IRN Terascale - Nantes

LFV Higgs and Z-boson decays: leptonic CPV phases and CP asymmetries

Emanuelle Pinsard

LPC - Clermont

Flavour: Interactions between fermion families

In the Standard Model, Yukawas encode the **flavour** dynamics (masses, mixings and CP violation)

Gauge interactions are **flavour universal**

Lepton sector: Neutrinos are strictly **massless** in the SM

- ⇝ **Conservation** of total **lepton number** and **lepton flavours**
- ⇝ **Lepton Flavour Universality** (only broken by Yukawas)
- ⇝ **No source of CPV** (only in the quark sector, but not enough for BAU ...)

Numerous **tensions** between SM and observation: $(g-2)_\ell$, B-meson "anomalies", ...

And **observational caveats** of the SM:

dark matter, neutrino oscillations, baryon asymmetry of the Universe

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

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

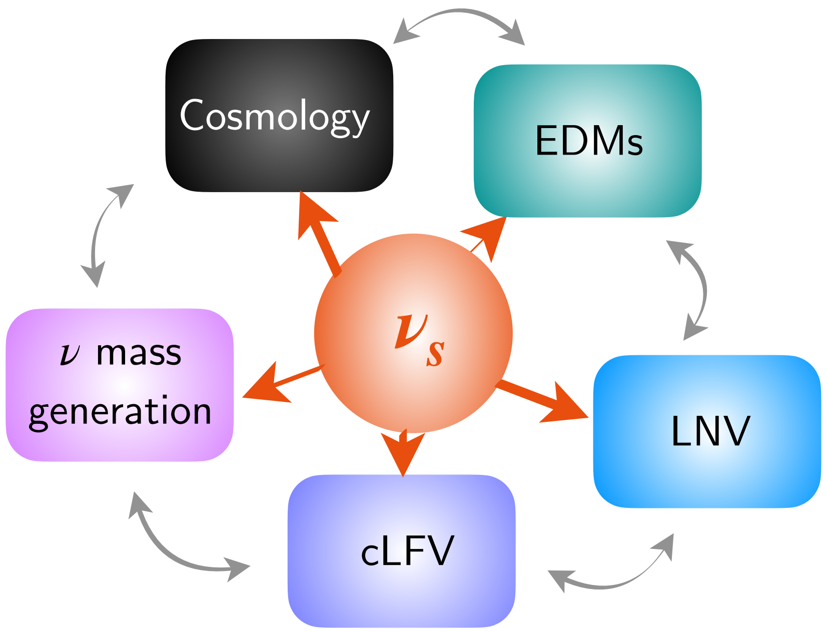
$\Longrightarrow$ **Need New Physics**

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

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

Strong arguments in favour of **New Physics** involving (neutral) leptons!

Majorana sterile fermions are a **very appealing hypothesis**, motivated by extensive **theoretical** and **observational** arguments

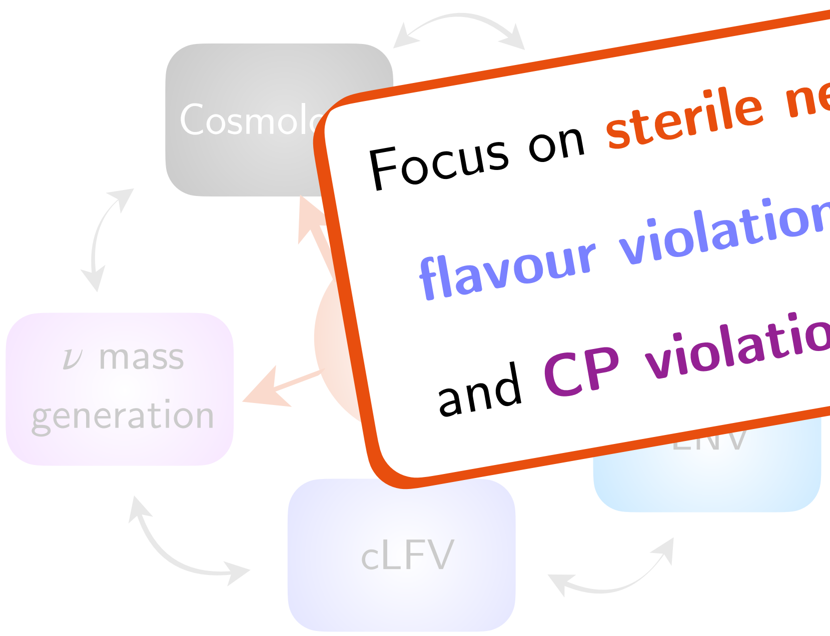


Potentially very "**visible NP portal**":

⇝ Extensive imprints from **colliders** to **low-energy** experiments, from **flavour** dedicated, to **CPV** searches, ...

Strong arguments in favour of **New Physics** involving (neutral) leptons!

Majorana sterile fermions are a **very appealing hypothesis**, motivated by extensive **theoretical** and **observational** arguments



... **NP portal**":
... from **colliders**
... experiments,
from **flavour** dedicated,
to **CPV** searches, ...

Focus on **sterile neutrinos** as sources of **flavour violation** in the lepton sector, and **CP violation** (Dirac & Majorana)

Sterile fermions ($\sim \nu_R$ RH neutrinos):

(minimal) SM extension to account for **neutrino masses & mixings**

- Interactions with SM fields only through **mixings** with active neutrinos
- No bound on the **number** and **mass scale** of the sterile states
- Common to numerous NP models, wide range of scales $\Lambda_{\text{EW}} \to \Lambda_{\text{GUT}}$

High-scale type I seesaw	"**Low-scale**" seesaw
$m_{\nu_s} = \mathcal{O}(10^{10-15}\,\text{GeV})$	$m_{\nu_s} = \mathcal{O}(\text{MeV} - \text{TeV})$
"**natural**" $Y^\nu \sim 1$	Finetune Y^ν
Decoupled new states	New states **within experimental reach!**

Sterile fermions:

(minimal) SM extension to account for **neutrino masses & mixings**

$\rightsquigarrow$ Interactions with SM fields only through **mixings** with active neutrinos

$\rightsquigarrow$ No bound on the **number** and **mass scale** of the sterile states

$\rightsquigarrow$ Common to numerous NP models, wide range of scales $\Lambda_{\text{EW}} \to \Lambda_{\text{GUT}}$

$\Longrightarrow$ Phenomenological implications strongly depend on their **masses**

Low-scale seesaw $\rightsquigarrow$ non-decoupled states, **modified lepton currents**!

Rich phenomenology at low-energies, high-intensity and colliders

EW precision tests, cLFV transitions and decays, $0\nu2\beta$ decays, rare meson decays, ...

Introducing sterile fermions

Sterile fermions:

(minimal) SM extension to account for **neutrino masses & mixings**

- Interactions with SM fields only through **mixings** with active neutrinos
- No bound on the **number** and **mass scale** of the sterile states
- Common to numerous NP models, wide range of scales $\Lambda_{\mathrm{EW}} \to \Lambda_{\mathrm{GUT}}$

$\Longrightarrow$ Phenomenological implicati… d on their **masses**

Low-scale sees… ied lepton currents!

Rich phen… …rgies, high-intensity and colliders

EW precision tests, cLFV transitions and decays, $0\nu2\beta$ decays, rare meson decays, …

Testability!

Minimal models

Minimal "toy model" for **phenomenological** analyses: SM + ν_s

⇝ **Ad-hoc** construction: extend SM with n_s **Majorana massive** states leading to **new mixings** and **CPV phases**

⇝ No assumption on the **mass generation mechanism**

⇝ **Well-defined** **interactions** in physical basis

⟹ Explore the **low-energy phenomenology** common to complete models (type I seesaw, ISS, ...)

