# Beauty 2023

## Impact of CPV phases on flavour violating H & Z decays

*Eur.Phys.J.C 83 (2023) 6, 494, [2207.10109], with A. Abada, J. Kriewald, S. Rosauro and A. M. Teixeira*

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SM **lepton sector**: neutrinos are strictly massless

⇒ **no source of CP Violation & charged Lepton Flavour Violation**

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$\Longrightarrow$ **Need New Physics**

⇝ Need new fields: **Majorana**? **LNV**? New sources of **CPV**?

Which model? At which scale? ⇝ **Searches for NP** in the **lepton sector**

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Which model? At which scale? ⇝ **Searches for NP** in the lepton sector

If new Majorana states exist, what is the **impact** of the new interactions (mixings & CPV) on **flavour observables**?

Minimal "toy model" for **phenomenological** analyses: SM + **2** Majorana

$\Longrightarrow$ Explore the low-energy phenomenology common to complete models (type I seesaw, ISS, ...)

# Minimal $3+2\nu_s$

- **Ad-hoc** construction: extend the SM with 2 **Majorana massive** states leading to **new mixings** and **CPV phases** (Dirac & Majorana)
- No assumption on the **mass generation mechanism** but **well-defined interactions** in physical basis

Enlarged **active-sterile** mixing $\mathcal{U}_{\alpha i}$

**Left-handed lepton** mixing $\tilde{\mathcal{U}}_{\text{PMNS}}$

$3\times3$ sub-block, **non-unitary**!

$\Rightarrow$ **Modified** charged & **neutral lepton currents**!

$$|n_L> = \mathcal{U}_{5\times5}|\nu_i>$$

$$\mathcal{U}_{5\times5} = \begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & \mathcal{U}_{e4} & \mathcal{U}_{e5} \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} & \mathcal{U}_{\mu4} & \mathcal{U}_{\mu5} \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} & \mathcal{U}_{\tau4} & \mathcal{U}_{\tau5} \\ \mathcal{U}_{s1} & \mathcal{U}_{s2} & \mathcal{U}_{s3} & \mathcal{U}_{s4} & \mathcal{U}_{s5} \\ \mathcal{U}_{s'1} & \mathcal{U}_{s'2} & \mathcal{U}_{s'3} & \mathcal{U}_{s'4} & \mathcal{U}_{s'5} \end{pmatrix}$$

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- **Sizeable contributions** to **cLFV observables**
- **Interference effects** between heavier states expected

**Constructive & destructive interference effects** in cLFV leptonic and boson decays!

Minimal "toy model" for **phenomenological** analyses: **SM** $+ 2\nu_s$

**2 heavy sterile states** with **masses** $m_4$ **and** $m_5$, **leptonic mixing** $\mathcal{U}_{5\times5}$ **and CPV phases** (**Dirac** $\delta$ and/or **Majorana** $\varphi$)

**Full phenomenological study**

$\Longrightarrow$ Take **into account all available experimental constraints**

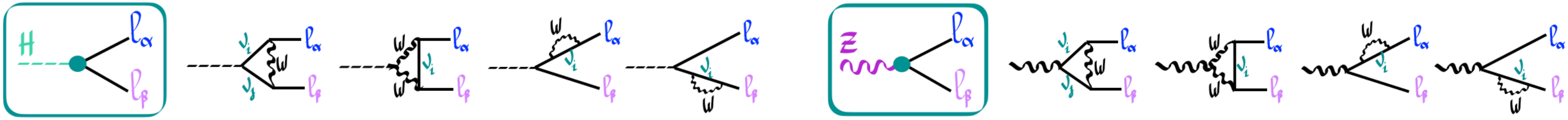
- Limits on **active-sterile mixings**
- Negative results of **searches for sterile states**
- **Electroweak precision** tests
- Bounds on searches for other **cLFV transitions**

$\Longrightarrow$ **No assumptions** on **active-sterile mixings** & all **CPV phases randomly varied**

# CPV and cLFV boson decays

**Gauge bosons ($Z, W$) and Higgs decays** are sensitive to **New Physics**

$\Rightarrow$ What is the **impact** of **CPV phases** on $H \to \mu\,\tau$ and $Z \to \mu\,\tau$ ?



