57th Rencontres de Moriond

Impact of CPV phases on flavour violating H & Z decays

based on 2207.10109, with A. Abada, J. Kriewald, S. Rosauro and A. M. Teixeira

Emanuelle Pinsard

LPC Clermont

Extend the SM lepton sector

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

$\Rightarrow$ **no source of CP Violation & charged Lepton Flavour Violation**

Neutrino oscillations: 1st laboratory **evidence of NP**

$\rightsquigarrow$ neutrinos are **massive** & **leptons mix** $\mathcal{U}_{\alpha i}^{\mathrm{PMNS}}$

Extend the SM lepton sector

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

$\Rightarrow$ **no source of CP Violation & charged Lepton Flavour Violation**

Neutrino oscillations: 1st laboratory **evidence of NP**

$\rightsquigarrow$ neutrinos are **massive** & leptons mix $\mathcal{U}_{\alpha i}^{\text{PMNS}}$

$\Longrightarrow$ **Need New Physics**

$\rightsquigarrow$ Need new fields: Majorana? **LNV**? New sources of CPV?

Which model? At which scale? $\rightsquigarrow$ **Searches for NP** in the lepton sector

Extend the SM lepton sector

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

$\Rightarrow$ **no source of CP Violation & charged Lepton Flavour Violation**

Neutrino oscillations: 1st laboratory **evidence of NP**

$\rightsquigarrow$ neutrinos are **massive** & leptons mix $\mathcal{U}_{\alpha i}^{\mathrm{PMNS}}$

$\Longrightarrow$ **Need New Physics**

$\rightsquigarrow$ Need new fields: Majorana? **LNV**? New sources of CPV?

Which model? At which scale? $\rightsquigarrow$ **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 $\tilde{\mathcal{U}}_{\mathrm{PMNS}}$

3×3 sub-block, **non-unitary**!

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

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

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

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 $\tilde{\mathcal{U}}_{\text{PMNS}}$

3×3 sub-block, **non-unitary**!

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

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

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

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

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

Constraints

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** δ and/or **Majorana** φ)

Full phenomenological study

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

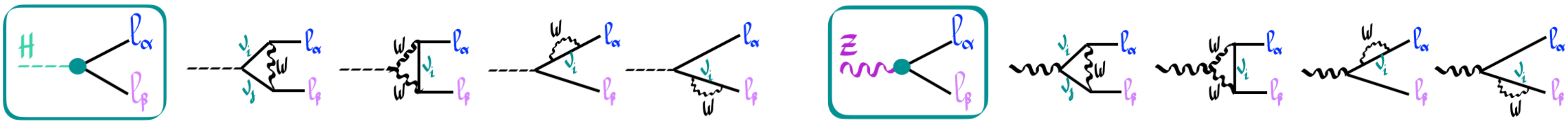
- Limits on **active-sterile mixings**
- Negative results of **searches for sterile states**
- **Electroweak precision** tests
- Bounds on searches for other **cLFV transitions**

$\Longrightarrow$ **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**

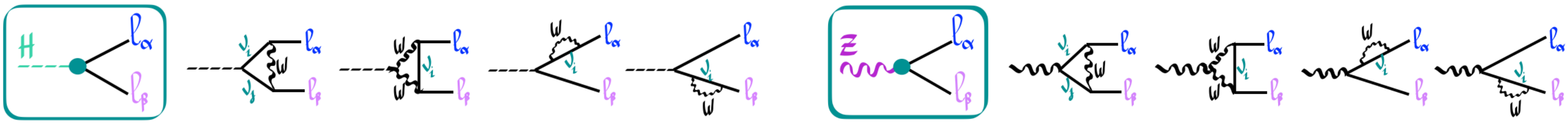
$\Rightarrow$ What is the **impact** of **CPV phases** on $H \to \mu\,\tau$ and $Z \to \mu\,\tau$?