Focus on **sterile** fermions and **cLFV observables**

Constructing simplified models

Minimal "toy model" for **phenomenological** analyses: SM $+1\,\nu_s$

Active-sterile mixing $\mathcal{U}_{\alpha i}$

$$|n_L\rangle = \mathcal{U}_{4\times4}|\nu_i\rangle$$

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

3×3 sub-block, **non-unitary**!

⇒ **Modified** charged

& **neutral lepton currents**!

$$\mathcal{U}_{4\times4} = \begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & \mathcal{U}_{e4} \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} & \mathcal{U}_{\mu4} \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} & \mathcal{U}_{\tau4} \\ \mathcal{U}_{s1} & \mathcal{U}_{s2} & \mathcal{U}_{s3} & \mathcal{U}_{s4} \end{pmatrix}$$

Physical parameters:

- ⇝ **4 masses**: 3 light mostly active & 1 heavy mostly sterile
- ⇝ **6 mixing angles**
- ⇝ **6 CPV phases** (3 Dirac δ_{ij} and 3 Majorana φ_i)

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

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

Active-sterile mixing $\mathcal{U}_{\alpha i}$

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

3×3 sub-block, **non-unitary**!

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

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

$\rightsquigarrow$ **Sizeable contributions** to **cLFV observables** (already present in $3+1$)

$\rightsquigarrow$ **Interference effects** between heavier states expected

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

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

Parametrise $\mathcal{U}$ via a series of 10 (complex) **rotations** R_{ij} and a diagonal matrix including the **4 physical Majorana phases** φ_i

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

$$\mathcal{U} = R_{45}\, R_{35}\, R_{25}\, R_{15}\, R_{34}\, R_{24}\, R_{14}\, R_{23}\, R_{13}\, R_{12} \times \mathrm{diag}(1, e^{i\varphi_2}, e^{i\varphi_3}, e^{i\varphi_4}, e^{i\varphi_5})$$

With, for illustration:

Mixing parameters θ_{ij}

$$R_{45} = \begin{pmatrix} \mathbb{1}_{3\times3} & \mathbb{0}_{2\times3} \\ \mathbb{0}_{3\times2} & \Theta_{45} \end{pmatrix} \qquad \Theta_{45} = \begin{pmatrix} \cos\theta_{45} & \sin\theta_{45}\, e^{-i\delta_{45}} \\ -\sin\theta_{45}\, e^{i\delta_{45}} & \cos\theta_{45} \end{pmatrix}$$

Dirac phases δ_{ij}

Simplified vs. Full analysis

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

2 heavy sterile states with **masses** m_4 **and** m_5 **, leptonic mixing** $\mathcal{U}_{5\times5}$

CPV phases (**Dirac** δ and/or **Majorana** φ)

Simplified

Illustrative (*simplified*) approach

$\Longrightarrow$ **No experimental constraint**

- Assume **degenerate masses** $m_4 = m_5$
- Assume **degenerate mixing angles** $\theta_{\alpha 4} = \theta_{\alpha 5}$
- Unconsidered phases set to 0

Illustrate the **impact** of **phases**

Full analysis

Take **into account all available experimental constraints** $\Longrightarrow$ **Full phenomenological study**

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

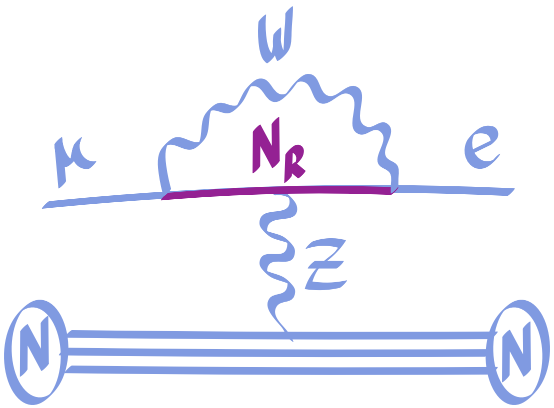
$\Longrightarrow$ **No assumptions** on **active-sterile mixings** & all **CPV phases randomly varied**

(Leptonic) cLFV with CPV phases

cLFV: $\mu - e$ **conversion** in nuclei with **CPV Dirac and Majorana phases**

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

Simplified



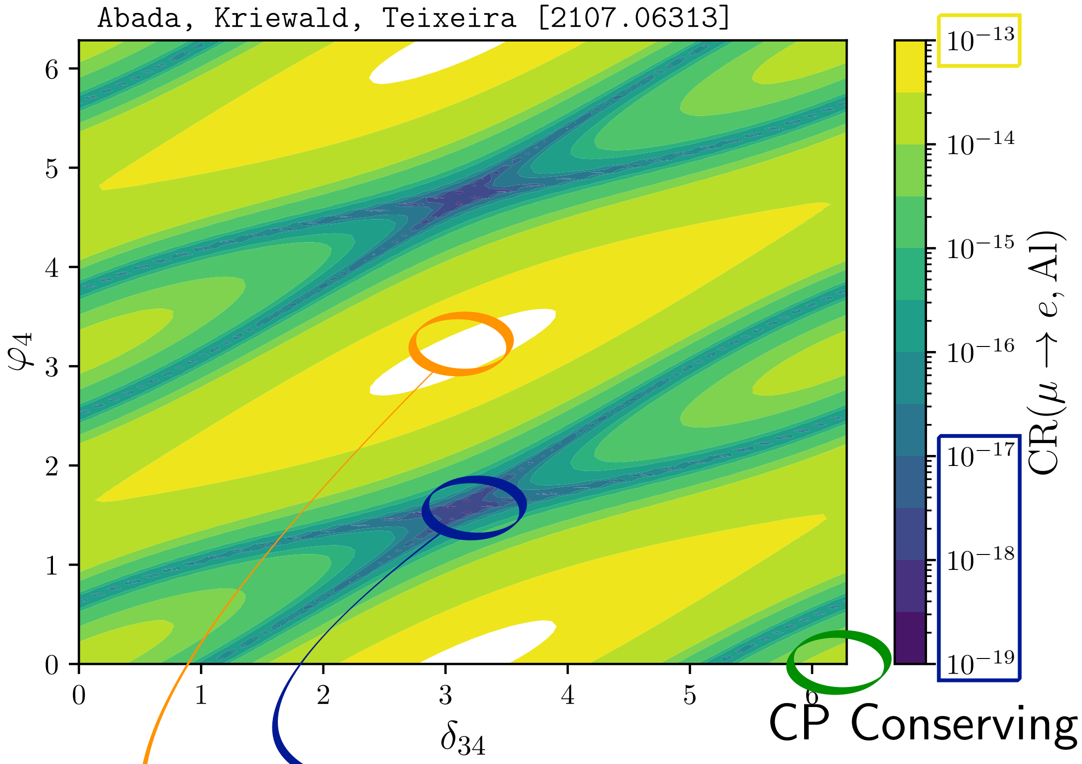
Both **destructive** and **constructive** interference effects

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

CPV phases & cLFV

cLFV: $\mu - e$ **conversion** in nuclei with **CPV Dirac and Majorana phases**

$3+2$ heavy ν_s: simplified approach $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$, $m_4 = m_5 = 1\,\mathrm{TeV}$ Simplified



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!