*Full computation of cLFV widths; both unitary & Feynman gauges for complete HNL models*

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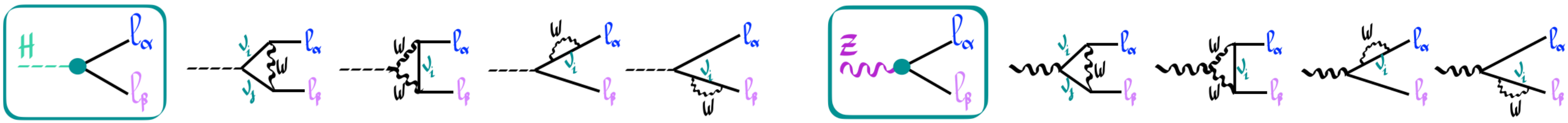

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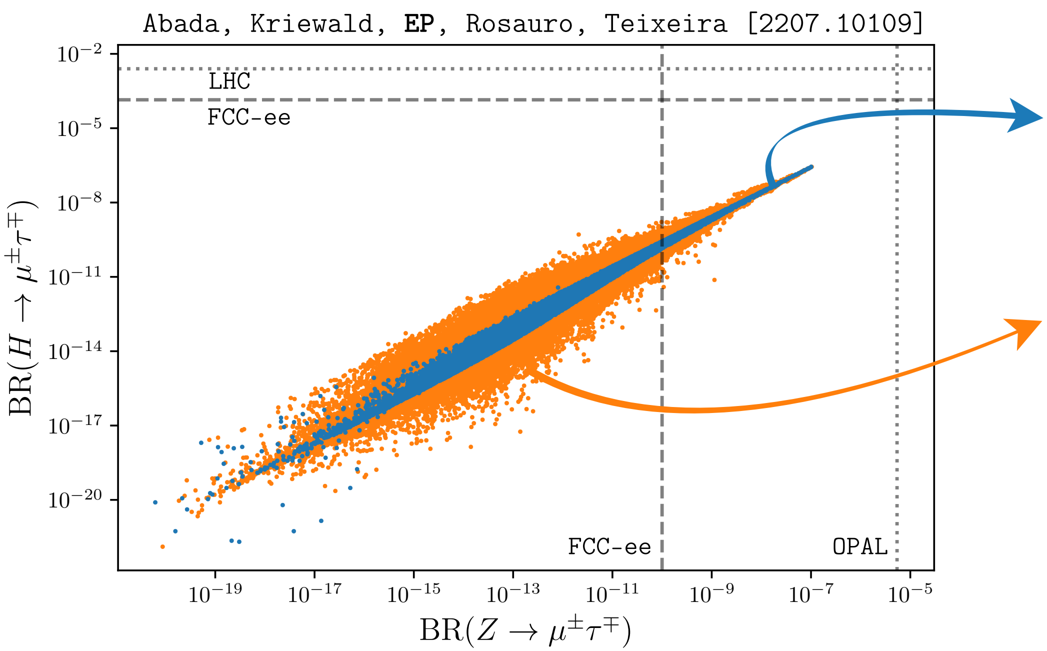
Randomly varying all **CPV phases** associated with the **sterile states**

$$m_4 = 5\,\text{TeV}$$
$$m_5 - m_4 \in [10\,\text{MeV}, 1\,\text{TeV}]$$




**CP conserving**
**Strong correlation**

**CP violating**
**Interferences** loss correlation

$\boldsymbol{Z \to \mu\,\tau}$ within
**future sensitivity**

$\boldsymbol{H \to \mu\,\tau}$ beyond future experimental reach

# CP-asymmetries in $Z$ decays

$Z \to \mu\,\tau$ decays potentially observable **AND** impacted by **CPV phases**

$\Longrightarrow$ Consider **CP-asymmetries**

$$\mathscr{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \frac{\Gamma(Z \to \ell_\alpha^- \ell_\beta^+) - \Gamma(Z \to \ell_\alpha^+ \ell_\beta^-)}{\Gamma(Z \to \ell_\alpha^- \ell_\beta^+) + \Gamma(Z \to \ell_\alpha^+ \ell_\beta^-)}$$

