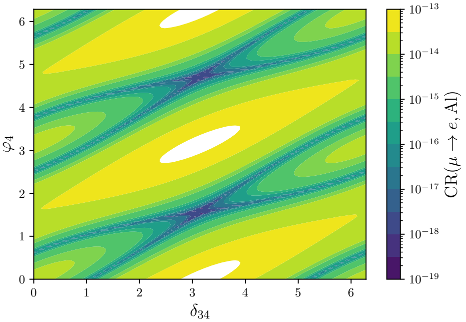


⇒ Sum over all **flavours** in Z-vertex ⇒ dependence on δ_{34}

⇒ Interference of contributions can be constructive, leading to **enhancements**!

Towards realistic scenarios

For $\mathbf{TeV}$-scale **HNL** several indirect constraints apply (besides **cLFV**):

- **Lepton Universality**: $\boldsymbol{W} \to \ell\nu$, $\boldsymbol{Z} \to \ell^+\ell^-$, **ratios** of leptonic Meson decays, ratios of (semi-leptonic) $\boldsymbol{\tau}$-lepton decays, **CKM** unitarity ...
- **LNV**: neutrinoless double beta decay
- **Perturbative Unitarity**: $\Gamma_{\boldsymbol{N_{4,5}}}/m_{\boldsymbol{N_{4,5}}} \leq 1/2$
- **Electroweak Precision**: $m_{\boldsymbol{W}}$, G_F, $\Gamma(\boldsymbol{Z} \to \text{invisibles})$

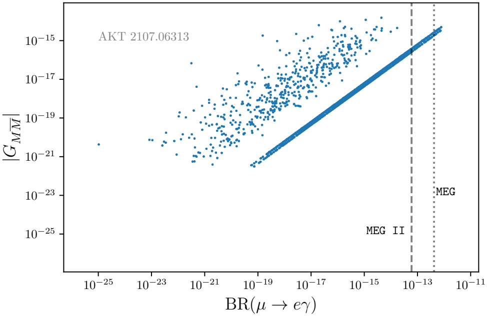
Constraints independent of **CPV phases**

$\Rightarrow$ Randomly scan **constrained** parameter space with $\boldsymbol{\theta_{\alpha 4}} \approx \pm\boldsymbol{\theta_{\alpha 5}}$ and $\boldsymbol{m_4} = \boldsymbol{m_5} = 1\,\mathbf{TeV}$

$\Rightarrow$ For each point vary phases $\boldsymbol{\delta_{\alpha 4}}$ and $\boldsymbol{\varphi_4}$ randomly and on a grid

Breaking correlations

Effective coupling $G_{M\overline{M}}$ of $\mathbf{Mu} - \overline{\mathbf{Mu}}$ oscillation ($\mu^+ e^- \to \mu^- e^+$) only depends on boxes
Both $\mu \to e\gamma$ and $G_{M\overline{M}}$ only depend on $\theta_{14,5}$ and $\theta_{24,5}$ $\Rightarrow$ expect strong correlation



blue: all phases vanishing;

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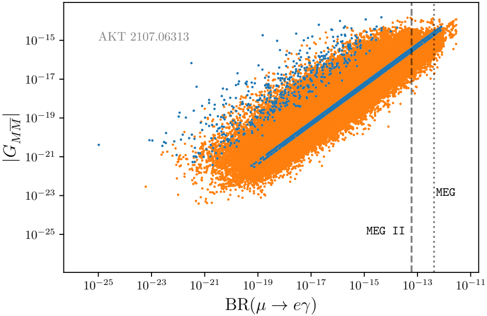

blue: all phases vanishing; **orange**: random phases;

$\Rightarrow$ Presence of phases **breaks correlation**!

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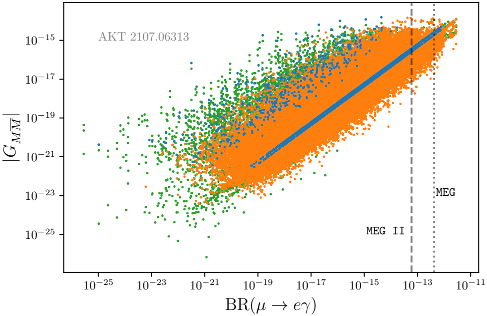
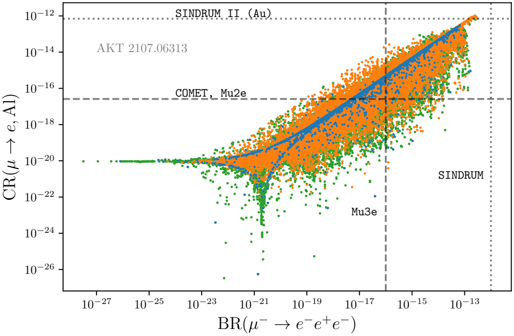


blue: all phases vanishing; **orange**: random phases; **green**: phases grid scan

$\Rightarrow$ Presence of phases **breaks correlation**!