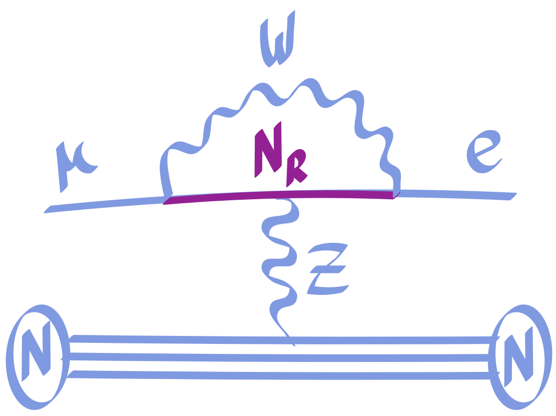
CPV (**max destructive** interference)

CPV (**max constructive** interference)

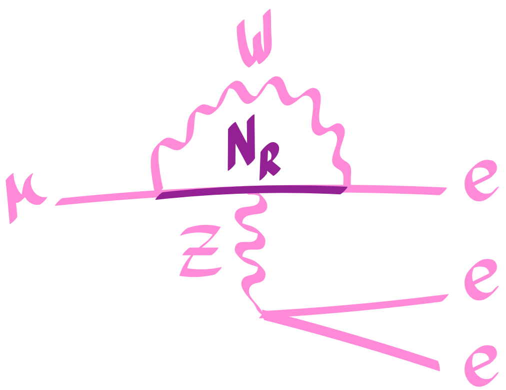
Ratios of cLFV observables to identify mediators & constrain their masses

An example: observables dominated by a **common topology** (Z -penguin)

$\mu - e$ conversion



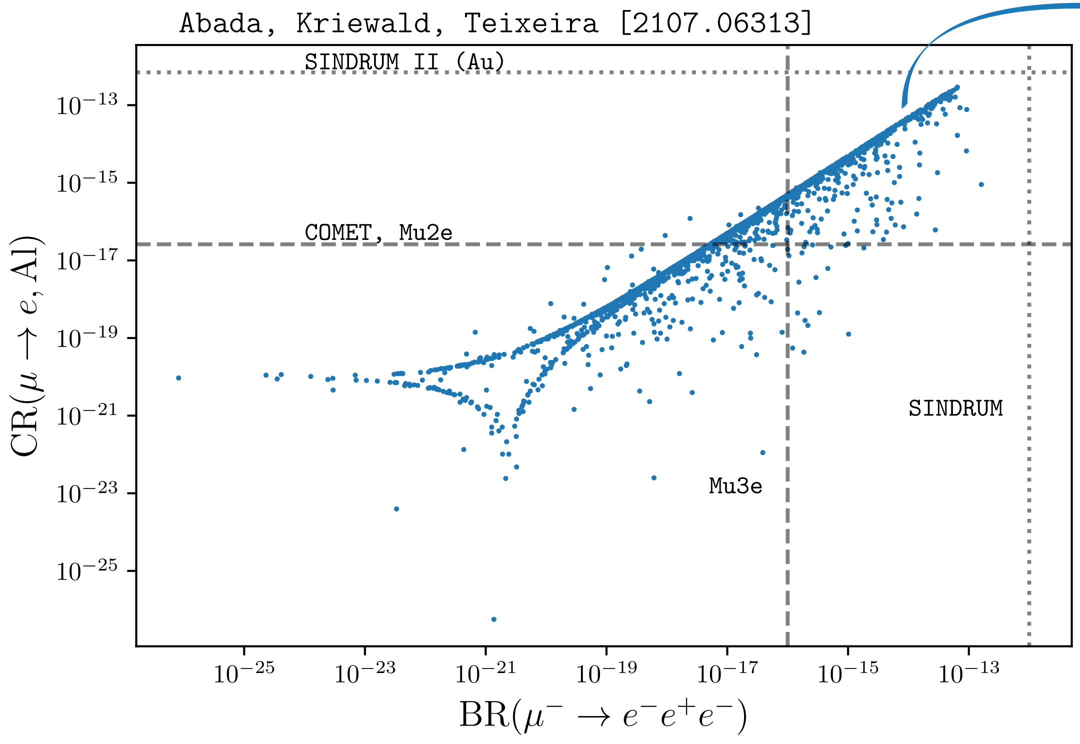
3-body muon decays ($\mu \to 3e$)



Ratios of cLFV observables to identify mediators & constrain their masses

Heavy sterile neutrino masses fixed to $m_4 = m_5 = 1\,\text{TeV}$

Full analysis



Strong correlation

(CP conserving)

Observation of $\mu \to 3e$

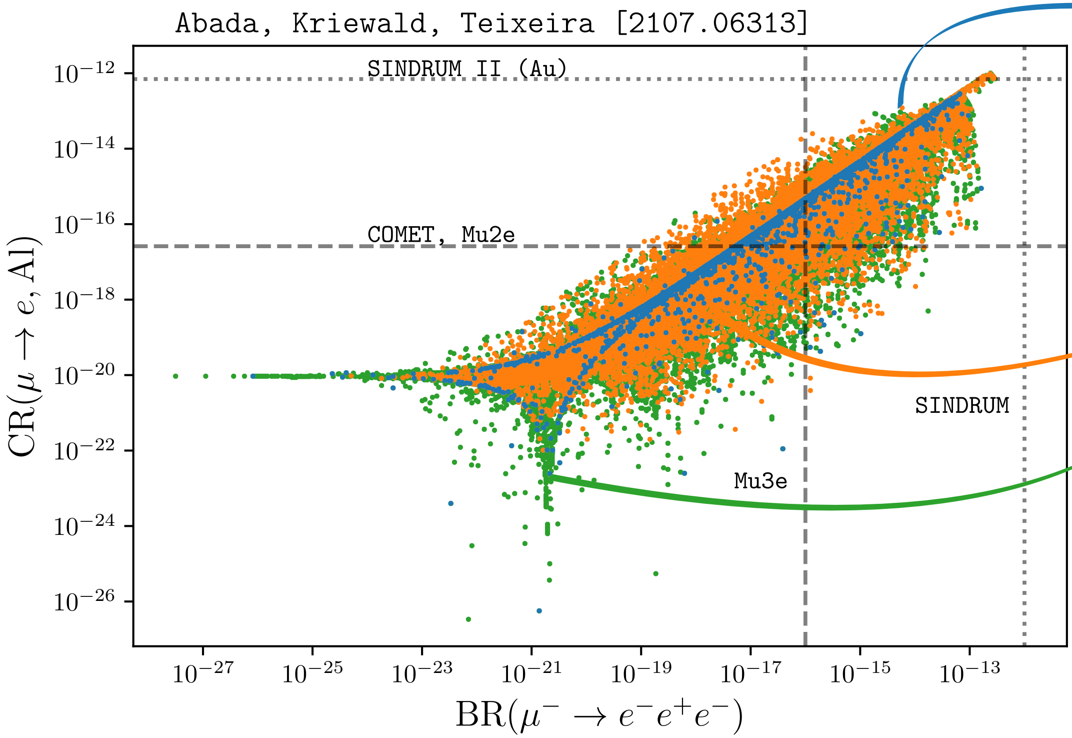
$\Longrightarrow$ observation of

$\mu - e$ **conversion**

Ratios of cLFV observables to identify mediators & constrain their masses

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

Full analysis



Strong correlation

(CP conserving)

Loss of correlation!

