

On the role of leptonic CPV phases in cLFV observables

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Based on: EPJC 81, 1016 (2021) [arXiv:2107.06313] with A. Abada and A. M. Teixeira

24.11. 2021

Introduction: lepton flavour

In the SM: neutrinos are (strictly) massless by construction

- ⇒ Accidental symmetries: conservation of **lepton flavour** and total lepton number
- ⇒ **Lepton flavour universality** preserved (only broken by Yukawas)
- ⇒ Lepton **EDMs** are tiny (4-loop from δ_{CKM})

BUT: Neutrinos oscillate ⇒ **neutral lepton flavour** is violated, neutrinos are **massive!**

~~ **charged** lepton flavour also violated? New sources of **CP violation!**

Trivially extend **SM**, accommodate $\nu_\alpha \rightsquigarrow \nu_\beta$ with 3 ν_R (\Rightarrow Dirac masses, SM_{m_ν})

- ⇒ **cLFV** possible, but not observable $\text{BR}(\mu \rightarrow e\gamma) \sim 10^{-54}$ (EDM @ 2 loop but tiny)
- ⇒ **lepton number conservation** “put by hand”, naturality issues $Y_\nu \simeq 10^{-16}$

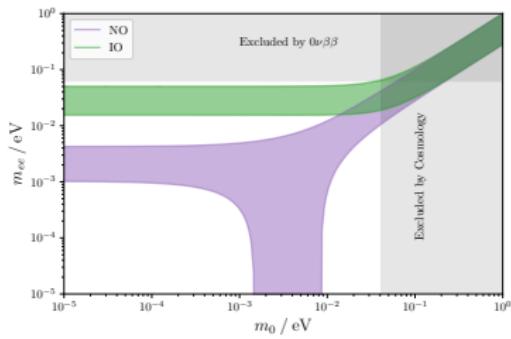
⇒ Any **cLFV** signal points towards non-trivial **SM** extensions... (possibly $\propto m_\nu$ generation)

CPV phases and LNV

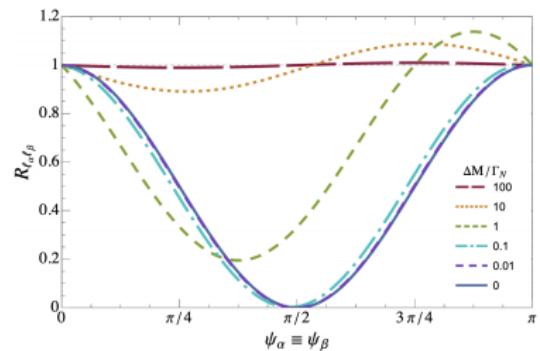
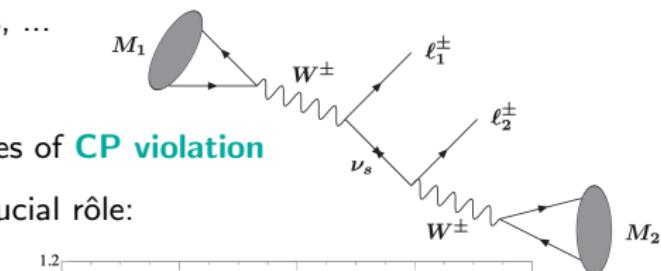
If neutrinos are **Majorana**, total **lepton number** is violated @ tree-level
 ⇒ Expect $0\nu\beta\beta$, **LNV** meson decays, ...

Massive (and mixing) neutrinos: new sources of **CP violation**

CP violating phases are known to play a crucial rôle:



PMNS phases lead to “neck” in $0\nu\beta\beta$



Sterile states interfere in **LNV** meson decays

A. Abada et. al. [1904.05367]

Neutrino mass m_ν generation

Mechanisms of m_ν generation: account for **oscillation data**

and ideally address **SM issues**: BAU (leptogenesis), DM candidates, ...

Many well-motivated possibilities, featuring distinct **NP states** (singlets, triplets)

⇒ Can be realised at **very different scales** $\Lambda_{EW} \rightsquigarrow \Lambda_{GUT}$

Compare “vanilla” type I seesaw vs. **low-scale seesaw**:

High scale: $\mathcal{O}(10^{10} - 10^{15} \text{ GeV})$

Theoretically “natural” $Y_\nu \sim 1$

“Vanilla” **leptogenesis**

New states **decoupled**

Low scale: $\mathcal{O}(\text{MeV} - \text{TeV})$

Finetuned Y^ν or symmetry arguments (e.g. ISS)

Leptogenesis possible (resonant, flavoured, ...)

New states in **experimental reach!**

Collider, high intensities (lepton observables)

⇒ **low-scale seesaws** (and variants): **non-decoupled states**, **modified lepton currents!**

⇒ Rich phenomenology at **colliders**, **high intensities** and **low energies**

TESTABILITY!