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

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

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

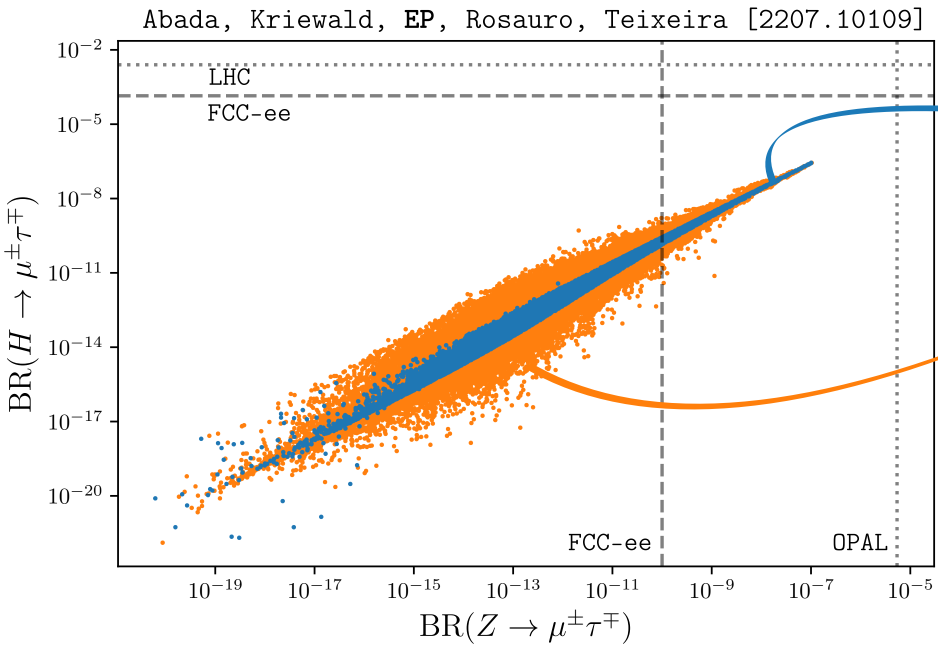


Full computation of cLFV widths; both unitary & Feynman gauges for complete HNL models

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

$m_4 = 5\,\mathrm{TeV}$

$m_5 - m_4 \in [10\,\mathrm{MeV}, 1\,\mathrm{TeV}]$



CP conserving

Strong correlation

CP violating

Interferences loss correlation

$Z \to \mu\,\tau$ within **future sensitivity**

$H \to \mu\,\tau$ beyond future experimental reach

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

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

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

If **sizeable, ultimate probes of the presence of CPV**

CP-asymmetries in Z decays

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

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

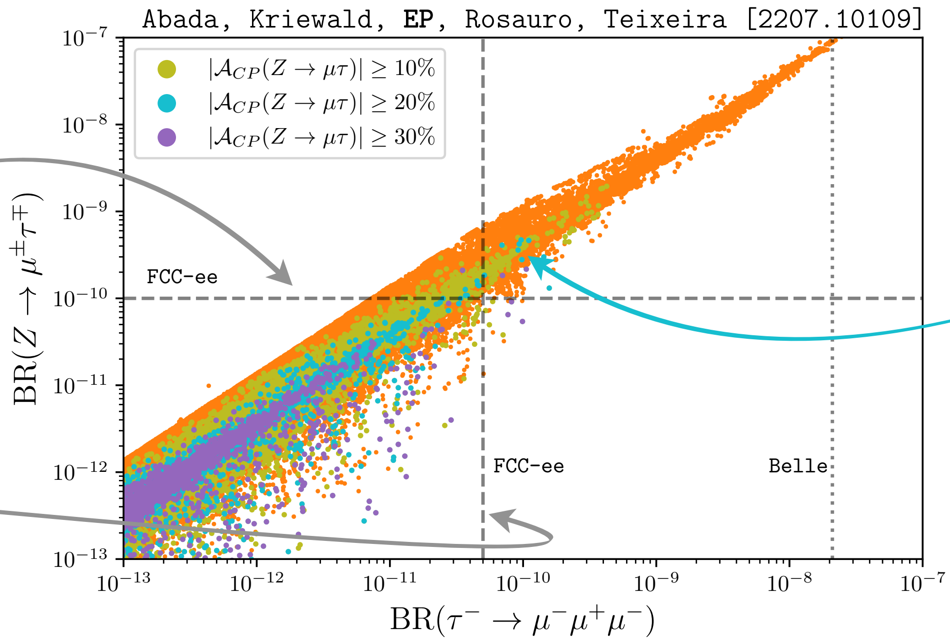
$$\mathcal{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \frac{\Gamma(Z \to \ell_\alpha^- \ell_\beta^+) - \Gamma(Z \to \ell_\alpha^+ \ell_\beta^-)}{\Gamma(Z \to \ell_\alpha^- \ell_\beta^+) + \Gamma(Z \to \ell_\alpha^+ \ell_\beta^-)}$$