(CP violating)

Observation of $\mu \to 3e$

$\not\Rightarrow$ observation of

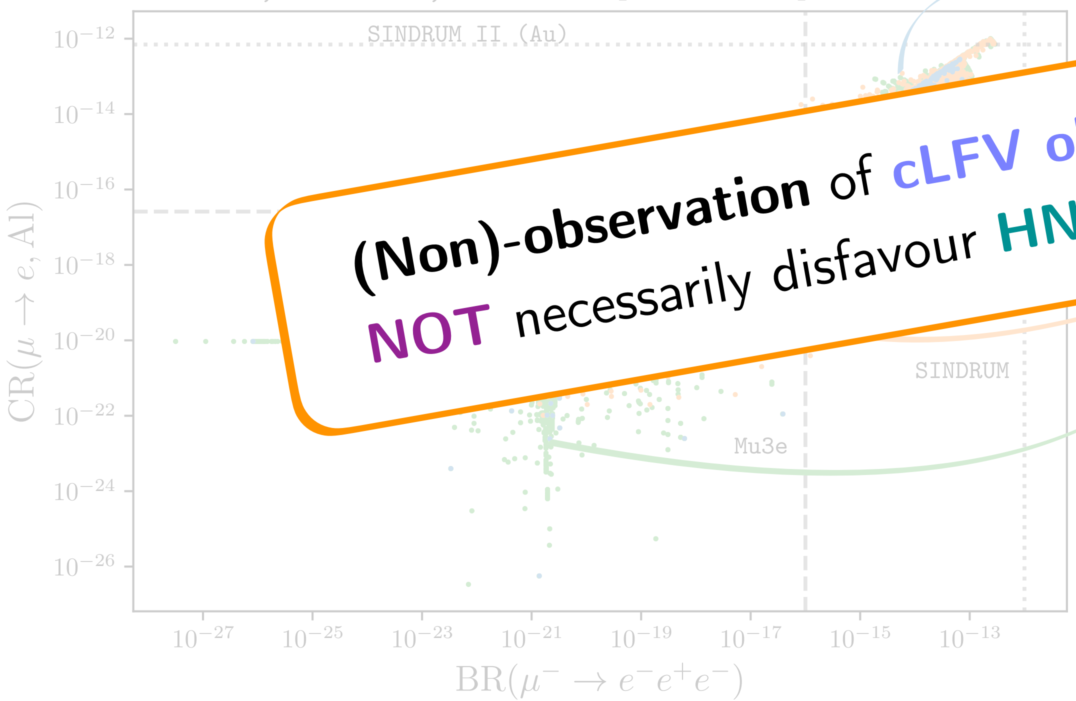
$\mu - e$ **conversion**

Ratios of cLFV observables to identify mediators & constrain their masses

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

Full analysis

Abada, Kriewald, Teixeira [2107.06313]



Strong correlation (CP conserving)

Loss of correlation! (CP violating)

Observation of $\mu \to 3e$ $\not\Rightarrow$ observation of **$\mu - e$ conversion**

(Non)-observation of **cLFV observable(s)** **NOT** necessarily disfavour **HNL extension**!

CPV & future cLFV data

Impact of **CPV phases** regarding **experimental** prospects

Some *illustrative* benchmark points - **CP conserving** vs **CP violating**

Abada, Kriewald, Teixeira [2107.06313]

	BR($\mu \to e\gamma$)	BR($\mu \to 3e$)	CR($\mu - e$, Al)	BR($\tau \to 3\mu$)	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} ✓

∘ beyond future reach
✓ within future sensitivity
✗ conflicts current bounds

P_2: only cLFV τ decays within future reach, cLFV μ decays beyond sensitivity...

P_2': all considered **cLFV transitions within reach!**

Observation of **cLFV observable(s)**
NOT necessarily disfavour **HNL extension**!

CPV & future cLFV data

Impact of **CPV phases** regarding **experimental** prospects

Some *illustrative* benchmark points - **CP conserving** vs **CP violating**

Abada, Kriewald, Teixeira [2107.06313]

	BR($\mu \to e\gamma$)	BR($\mu \to 3e$)	CR($\mu - e$, Al)	BR($\tau \to 3\mu$)	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} ✓

∘ beyond future reach
✓ within future sensitivity
✗ conflicts current bounds

P_3: large active-sterile mixings, excluded due to bounds on cLFV μ decays

P'_3: suppression of rates from **CPV phases: reconcile large mixings with observation!**

CPV phases matter and **must be included!**

cLFV boson decays and CPV

CPV & cLFV boson decay

Gauge bosons (Z, W) **and Higgs decays** are sensitive to **New Physics** including **heavy sterile states!**

Significant contributions leading to **strong constraints**:

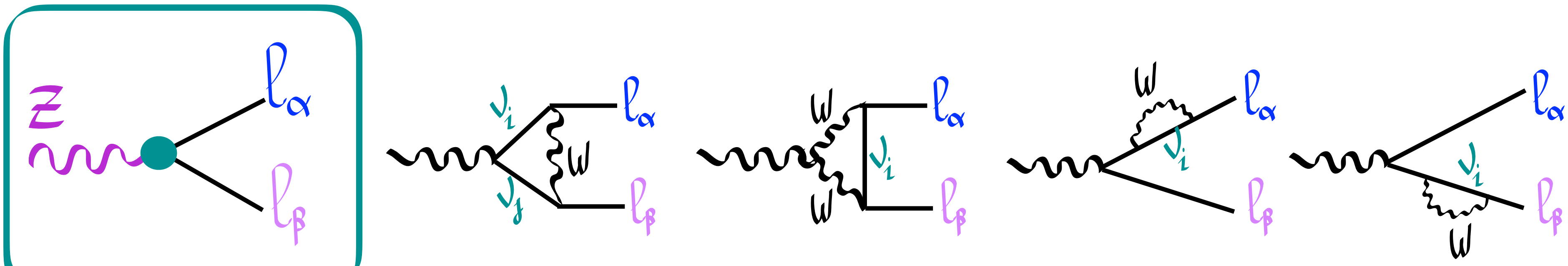
$$\Gamma_Z^{\text{inv}} \text{ and } Z \to \ell_\alpha \ell_\beta \,,\; H \to \ell_\alpha \ell_\beta$$

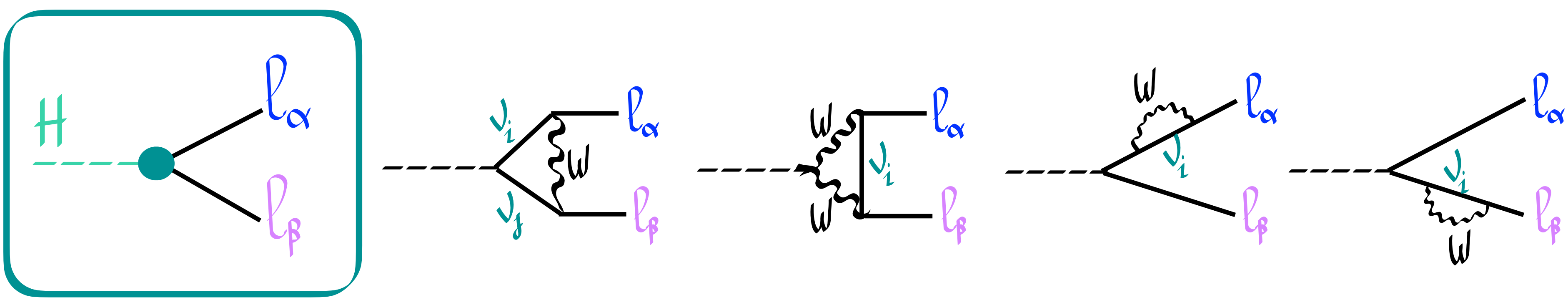
$\Longrightarrow$ What is the **impact** of **CPV Dirac & Majorana phases** on cLFV Z and Higgs decays?