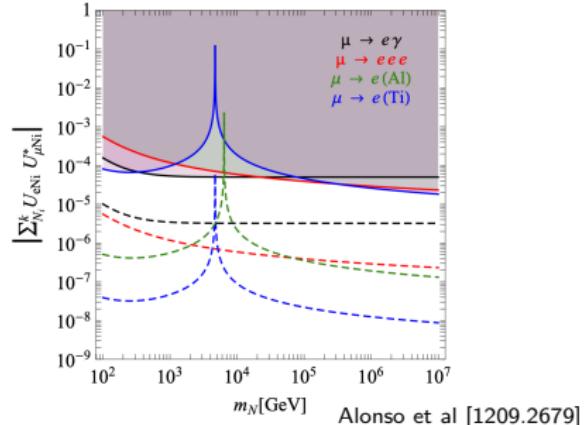
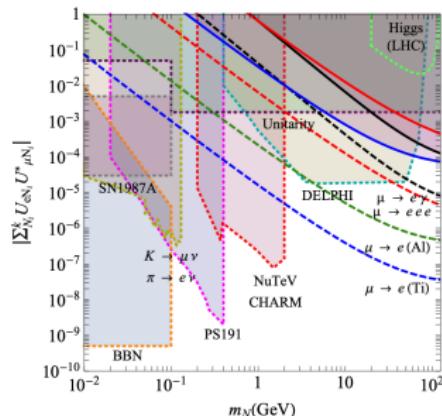
Low-scale type I seesaw

Extend SM with 3 “heavy” RH Majorana neutrinos: $\text{MeV} \lesssim m_{N_i} \lesssim 1 - 100 \text{ TeV}$

Masses and mixings: $m_\nu \simeq -v^2 Y_\nu^T \mathbf{M}_N^{-1} Y_\nu$, $\mathcal{U}^T \mathcal{M}_\nu^{6 \times 6} \mathcal{U} = \text{diag}(m_i)$

$$\mathcal{U} = \begin{pmatrix} \mathbf{U}_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix}, \quad \mathbf{U}_{\nu\nu} \simeq (1 - \eta) \mathbf{U}_{\text{PMNS}}$$

Heavy states not decoupled \Rightarrow neutral and charged lepton currents modified
 \Rightarrow very rich phenomenology: colliders, cLFV, LNV, ...

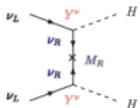


Disentangling seesaws: correlations

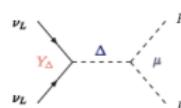
So many models of m_ν , how to distinguish **experimentally**?

In absence of direct discovery (but **cLFV** signals): **correlations** might allow to disentangle models

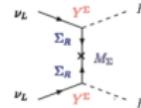
Depending on **seesaw** realisation: distinctive signatures for numerous **cLFV observables**
 \Rightarrow Ratios of **observables** provide complementary information (to **identify seesaw mediators**)



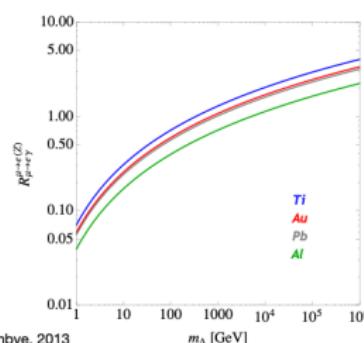
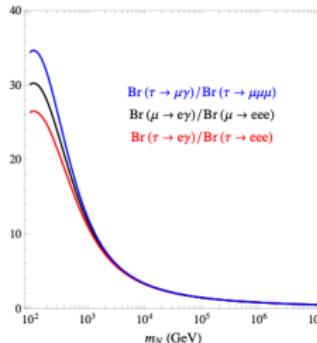
Type I (fermion singlet)



Type II (scalar triplet)



Type III (fermion triplet)



$$\frac{\text{BR}(\mu \rightarrow e\gamma)}{\text{BR}(\mu \rightarrow 3e)} = 1.3 \times 10^{-3}$$

$$\frac{\text{BR}(\tau \rightarrow \mu\gamma)}{\text{BR}(\tau \rightarrow 3\mu)} = 1.3 \times 10^{-3}$$

$$\frac{\text{BR}(\mu \rightarrow e\gamma)}{\text{CR}(e - \mu, \text{Ti})} = 3.1 \times 10^{-4}$$

Disentangling seesaws: correlations

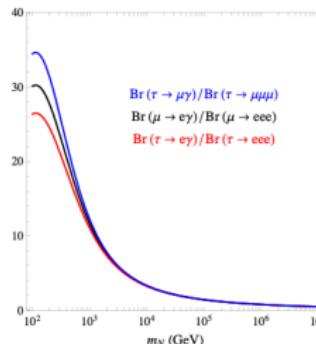
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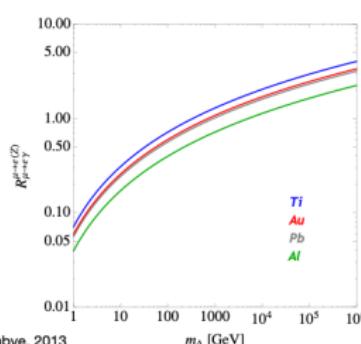
Depending on **seesaw realisation**: distinctive signatures for numerous **cLFV observables**
 \Rightarrow Ratios of **obs**

BUT: what is the effect of CP violating phases on cLFV?