If **sizeable, ultimate probes of the presence of CPV**

Behaviour of $\mu - \tau$ 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

$m_4 = 5$ TeV, $m_5 = 5.1$ TeV,

$s_{14} = -0.0028\,, s_{15} = 0.0045\,, s_{24} = -0.0052\,, s_{25} = -0.0037\,, s_{34} = -0.052\,, s_{35} = -0.028\,,$

$\delta_{ij} = \varphi_i = 0\,,$

P_B $=$ CP Violating

$m_4 = 5$ TeV, $m_5 = 5.1$ TeV,

$s_{14} = 0.00020\,, s_{15} = -7.1\times 10^{-5}\,, s_{24} = -0.0024\,, s_{25} = 0.029\,, s_{34} = -0.073\,, s_{35} = -0.037\,,$

$\delta_{14} = 0.71\,, \delta_{15} = 5.21\,, \delta_{24} = 2.06\,, \delta_{25} = 4.78\,, \delta_{34} = 3.80\,, \delta_{35} = 4.74\,, \varphi_4 = 1.77\,, \varphi_5 = 4.33\,.$

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

Disentangling scenarios?

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

P_A $\quad m_4 = 5\,\text{TeV}, m_5 = 5.1\,\text{TeV},$ $\quad P_A$ = CP Conserving

$s_{14} = -\,0.0028\,, s_{15} = 0.0045\,, s_{24} = -\,0.0052\,, s_{25} = -\,0.0037\,, s_{34} = -\,0.052\,, s_{35} = -\,0.028\,,$
$\delta_{ij} = \varphi_i = 0\,,$

P_B $\quad m_4 = 5\,\text{TeV}, m_5 = 5.1\,\text{TeV},$ $\quad P_B$ = CP Violating

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

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

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

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

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

Conclusions

$\leadsto$ **Minimal** and **simple** BSM construction:
SM + 2 **heavy Majorana** fermions
First steps towards **low-energy phenomenological studies** of complete models

$\leadsto$ **cLFV boson decays** sensitive to the presence of HNL:
CPV phases have a **clear impact** on the decay rates

$\leadsto$ $Z \to \mu\tau$ within future sensitivity and large associated $\mathscr{A}_{CP}$
$\Rightarrow$ Importance of taking **multiple observables** into account to **probe CPV** or **CP conserving** scenarios!

CP asymmetry key to establish the presence of CP violation!

LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont
UCA Université Clermont Auvergne
cnrs IN2P3 Les deux infinis

- 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 violating phases do matter!

and should be generally taken into account for lepton flavoured observables

CP asymmetry key to establish the presence of CP violation!