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

cLFV boson decays: $Z \to \ell_\alpha \ell_\beta$, $H \to \ell_\alpha \ell_\beta$ with **HNL** and **CPV phases**

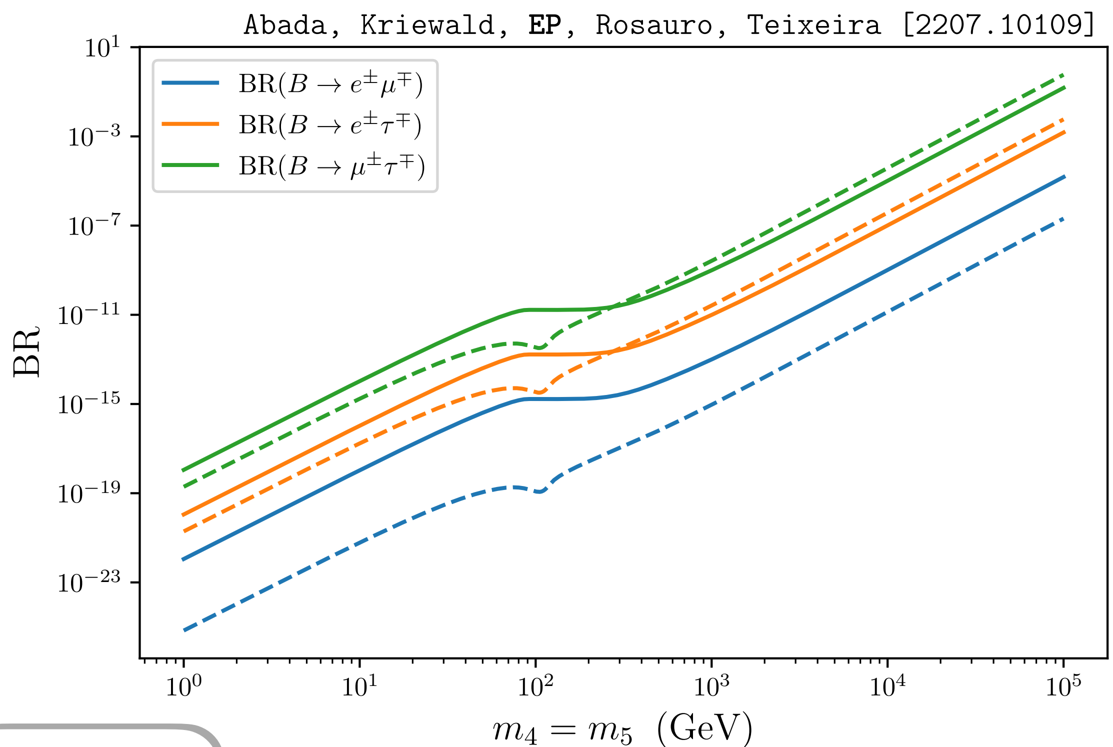
Full computation of cLFV widths; both unitary & Feynman gauges for complete HNL models





$Z \to \ell_\alpha \ell_\beta$ and $H \to \ell_\alpha \ell_\beta$ with **HNL** (degenerate masses)

Simplified



$\theta_{14} = \theta_{15} = 10^{-3}$
$\theta_{24} = \theta_{25} = 10^{-2}$
$\theta_{34} = \theta_{35} = 10^{-1}$

No CPV phases included

——— $Z \to \ell_\alpha \ell_\beta$

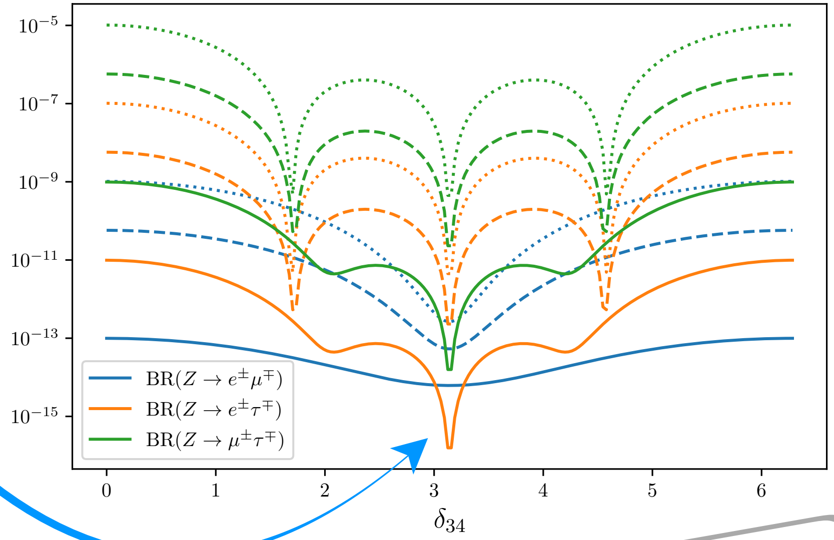
- - - $H \to \ell_\alpha \ell_\beta$

Significant dependance of **cLFV boson decays** on **HNL masses**

Including CPV phases

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

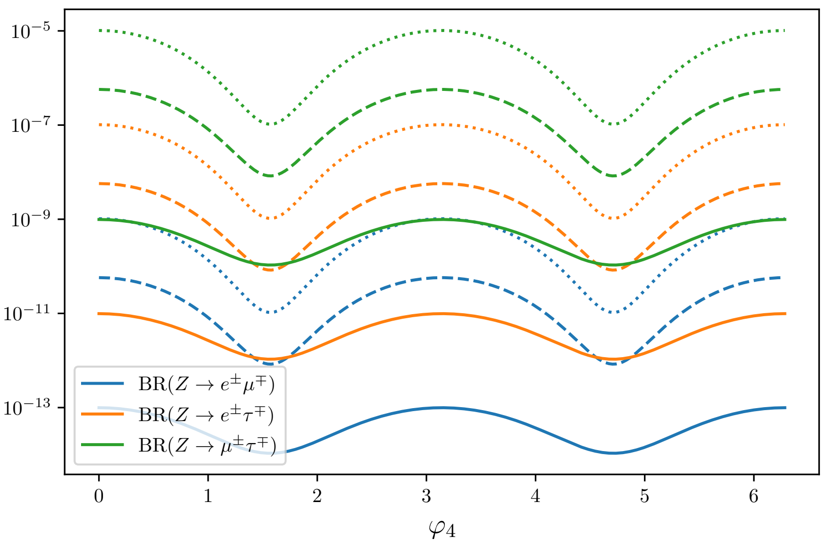
Abada, Kriewald, **EP**, Rosauro, Teixeira [2207.10109]



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

Possibility of decay rate **suppressions**

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



Simplified

1 TeV
5 TeV
10 TeV

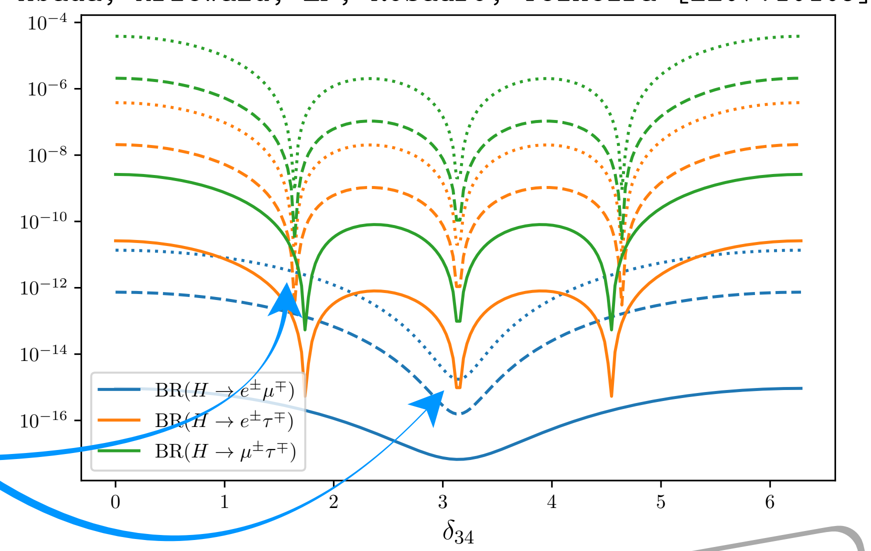
Sensitivity to **Majorana CPV phase** (φ_4)