Type I (fermion singlet)



Type II (scalar triplet)



Type III (fermion triplet)

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“3+2” toy model

A plethora of models feature **heavy neutral leptons (HNL)** ...

Ignore precise origin of m_ν , assume 2 (heavy) **Majorana** neutrinos $N_{4,5}$ present
 \Rightarrow 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
 \Rightarrow accommodate osc. data in (enlarged) **PMNS** mixing matrix

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

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

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

Take sterile masses $m_{4,5}$ at **TeV**-scale

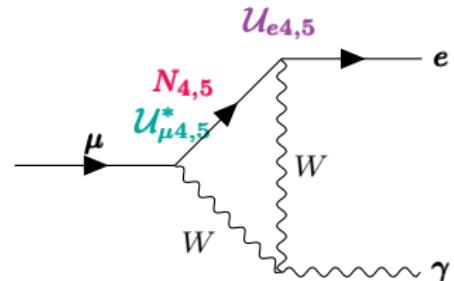
\Rightarrow sizeable **cLFV** rates @ 1 loop-level, what is the effect of **CPV phases**?

Example: $\mu \rightarrow e\gamma$

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

$\text{BR}(\mu \rightarrow e\gamma) \propto |G_\gamma^{\mu e}|^2$ **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 $\sin \theta_{\alpha 4} \approx \sin \theta_{\alpha 5} \ll 1$:

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

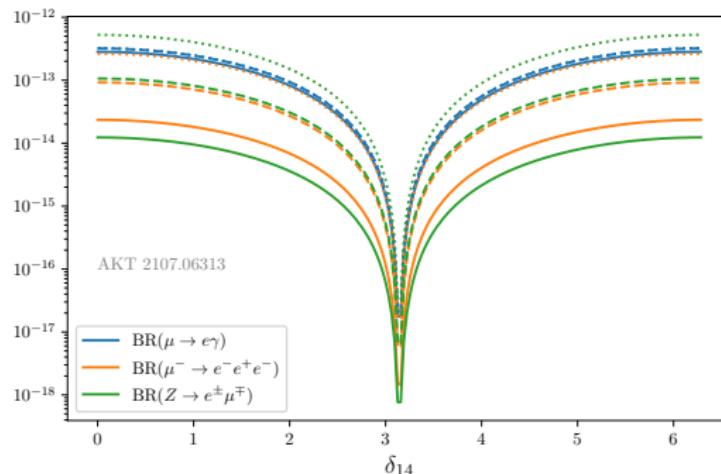
\Rightarrow Rate depends on **Dirac phases**, full **cancellation** for $\delta_{14} + \delta_{25} - \delta_{15} - \delta_{24} = \pi$

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
 $\mu \rightarrow 3e$ additionally depends Z -penguins and box-diagrams

Take $\sin \theta_{\alpha 4} = \sin \theta_{\alpha 5}$ and $\mathbf{m}_4 = \mathbf{m}_5 = (1, 5, 10) \text{ TeV}$, only $\delta_{14} \neq 0$:

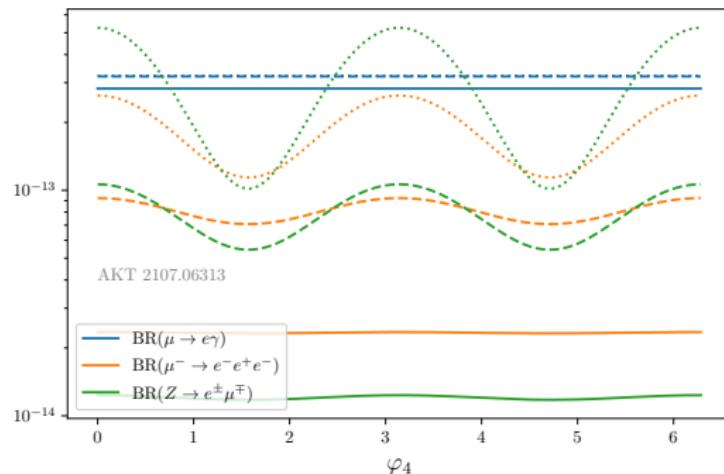


⇒ Strong cancellation for $\delta_{14} = \pi$ in all observables (similar results for $\delta_{24}, \delta_{15}, \delta_{25}$)