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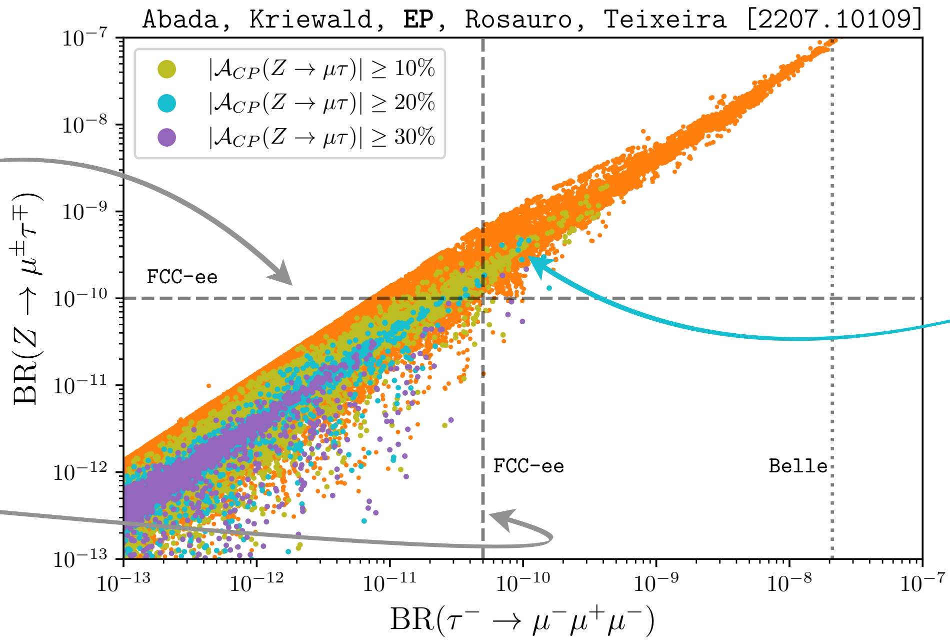
Behaviour of $\boldsymbol{\mu - \tau}$ sector observables

$Z \to \mu\tau$ within future reach

$\tau \to 3\mu$ within future reach




For $Z \to \mu\tau$ and $\tau \to 3\mu$ within future sensitivity $|\mathcal{A}_{CP}(Z \to \mu\tau)|$ can reach $\geq 20\,\%$

If **joint observation** $\Longrightarrow$ **highly suggestive** of such an **extension**!

By *at least* 2 heavy Majorana fermions

# Disentangling scenarios?

Impact of (potential) **measurement** of the **CP asymmetries**

$P_A$ = CP Conserving

$$P_A: \quad m_4 = 5\text{ TeV}, m_5 = 5.1\text{ TeV}, \quad s_{14} = -0.0028\,, s_{15} = 0.0045\,, s_{24} = -0.0052\,, s_{25} = -0.0037\,, s_{34} = -0.052\,, s_{35} = -0.028\,, \quad \delta_{ij} = \varphi_i = 0\,,$$

$P_B$ = CP Violating

$$P_B: \quad m_4 = 5\text{ TeV}, m_5 = 5.1\text{ TeV}, \quad s_{14} = 0.00020\,, s_{15} = -7.1\times 10^{-5}\,, s_{24} = -0.0024\,, s_{25} = 0.029\,, s_{34} = -0.073\,, s_{35} = -0.037\,, \quad \delta_{14} = 0.71\,, \delta_{15} = 5.21\,, \delta_{24} = 2.06\,, \delta_{25} = 4.78\,, \delta_{34} = 3.80\,, \delta_{35} = 4.74\,, \varphi_4 = 1.77\,, \varphi_5 = 4.33\,.$$

Both benchmark points $P_A$ and $P_B$ lead to **common cLFV predictions:**

all leading to $\mu \to 3e$ , $\mu - e$ conversion, $\tau \to 3\mu$ and $Z \to \mu\tau$ within future sensitivity

**Indistinguishable** if **cLFV** signals are observed

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**BUT CP asymmetries** in $Z$ - boson decays offer a **clear distinction**:

$P_B$ leads to $\mathcal{A}_{CP}(Z \to \mu\tau) = 30\,\%$

$\Longrightarrow$ Can **disentangle between CP conserving** et **CPV** scenarios!

# Conclusions

⇝ **Minimal** and **simple** BSM construction:

SM + 2 **heavy** **Majorana** fermions

First steps towards **low-energy phenomenological studies** of complete models

⇝ **cLFV boson decays** sensitive to the presence of HNL:

**CPV phases** have a **clear impact** on the decay rates

⇝ $Z \to \mu\tau$ within future sensitivity and large associated $\mathcal{A}_{CP}$

⇒ Importance of taking **multiple observables** into account to **probe CPV** or **CP conserving** scenarios!