These effects are amplified for larger HNL masses

Including CPV phases

$$H \to \ell_\alpha \ell_\beta$$

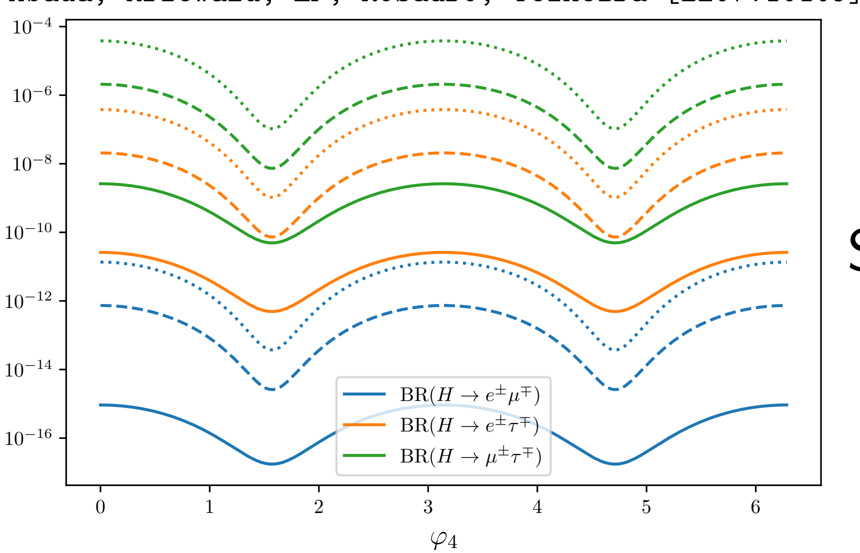
Abada, Kriewald, **EP**, Rosauro, Teixeira [2207.10109]



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

Possibility of decay rate **suppressions**

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

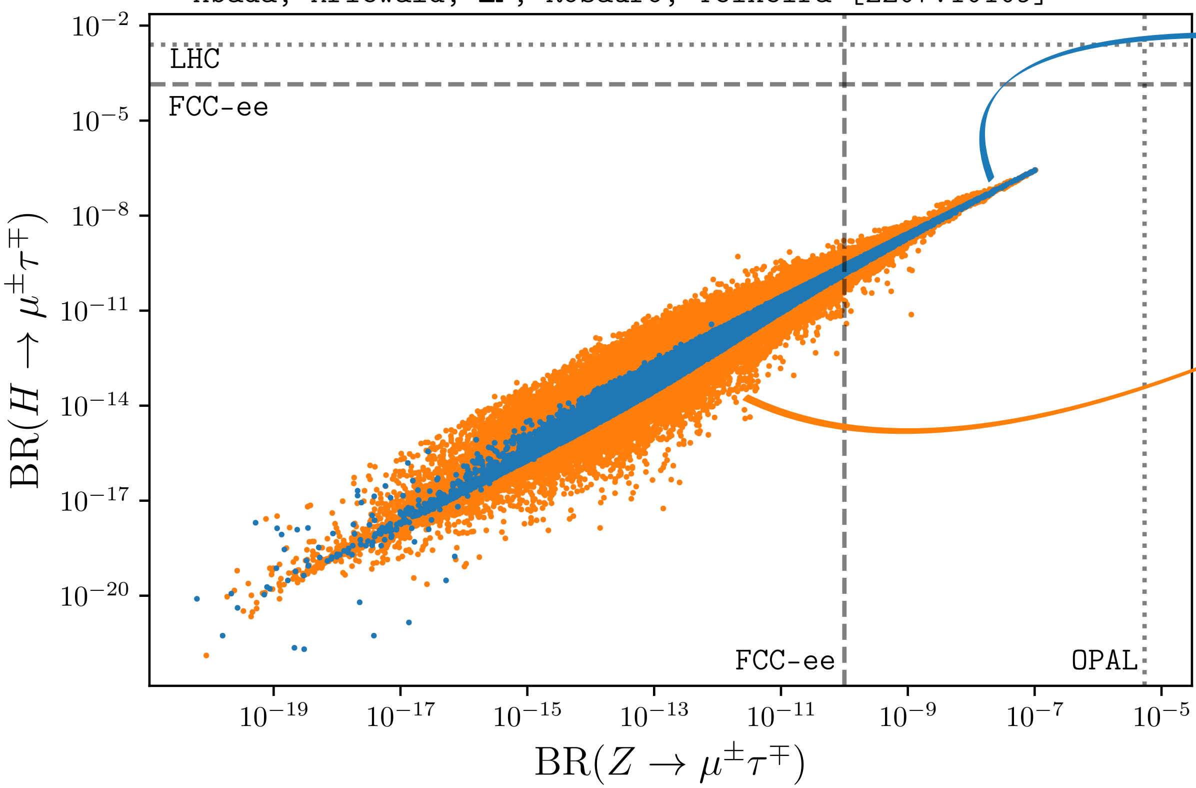
Varying all **CPV phases** associated with the **sterile states**

Full analysis

$H \to \mu\tau$ vs. $Z \to \mu\tau$

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

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



Strong correlation
(CP conserving)

Loss of correlation
(CP violating)
Constructive & destructive

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

$H \to \mu\tau$ beyond future experimental sensitivity

An interesting observable:

CP asymmetries in Z-decays

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

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

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

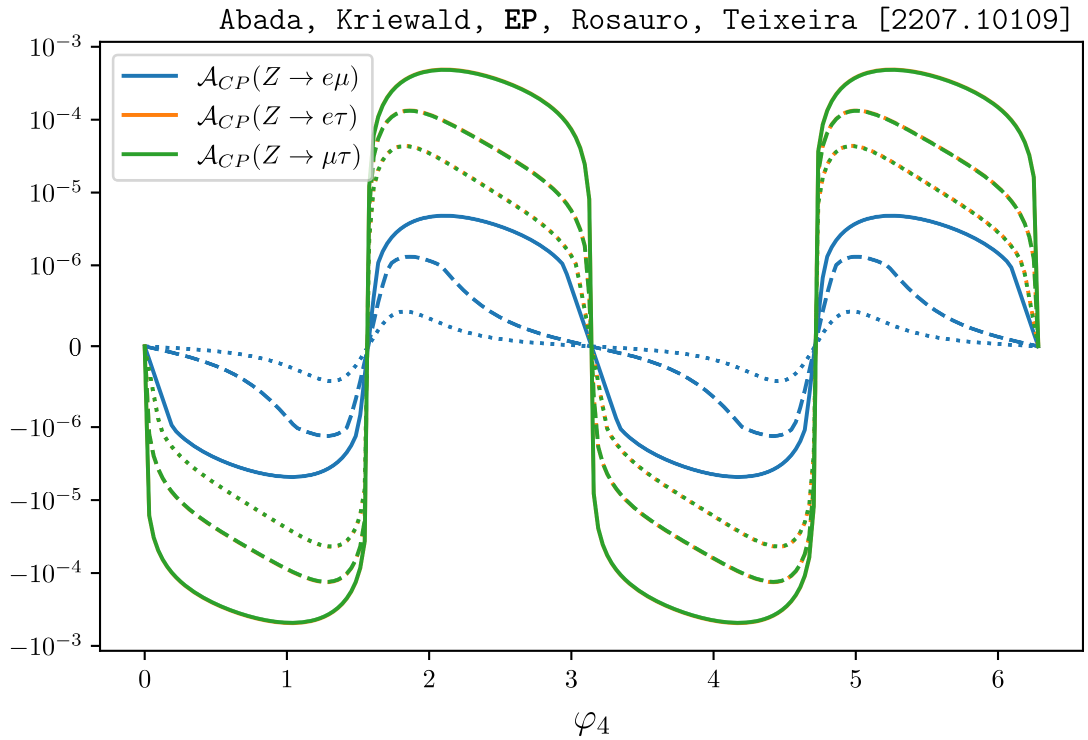
Additional observables to ultimately probe the presence of CPV

$\rightsquigarrow$ Up to which extent can such a **minimal BSM** model be at the source of **non-vanishing contributions to** CP-asymmetries?