Thank you for your attention

Modified lepton currents

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

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

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

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

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

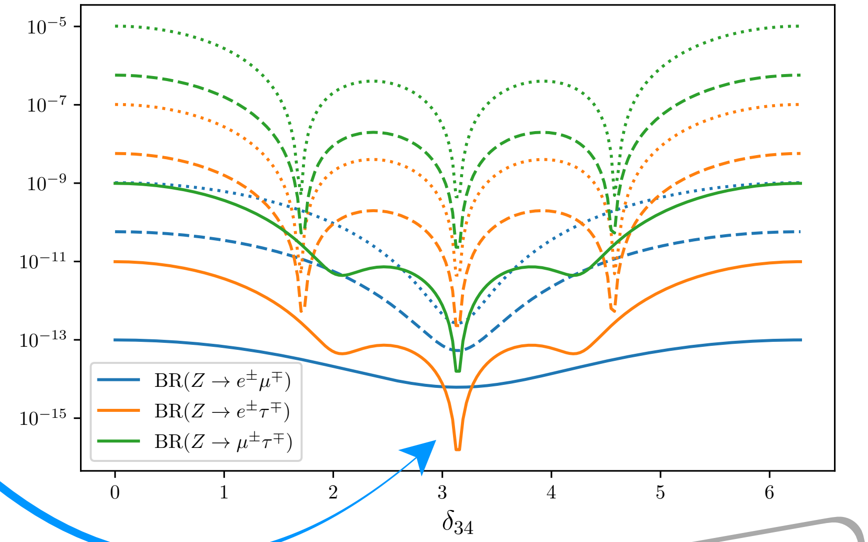
Including CPV phases

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

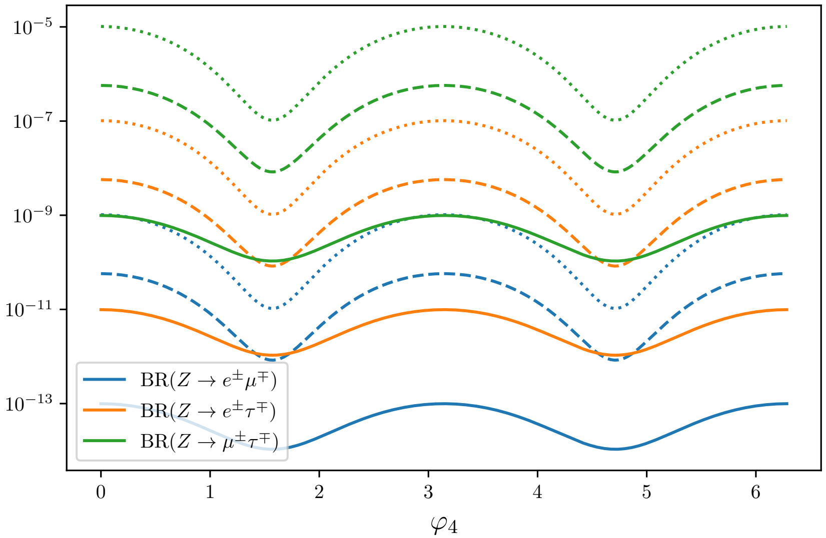
Strong dependence on **Dirac CPV phase** (δ_{34})

Possibility of decay rate **suppressions**

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



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



Simplified

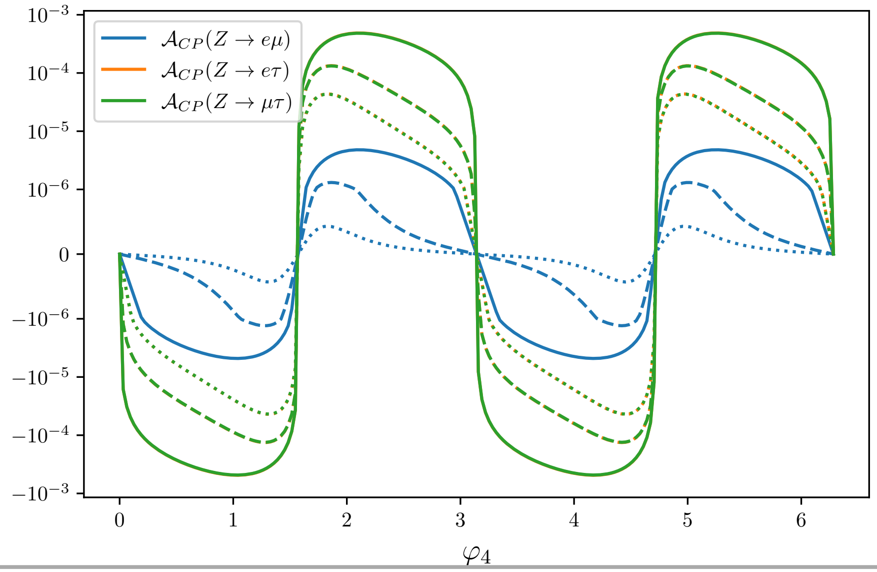
— 1 TeV
– – 5 TeV
······ 10 TeV

Sensitivity to **Majorana CPV phase** (φ_4)