**CP asymmetry key to establish the presence of CP violation!**

# Conclusions

⇝ **Minimal** and **simple** BSM construction:
SM + 2 **heavy Majorana** fermions
First steps towards **low-energy phenom**... ...plete models

⇝ cl...
CPV pl...

⇝ $Z \rightarrow$ ... $CP$
⇒ Import... ...ables into account to **probe CPV** or
**CP co**... ...scenarios!

**CP asymmetry key to establish the presence of CP violation!**

**CP violating phases do matter!**

*and should be generally taken into account for lepton flavoured observables*

# Thank you for your attention

# Modified lepton currents

$$\mathcal{L}_{W^\pm} = -\frac{g_w}{\sqrt{2}} W_\mu^- \sum_{\alpha=1}^{3} \sum_{j=1}^{3+n_S} \mathcal{U}_{\alpha j} \bar{\ell}_\alpha \gamma^\mu P_L \nu_j + \text{H.c.}\,,$$

$$\mathcal{L}_{Z^0}^{\nu} = -\frac{g_w}{4\cos\theta_w} Z_\mu \sum_{i,j=1}^{3+n_S} \bar{\nu}_i \gamma^\mu \left(P_L C_{ij} - P_R C_{ij}^*\right) \nu_j\,,$$

$$\mathcal{L}_{Z^0}^{\ell} = -\frac{g_w}{2\cos\theta_w} Z_\mu \sum_{\alpha=1}^{3} \bar{\ell}_\alpha \gamma^\mu \left(\mathbf{C}_V - \mathbf{C}_A \gamma_5\right) \ell_\alpha\,,$$

$$\mathcal{L}_{H^0} = -\frac{g_w}{4M_W} H \sum_{i\neq j=1}^{3+n_S} \bar{\nu}_i \left[C_{ij}\,\left(P_L m_i + P_R m_j\right) + C_{ij}^*\left(P_R m_i + P_L m_j\right)\right] \nu_j\;,$$

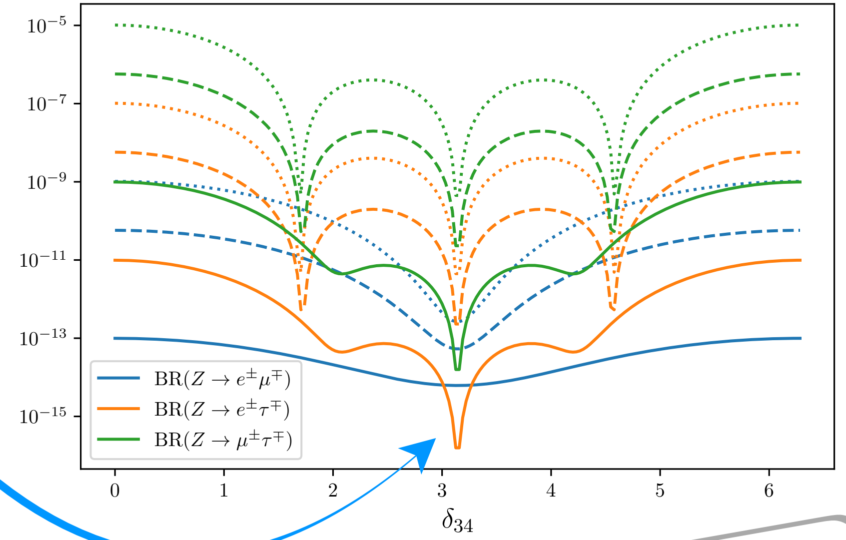
$$C_{ij} = \sum_{\rho=1}^{3} \mathcal{U}_{i\rho}^\dagger \mathcal{U}_{\rho j}$$

$Z \to \ell_\alpha \ell_\beta$

Strong dependence on **Dirac CPV phase** ($\delta_{34}$)

Possibility of decay rate **suppressions**

Abada, Kriewald, **EP**, Rosauro, Teixeira [2207.10109]