Effects of Majorana phases

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

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

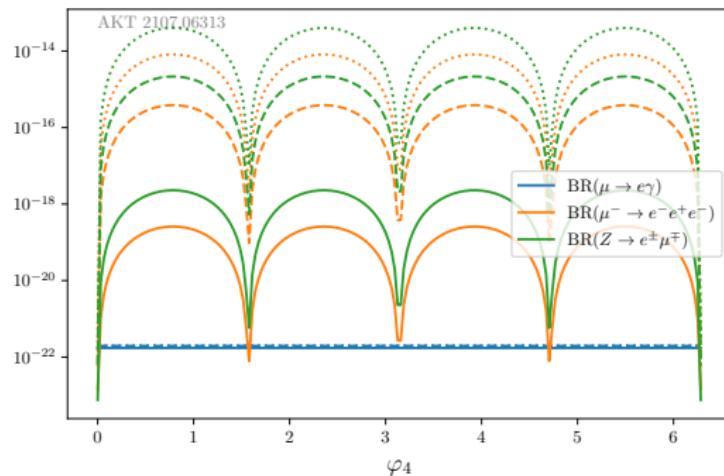


- ⇒ Variational behaviour amplified with increasing $m_{4,5}$
- ⇒ Photon penguin independent of φ_4 (analytically expected)

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 $m_4 = m_5 = (1, 5, 10)$ TeV, vary φ_4 , fix $\delta_{14} = \pi$:



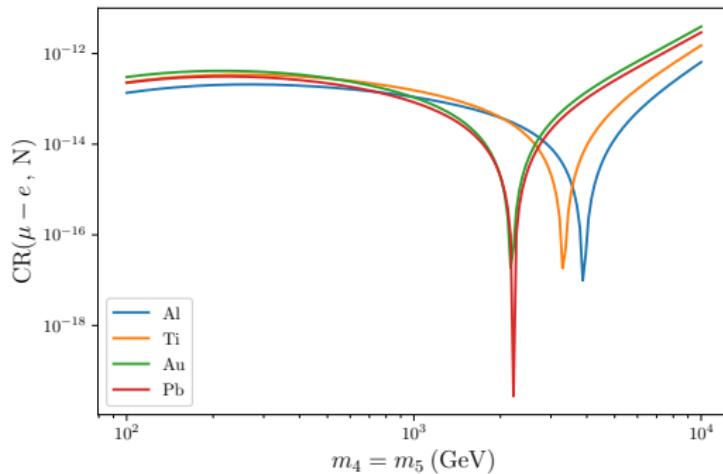
⇒ Cancel dipole contributions, presence of $\varphi_4 \neq 0$ enhances Z-penguin and boxes

Interfering diagrams

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

⇒ Depending on **nucleus**, known **interference** between diagrams (Z -penguin and boxes):
CP conserving case:

(see also Alonso et al 1209.2679)

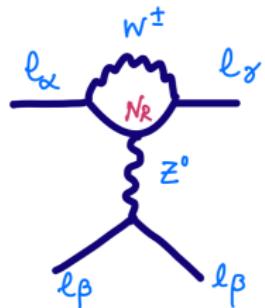
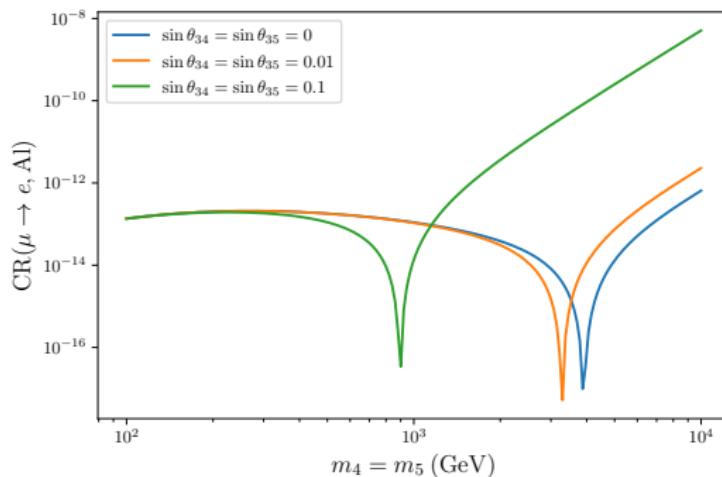


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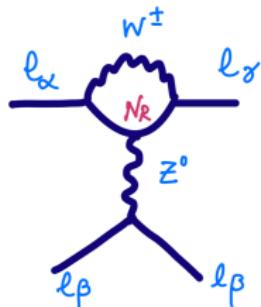
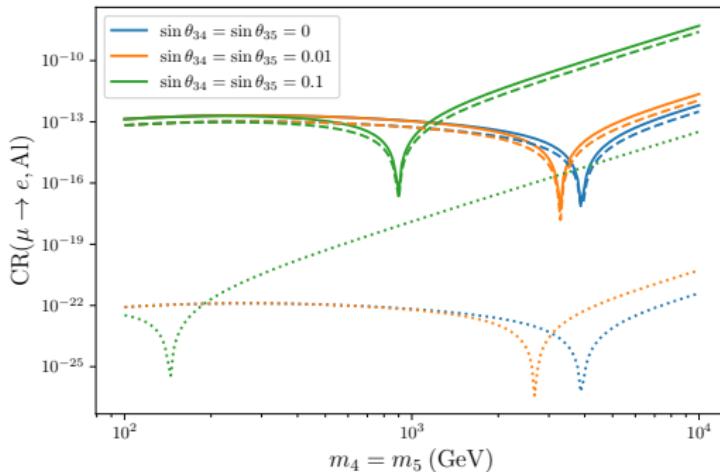
Z-penguin also depends on “tau angles”