These effects are amplified for larger HNL masses

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

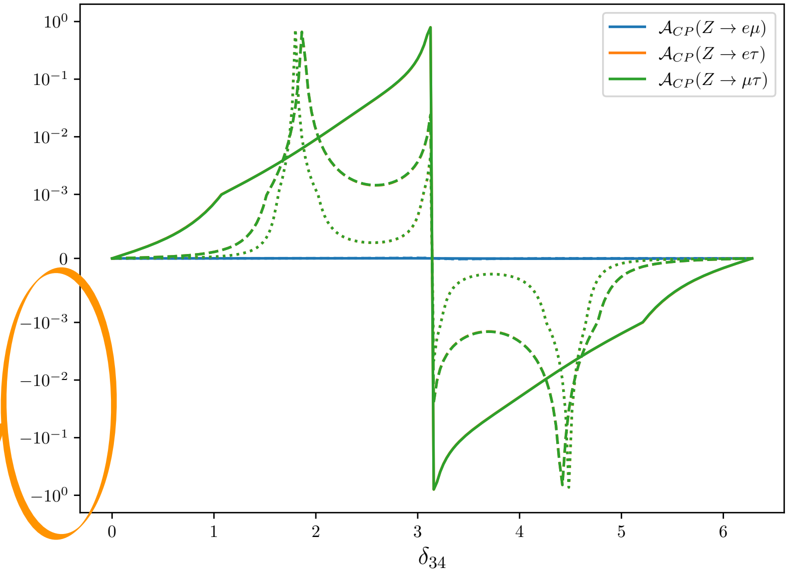
Simplified



Impact of **Majorana** **CPV phases**

Impact of **Dirac** **CPV phases!**

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

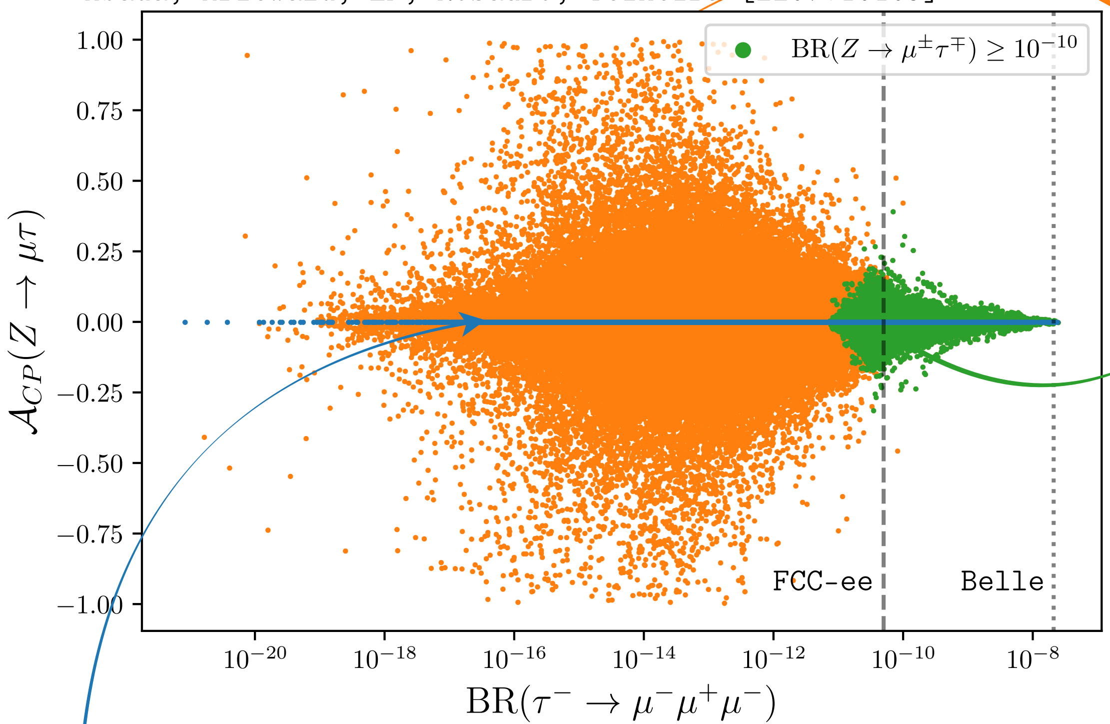


CP-asymmetry vs. $\tau \to 3\mu$

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%**

Constraints

Active mixings ($\theta_{\alpha\beta}$) and Dirac CPV δ_{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 τ decays
Light mesons leptonic decays
} Construct ratios; sensitivity to **modified** $W\ell\nu$ vertex