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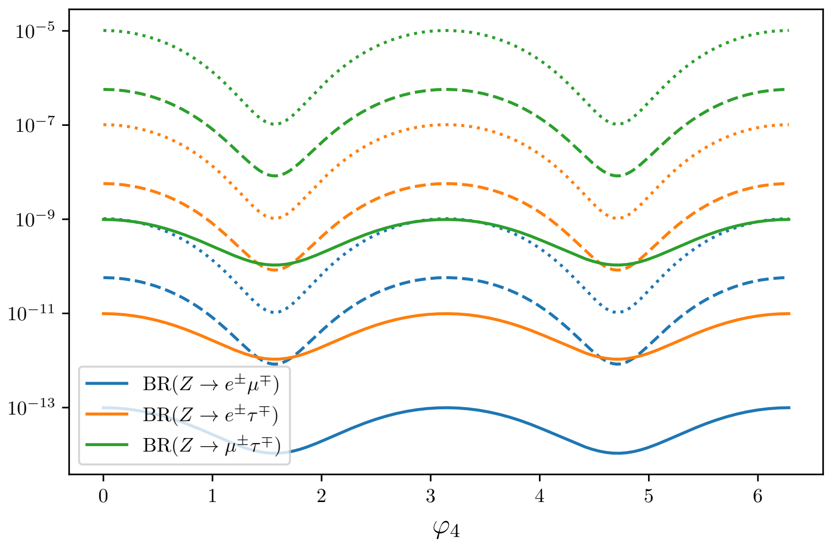


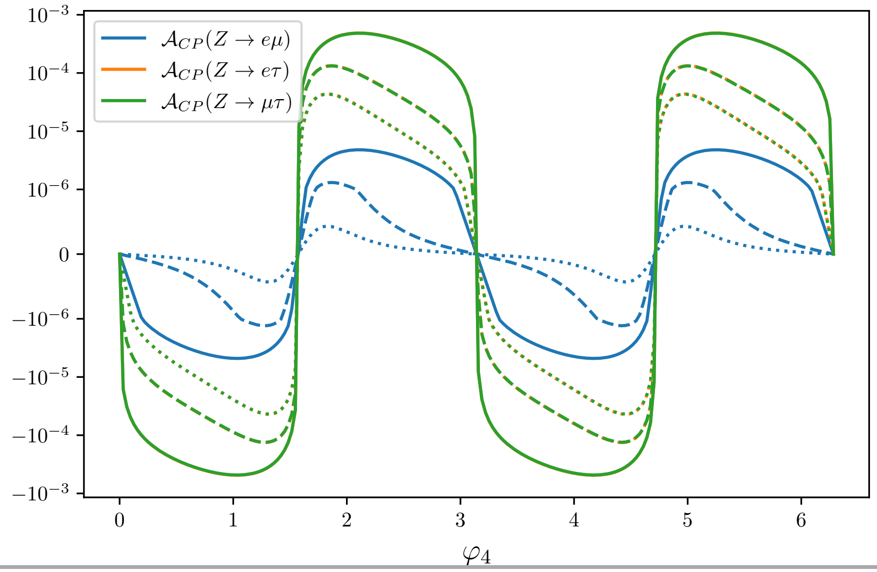

Simplified

1 TeV
5 TeV
10 TeV

Sensitivity to **Majorana CPV phase** ($\varphi_4$)

*These effects are amplified for larger HNL masses*

Abada, Kriewald, **EP**, Rosauro, Teixeira [2207.10109]




Simplified

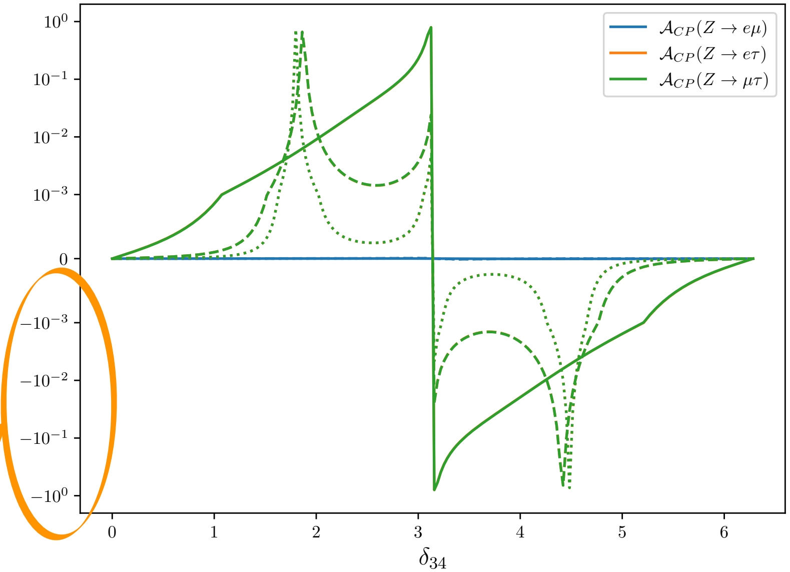
Impact of **Majorana**

**CPV phases**

Impact of **Dirac**

**CPV phases!**

Can lead to **very large** **CP-asymmetry**!