$\rightsquigarrow$ Contributions induced by *both* **Majorana** and **Dirac** **CPV phases**

Up to which extent can such a **minimal BSM** model be at the source of **non-vanishing contributions to** CP-asymmetries?

Simplified



Impact of **Majorana**

CPV phases

on CP-asymmetry!

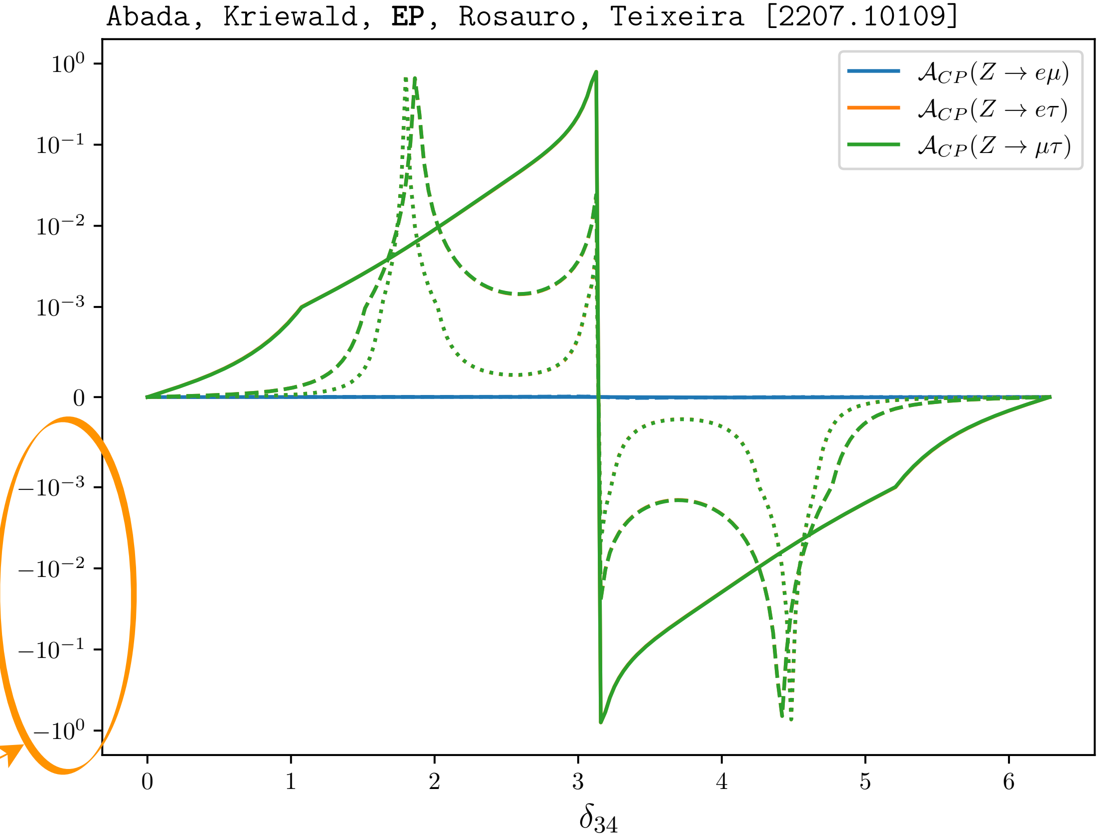
Up to which extent can such a **minimal BSM** model be at the source of **non-vanishing contributions to** CP-asymmetries?

Simplified

Impact of **Dirac CPV phases!**

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

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

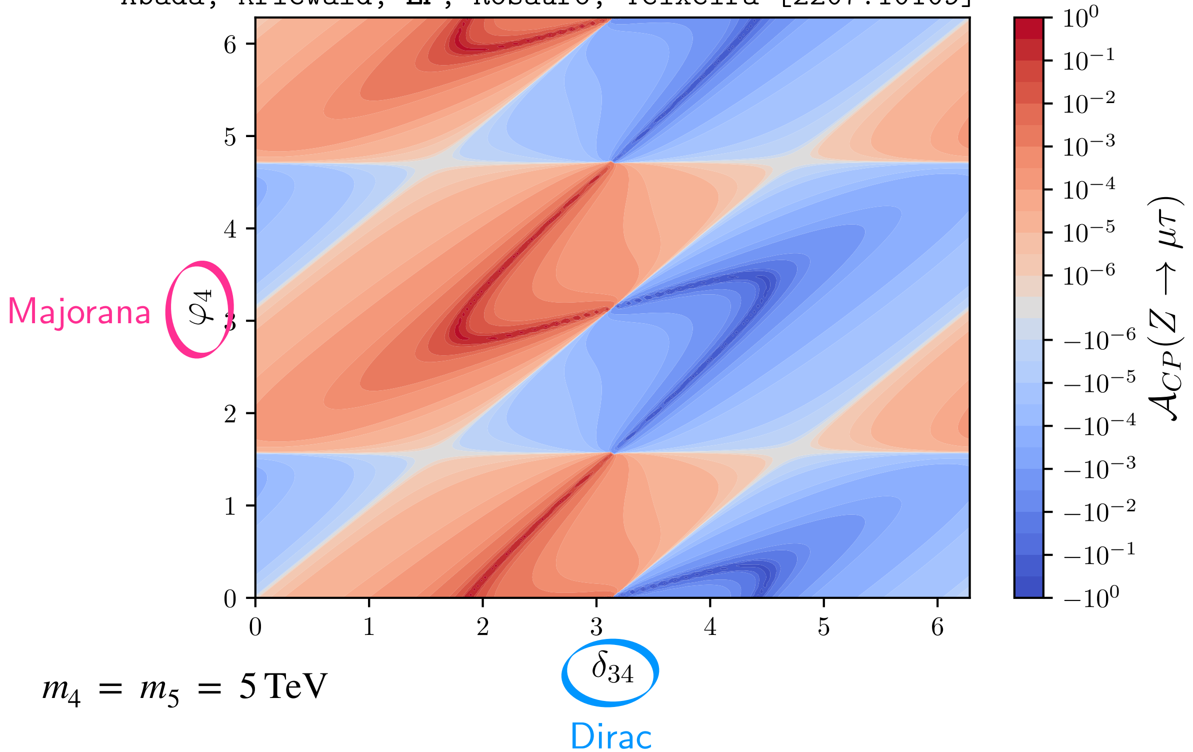


Up to which extent can such a **minimal BSM** model be at the source of **non-vanishing contributions to** CP-asymmetries?