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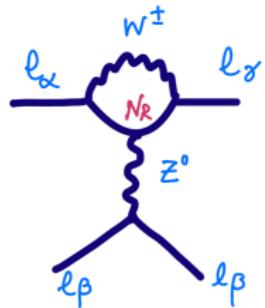
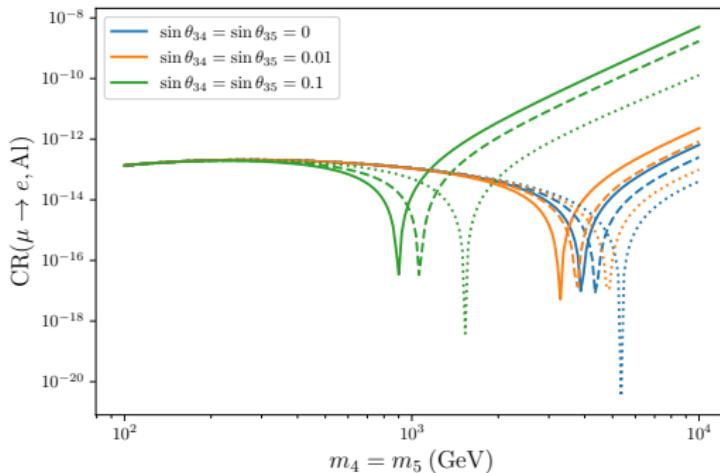
... : $\delta_{14} = \pi/2$, --- : $\delta_{14} = \pi \Rightarrow \text{CPV phases}$ significantly shift the dip

Interfering diagrams

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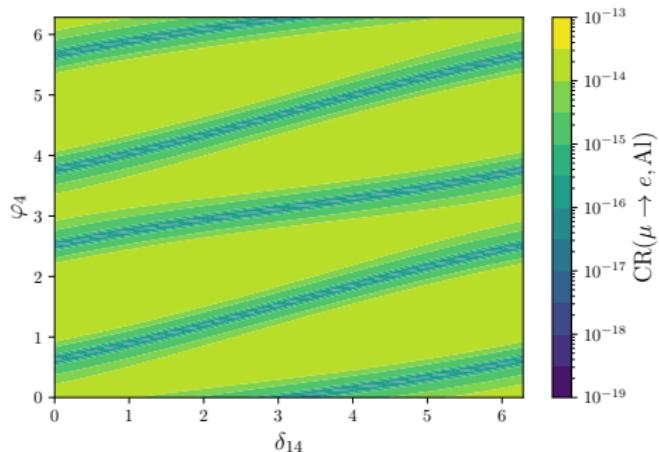
Z-penguin also depends on “tau angles” and **Majorana phases**

... : $\varphi_4 = \pi/4$, --- : $\varphi_4 = \pi/2 \Rightarrow$ **CPV phases** significantly shift the dip

Joint behaviour of Dirac and Majorana CPV phases CR($\mu - e, N$)

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

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

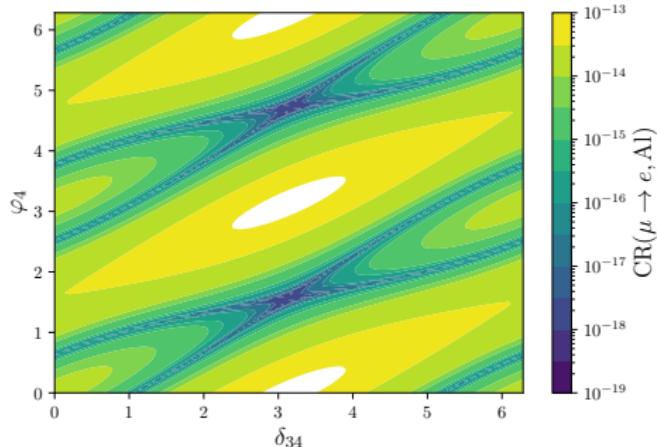


\Rightarrow Varying only φ_4 can lead to strong cancellations as well, interference of contributions

Joint behaviour of Dirac and Majorana CPV phases CR($\mu - e, N$)

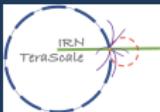
Neutrinoless $\mu - e$ conversion in nuclei, process depends on all topologies and phases

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



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

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



Towards realistic scenarios

For **TeV**-scale **HNL** several indirect constraints apply (besides **cLFV**):