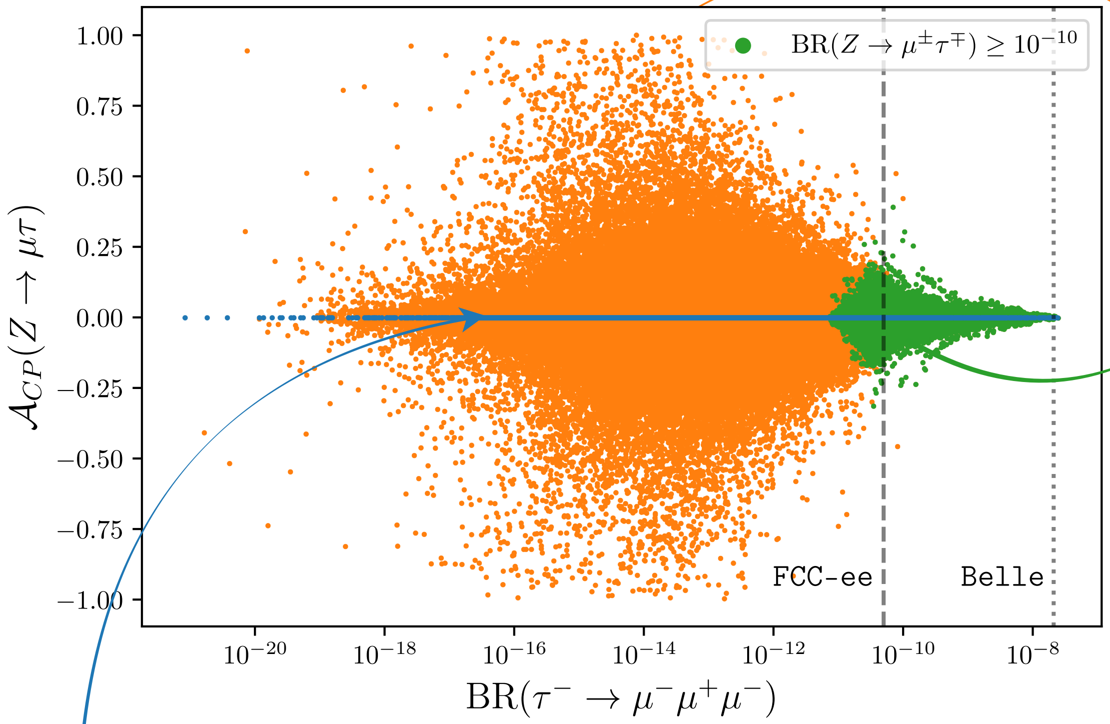


# CP-asymmetry vs. $\tau \to 3\mu$

Varying all **CPV phases** associated with the **sterile states** randomly

Full analysis

Abada, Kriewald, **EP**, Rosauro, Teixeira [2207.10109]




CP conserving

$\mathscr{A}_{CP}$ can be as **large** as **100%**

$Z \to \mu\tau$ and $\tau \to 3\mu$ within **future sensitivity**!

Associated $\mathscr{A}_{CP}$ up to **20%**

Active mixings ($\theta_{\alpha\beta}$) and Dirac CPV $\delta_{13}$: Central values of NuFIT 5.1 results

Active-sterile mixing angles $\theta_{\alpha 4,5}$ constrain from **low-** and **high**-energy observables:

- (Semi-)leptonic $\tau$ decays
- Light mesons leptonic decays

} Construct ratios; sensitivity to **modified** $W\ell\nu$ vertex

$$R_W^{\ell_1 \ell_2} = \frac{\Gamma(W \to \ell_1 \nu)}{\Gamma(W \to \ell_2 \nu)} \qquad \Gamma(Z \to \mathrm{inv})$$

Upper bounds on the entries of $\eta$ indirectly taking into account constrains from **modifications** of $G_F$, $\sin^2\theta_w$ and $M_W$

Bound on **HNL decay width** to comply with perturbative unitarity
$\Longrightarrow$ bound on sterile **masses** and **couplings to active states**