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

Upper bounds on the entries of η 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**

$0\nu2\beta$: upper limit on the **effective mass** m_{ee} from `KamLAND-ZEN`

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

Overview of the parameter space

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

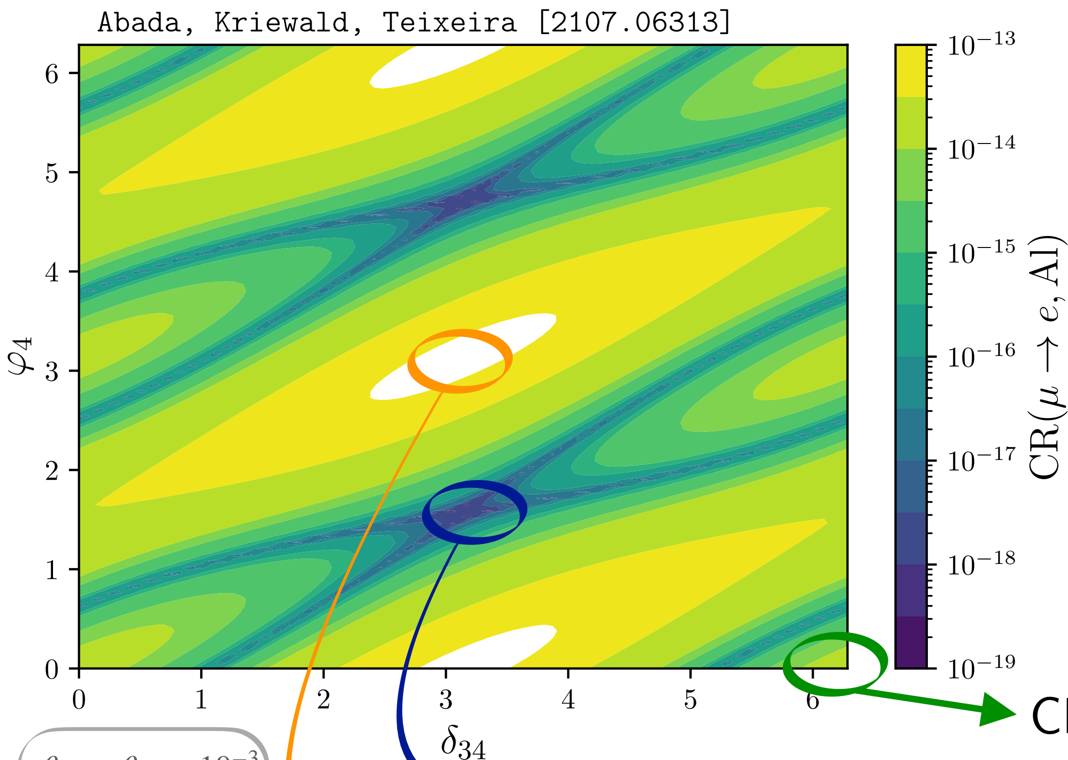
$$\begin{aligned} m_5 - m_4 &\in [10\ \mathrm{MeV}, 1\ \mathrm{TeV}]\,, \\ |\sin\theta_{14,15}| &\in [6.0\times10^{-5}, 6.0\times10^{-3}]\,, \\ |\sin\theta_{24,25}| &\in [1.9\times10^{-4}, 0.036]\,, \\ |\sin\theta_{34,35}| &\in [8.3\times10^{-4}, 0.13]\,. \end{aligned}$$