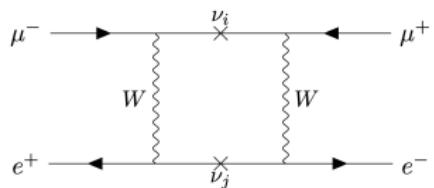
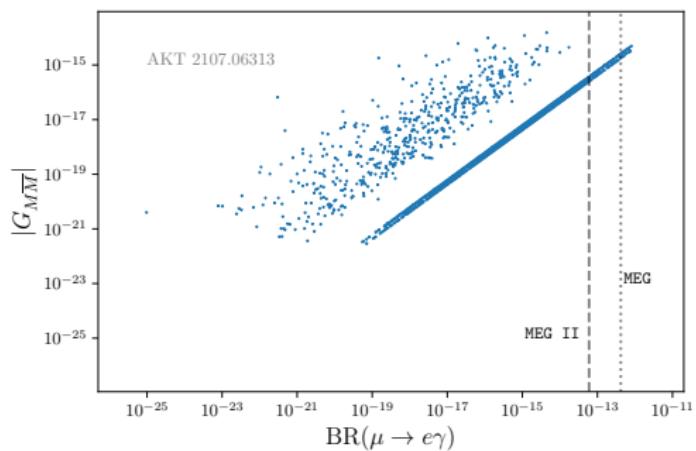
- **Lepton Universality:** $W \rightarrow \ell\nu$, $Z \rightarrow \ell^+\ell^-$, **ratios** of leptonic Meson decays, ratios of (semi-leptonic) τ -lepton decays, **CKM** unitarity ...
- **LNV:** neutrinoless double beta decay
- **Perturbative Unitarity:** $\Gamma_{\mathbf{N}_{4,5}}/m_{\mathbf{N}_{4,5}}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

Constraints independent of **CPV phases**

- ⇒ Randomly scan **constrained** parameter space with $\theta_{\alpha 4} \approx \pm \theta_{\alpha 5}$ and $\mathbf{m}_4 = \mathbf{m}_5 = 1 \text{ TeV}$
- ⇒ For each point vary phases $\delta_{\alpha 4}$ and φ_4 randomly and on a grid

Breaking correlations

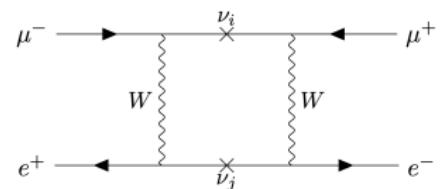
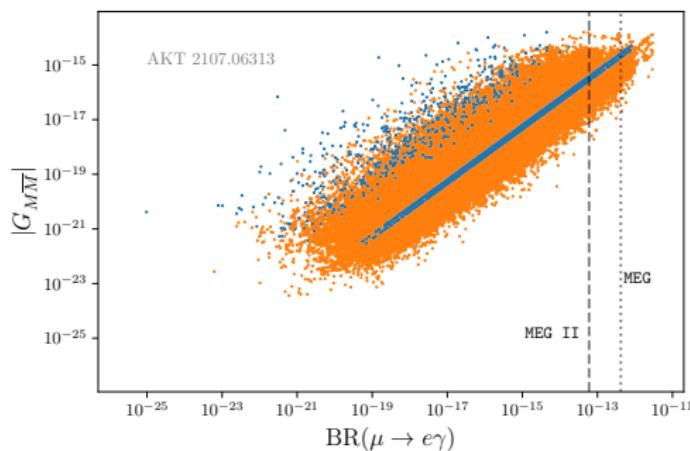
Effective coupling $G_{M\bar{M}}$ of $\text{Mu} - \overline{\text{Mu}}$ oscillation ($\mu^+ e^- \rightarrow \mu^- e^+$) only depends on boxes
 Both $\mu \rightarrow e\gamma$ and $G_{M\bar{M}}$ only depend on $\theta_{14,5}$ and $\theta_{24,5} \Rightarrow$ expect strong correlation



blue: all phases vanishing;

Breaking correlations

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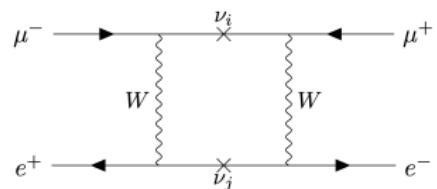
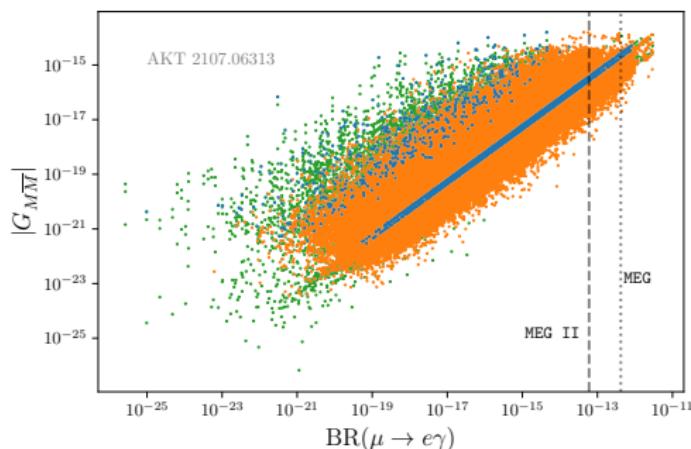


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\Rightarrow Presence of **CP violating** phases **breaks correlation!**