$0\nu 2\beta$: upper limit on the **effective mass** $m_{ee}$ from KamLAND-ZEN

*For TeV-scale HNL, collider searches and cosmological bounds are not competitive*

**Heavier masses**: assumed to be **sufficiently close** to allow for **interferences**

↝ Fix $m_4$ and take random values of $m_5$ from half-normal distributions

*(scale representative of the sterile states width)*

**Active-sterile mixing angles**: **independently** varied & randomly varying signs

For $m_4 = 5\,\text{TeV}$, the range of parameters to be explored is:

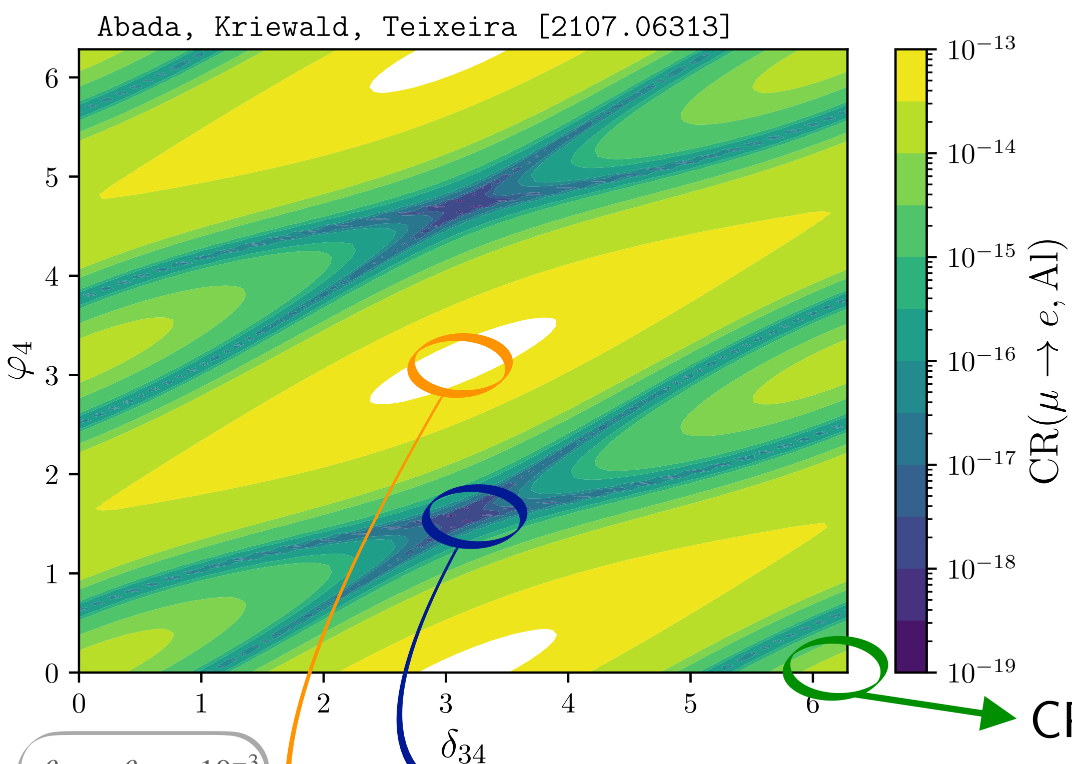
$$\begin{aligned} m_5 - m_4 &\in [10\text{ MeV}, 1\text{ TeV}]\,, \\ |\sin\theta_{14,15}| &\in [6.0\times10^{-5}, 6.0\times10^{-3}]\,, \\ |\sin\theta_{24,25}| &\in [1.9\times10^{-4}, 0.036]\,, \\ |\sin\theta_{34,35}| &\in [8.3\times10^{-4}, 0.13]\,. \end{aligned}$$

$\Longrightarrow$ Correspond to regimes complying with **experimental data** for the **CP conserving case**

**Analysis**: Select randomly $10^4$ points (consistent with experimental data), vary all **CPV phases** associated with sterile states $\delta_{\alpha 4,5}$, $\varphi_{4,5}$ for each tuple of mixing angles.

Consider only regimes that do not lead to cLFV predictions far away from the corresponding **future experimental sensitivity** cLFV: $\boldsymbol{\mu - e}$ **conversion** in nuclei with **CPV Dirac and Majorana phases**

toy model $3+2$ heavy sterile, simplified approach $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$ , $m_4 = m_5 = 1\,\mathrm{TeV}$




Both **destructive** and **constructive** interference effects

Joint effect of **Dirac** ($\boldsymbol{\delta_{34}}$) and **Majorana** ($\boldsymbol{\varphi_4}$) **CPV phases**

$\Longrightarrow$ From beyond experimental sensitivity...
to within future reach...
and even already excluded!