$\Longrightarrow$ 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 $\delta_{\alpha4,5}$, $\varphi_{4,5}$ 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: **$\mu - e$ conversion** in nuclei with **CPV Dirac and Majorana phases**

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



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

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

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

CP Conserving

CPV (**max destructive** interference)

CPV (**max constructive** interference)

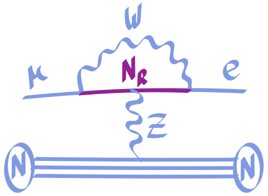
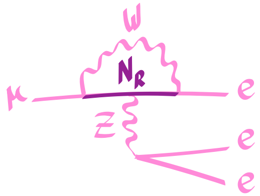
Both **destructive** and **constructive** interference effects

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

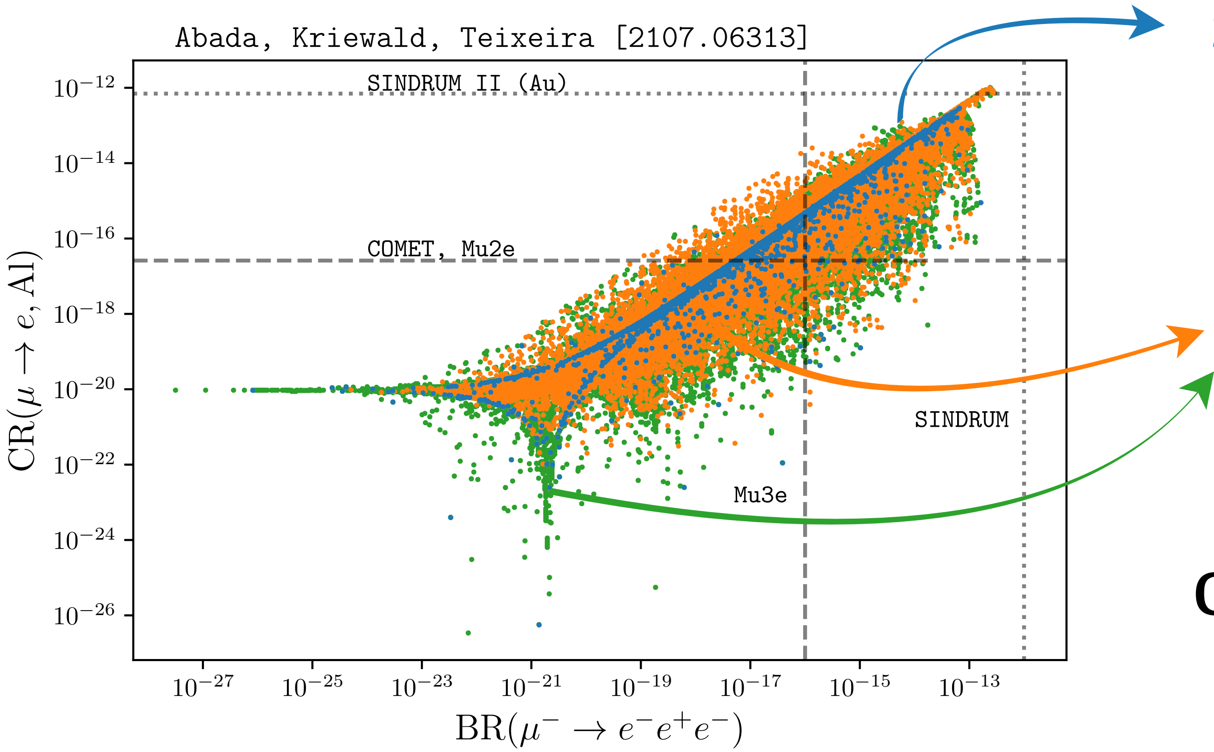
$\Longrightarrow$ From beyond experimental sensitivity...
to within future reach...
and even already excluded!

CPV phases & cLFV

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