Breaking correlations (continued)

Both $\mu - e$ conversion and $\mu \to 3e$ dominated by Z-penguins, expect strong correlation

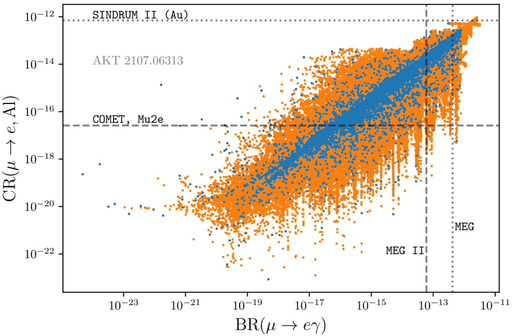


blue: all phases vanishing; **orange**: random phases; **green**: phases grid scan

⇒ Hypothetical signal e.g. only in $\mu \to 3e$ does not disfavour **HNL models**!

General view on parameter space

Scan $\theta_{\alpha 4}$ and $\theta_{\alpha 5}$ independently, randomly vary **all phases**, (apply all constraints)
Mass splitting varied within in $\Gamma_{N_{4,5}}$, $m_4 = 1\,\mathrm{TeV}$, $m_5 - m_4 \in (40\,\mathrm{MeV}, 210\,\mathrm{GeV})$



⇒ Sizeable $\mu \to e\gamma$ rate possible without $\mu - e$ conversion and vice versa!
⇒ Effects of **CPV phases** significant!

Summary & Conclusion

Presence of **CPV** Majorana and Dirac phases can suppress and enhance the rate of **cLFV** observables with significant impact on the interpretation of future data:

- $\mathbf{P_1^{(\prime)}}$: **Enhancing** rates to future sensitivities in $\mu\tau$-sector
- $\mathbf{P_2^{(\prime)}}$: **Enhancing** rates in μe-sector
- $\mathbf{P_3^{(\prime)}}$: **Suppressing** rates in μe-sector

	$\text{BR}(\mu \to e\gamma)$	$\text{BR}(\mu \to 3e)$	$\text{CR}(\mu - e,\ \text{Al})$	$\text{BR}(\tau \to 3\mu)$	$\text{BR}(Z \to \mu\tau)$
P_1	3×10^{-16} ○	1×10^{-15} ✓	9×10^{-15} ✓	2×10^{-13} ○	3×10^{-12} ○
P_1'	1×10^{-13} ✓	2×10^{-14} ✓	1×10^{-16} ✓	1×10^{-10} ✓	2×10^{-9} ✓
P_2	2×10^{-23} ○	2×10^{-20} ○	2×10^{-19} ○	1×10^{-10} ✓	3×10^{-9} ✓
P_2'	6×10^{-14} ✓	4×10^{-14} ✓	9×10^{-14} ✓	8×10^{-11} ✓	1×10^{-9} ✓
P_3	2×10^{-11} ✗	3×10^{-10} ✗	3×10^{-9} ✗	2×10^{-8} ✓	8×10^{-7} ✓
P_3'	8×10^{-15} ○	1×10^{-14} ✓	6×10^{-14} ✓	2×10^{-9} ✓	1×10^{-8} ✓

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$\Rightarrow$ Presence **CPV phases**: data needs to be interpreted carefully

- Non-observation of a certain observable does not (necessarily) disfavour **HNL** models
- Sizeable mixing angles possible, if phases lead to suppression of **cLFV**
- **CPV phases** need to be consistently included in phenomenological analyses of **HNL**

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ✓	3×10^{-9} ✓
[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ✓	1×10^{-9} ✓
[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ✓	8×10^{-7} ✓
[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ✓	1×10^{-8} ✓

You cannot spell **flavour** without **CP Violation**!

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Thank you!!!