CP Conserving

**CPV** (**max destructive** interference)

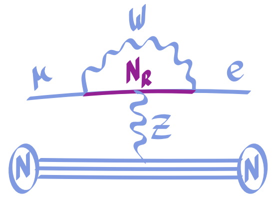
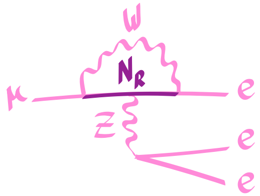
**CPV** (**max constructive** interference)

$\theta_{e4} = \theta_{e5} = 10^{-3}$

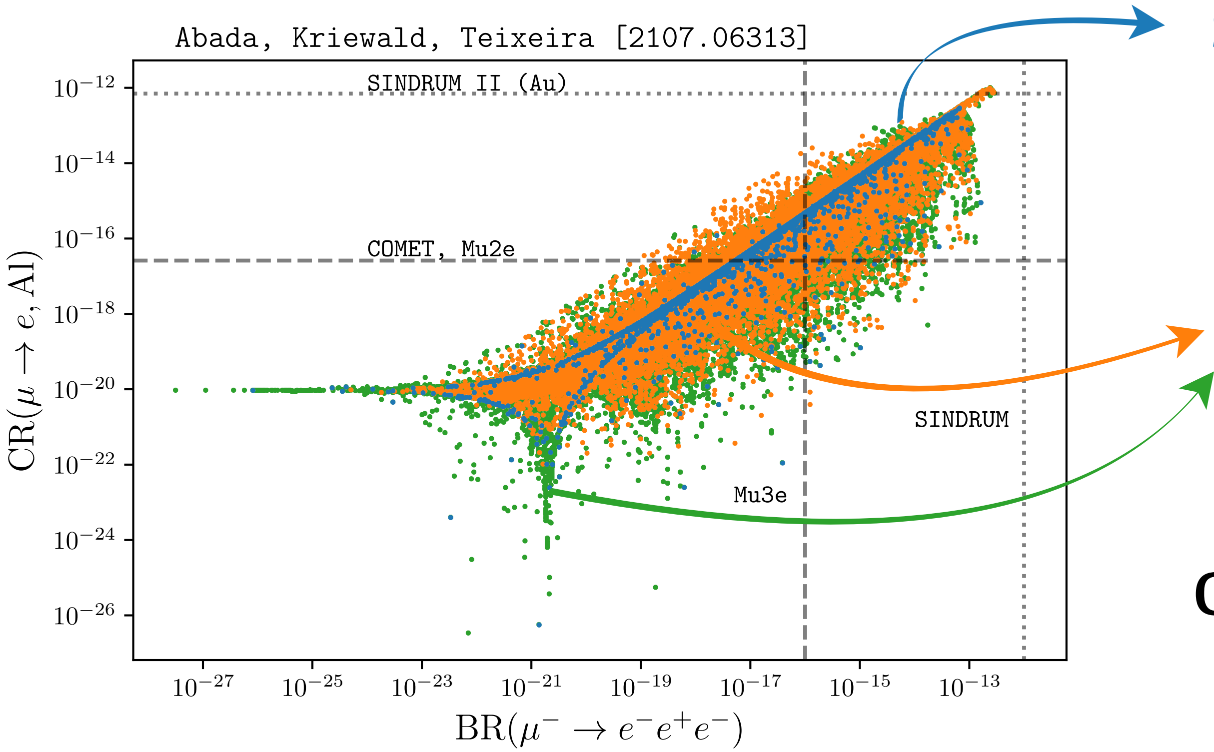
$\theta_{\mu 4} = \theta_{\mu 5} = 0.01$

$\theta_{\tau 4} = \theta_{\tau 5} = 0.1$

Ratios of cLFV observables to identify mediators & constrain their masses

$\mu - e$ **conversion**  vs.  $\mu \to 3e$

But **CP violating phases do matter**! And impact naïve expectations....




**Strong correlation**

(CP conserving)

**Loss of correlation!**

(CP violating)

**Observation** of $\mu \to 3e$

$\not\Rightarrow$ observation of

$\mu - e$ **conversion**