Breaking correlations

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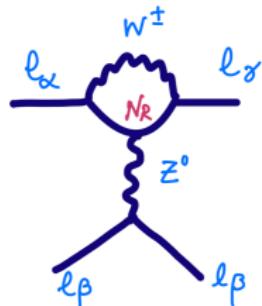
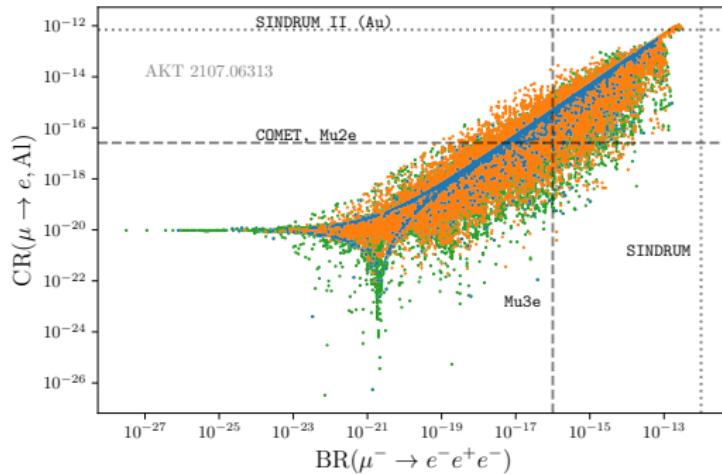


blue: all phases vanishing; orange: random phases; green: phases grid scan

\Rightarrow Presence of **CP violating** phases **breaks correlation!**

Breaking correlations (continued)

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



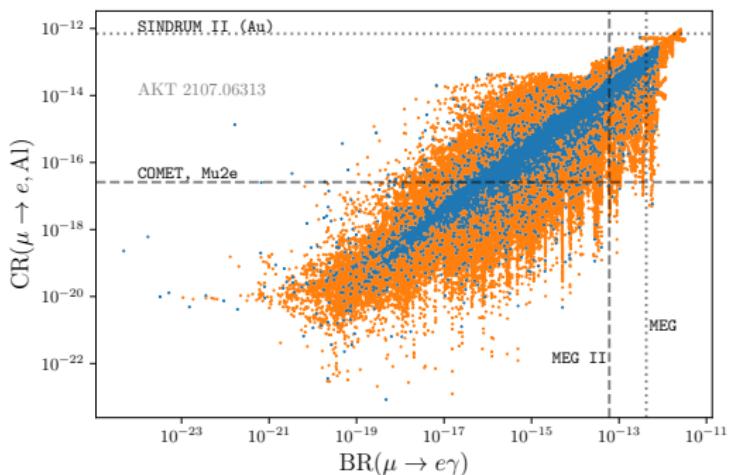
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⇒ Hypothetical signal e.g. only in $\mu \rightarrow 3e$ does not disfavour **HNL models!**

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 $\Gamma_{N_{4,5}}$, $m_4 = 1 \text{ TeV}$, $m_5 - m_4 \in (40 \text{ MeV}, 210 \text{ GeV})$



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



Summary & Conclusion

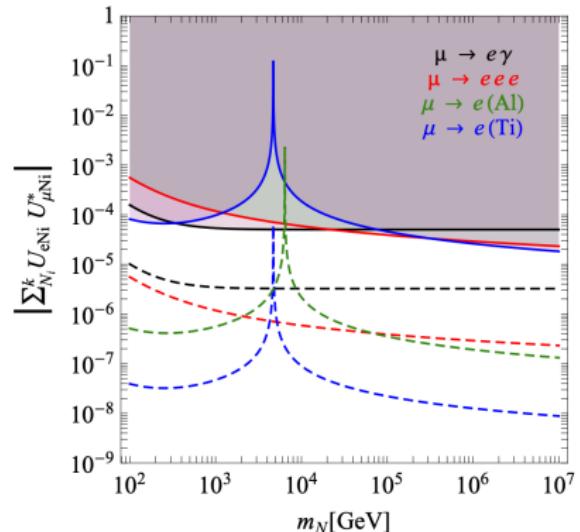
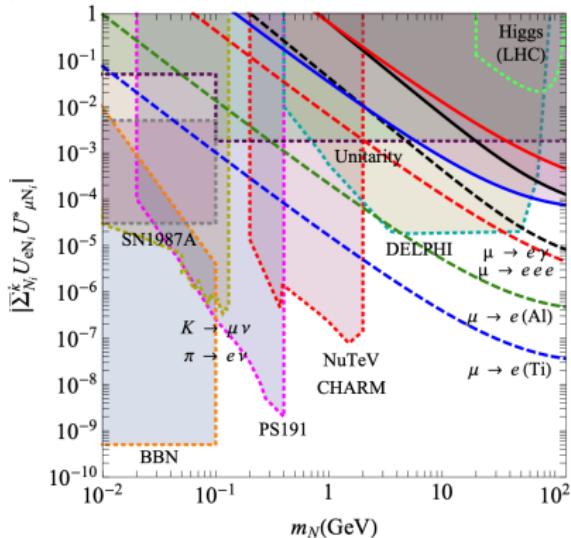
Presence of **CPV** Majorana and Dirac phases can suppress and enhance the rate of **cLFV** observables with significant impact on the interpretation of future data:

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

	BR($\mu \rightarrow e\gamma$)	BR($\mu \rightarrow 3e$)	CR($\mu - e$, Al)	BR($\tau \rightarrow 3\mu$)	BR($Z \rightarrow \mu\tau$)
P ₁	3×10^{-16} ○	1×10^{-15} ✓	9×10^{-15} ✓	2×10^{-13} ○	3×10^{-12} ○
	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} ✓
	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} ✓
	8×10^{-15} ○	1×10^{-14} ✓	6×10^{-14} ✓	2×10^{-9} ✓	1×10^{-8} ✓

Summary & Conclusion

Presence of **CPV** Majorana and Dirac phases can suppress and enhance the rate of $\mu \rightarrow e$ conversion with significant impact on the interpretation of future data.



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

	$\text{BR}(\mu \rightarrow e\gamma)$	$\text{BR}(\mu \rightarrow 3e)$	$\text{CR}(\mu - e, \text{Al})$	$\text{BR}(\tau \rightarrow 3\mu)$	$\text{BR}(Z \rightarrow \mu\tau)$
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} ✓

⇒ 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**

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:

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

	$\text{BR}(\mu \rightarrow e\gamma)$	$\text{BR}(\mu \rightarrow 3e)$	$\text{CR}(\mu - e, \text{Al})$	$\text{BR}(\tau \rightarrow 3\mu)$	$\text{BR}(Z \rightarrow \mu\tau)$
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} ✓
				9 ✓	3×10^{-9} ✓
				1 ✓	1×10^{-9} ✓
				1 ✓	8×10^{-7} ✓
				1 ✓	1×10^{-8} ✓

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

⇒ 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**

Thank you!!!



Bonus slides





Benchmark points

Masses $m_4 = m_5 = 5$ TeV

$$P_1 : \quad s_{14} = 0.0023, \quad s_{15} = -0.0024, \quad s_{24} = 0.0035, \quad s_{25} = 0.0037, \quad s_{34} = 0.0670, \quad s_{35} = -0.0654,$$

$$P_2 : \quad s_{14} = 0.0006, \quad s_{15} = -0.0006, \quad s_{24} = 0.008, \quad s_{25} = 0.008, \quad s_{34} = 0.038, \quad s_{35} = 0.038,$$

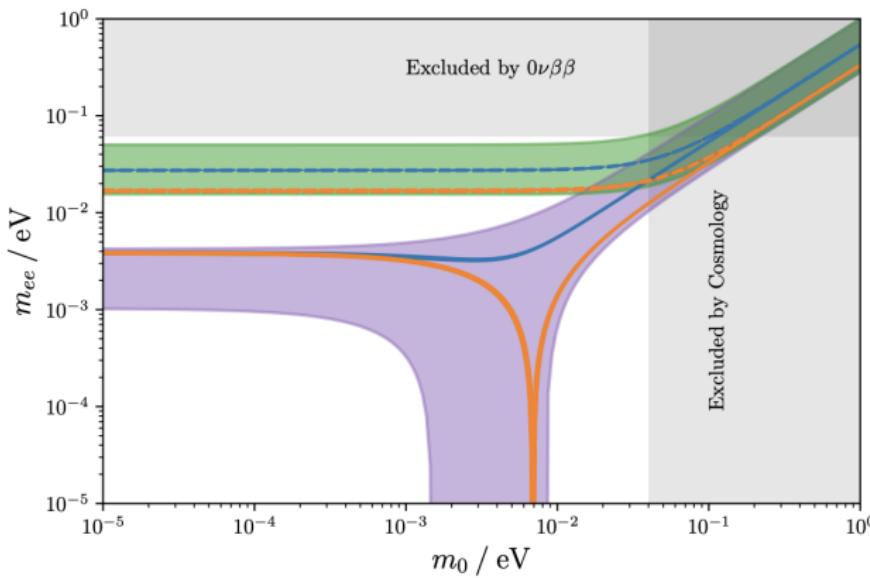
$$P_3 : \quad s_{14} = 0.003, \quad s_{15} = 0.003, \quad s_{24} = 0.023, \quad s_{25} = 0.023, \quad s_{34} = 0.068, \quad s_{35} = 0.068.$$

$$P'_1 : \delta_{14} = \frac{\pi}{2}, \quad \varphi_4 = \frac{3\pi}{4}; \quad P'_2 : \delta_{24} = \frac{3\pi}{4}, \quad \delta_{34} = \frac{\pi}{2}, \quad \varphi_4 = \frac{\pi}{\sqrt{8}}; \quad P'_3 : \delta_{14} \approx \pi, \quad \varphi_4 \approx \frac{\pi}{2}.$$

Flavour and CP symmetries to the rescue!

Consider e.g. $\Delta(3n^2)$ and $\Delta(6n^2)$ symmetries, predict CP phases

Example for (3,3) ISS with $m_N \simeq 1\text{TeV}$



see C. Hagedorn, JK, J. Orloff, A. M. Teixeira [2107.07537]