Simplified

Contributions induced by *both* **Majorana** and **Dirac** **CPV phases**

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



$m_4 = m_5 = 5\,\text{TeV}$

Provided that **Dirac** CPV phases are present

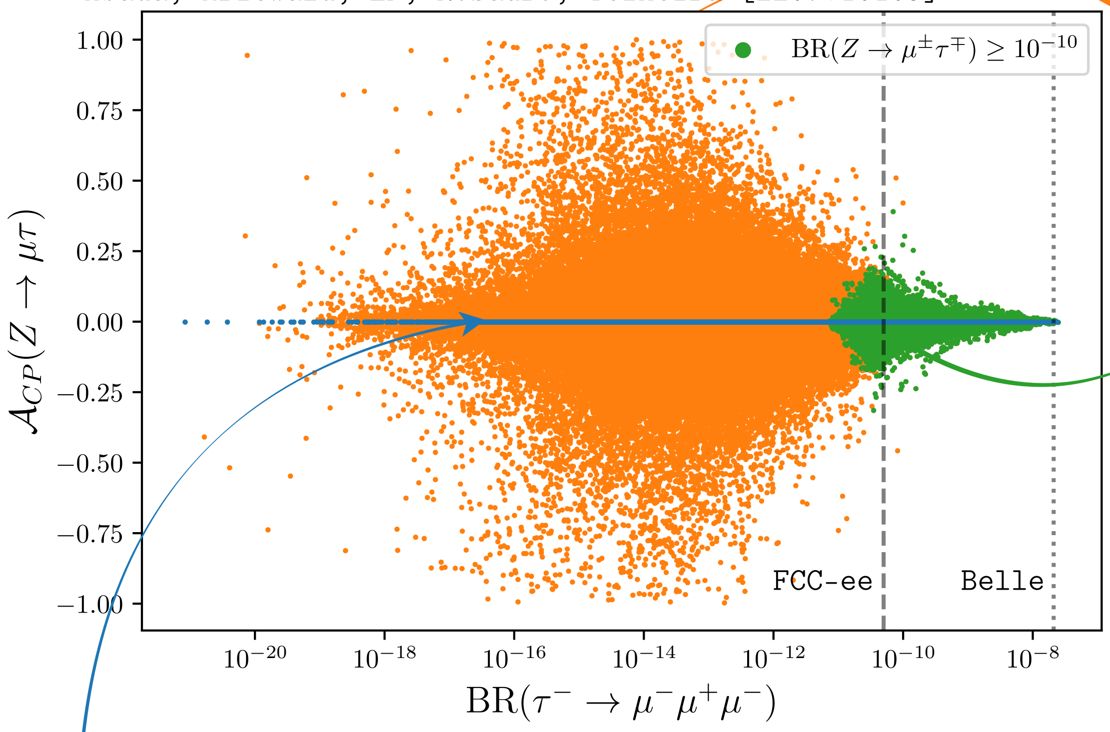
$\Longrightarrow$ **Majorana** phases have a **significant impact on** CP-asymmetries!

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

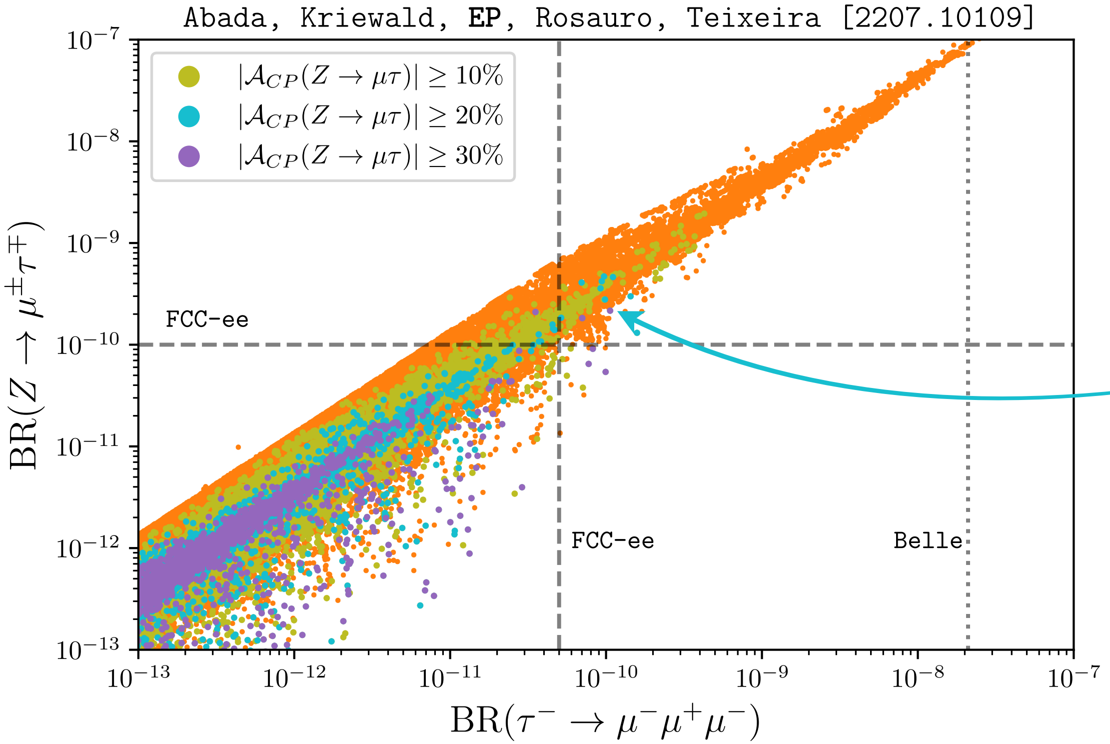
$\mathscr{A}_{CP}$ can be as **large** as **100%**

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

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

Looking at the joint behaviour of $Z \to \mu\tau$, $\mathscr{A}_{CP}(Z \to \mu\tau)$ and $\tau \to 3\mu$

Full analysis



For $Z \to \mu\tau$ and $\tau \to 3\mu$ within future sensitivity

$|\mathscr{A}_{CP}(Z \to \mu\tau)|$ can reach $\geq 20\,\%$

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

With *at least* 2 heavy Majorana fermions

Disentangling scenarios?

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

P_1 — CP Conserving

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

P_2 — CP Violating

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

Both benchmark points P_1 and P_2 lead to **common** **cLFV predictions:** with $\mu \to 3e$, $\mu - e$ conversion, $\tau \to 3\mu$ and $Z \to \mu\tau$ within future sensitivity

Indistinguishable if cLFV signals are observed

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

P_1 — $m_4 = 5\,\text{TeV}, m_5 = 5.1\,\text{TeV},$ $s_{14} = -0.0028\,,\ s_{15} = 0.0045\,,\ s_{24} \ldots$ $\delta_{ij} = \varphi_i = 0\,.$ …ving

P_2 — …ng …33.

Bo… and P_2 lead to **common** cLFV predictions:
wit… $\mu \to 3e$, $\mu - e$ 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_2 leads to $\mathcal{A}_{CP}(Z \to \mu\tau) = 30\,\%$

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

In summary...

Conclusions

$\rightsquigarrow$ **Minimal** and **simple** BSM construction:

SM + 2 **heavy** **Majorana** **sterile** states (no assumption on mass mechanism)

Low-energy phenomenology of complete (high-energy) models

$\rightsquigarrow$ **Impact** of the **heavy steriles**:

Depends on **masses** & **mixings** with active states (**CPV**) $\Rightarrow$ non unitary $\tilde{\mathcal{U}}_{\text{PMNS}}$

$\rightsquigarrow$ **cLFV**: **CPV phases** affect **correlations** & **interpretation** of exp data!

$\rightsquigarrow$ **cLFV boson decays** sensitive to the presence of HNL: **CPV phases** have a **clear impact** on the decay rates (Dirac CPV striking reductions)

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

CP asymmetry key to establish the presence of CP violation!

Conclusions

- **Minimal** and **simple** BSM construction:

SM + 2 **heavy Majorana sterile** states (no assumption on mass mechanism)

Low-energy phenomenology of complete (high-energy) models

- **Impact** of the **heavy steriles**:

Depends on **masses** & **mixings** wit… unitary $\tilde{\mathcal{U}}_{\text{PMNS}}$

- **cLFV**: C… xp data!

- **cLFV bos**… …ce of HNL: **CPV phases** have a **clear impac**… …ay rates (Dirac CPV striking reductions)

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

CP violating phases do matter!

and should be taken into account

Thank you for your attention

Modified lepton currents

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

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

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

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

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

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

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

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**

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

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

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:

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

$\Longrightarrow$ 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**

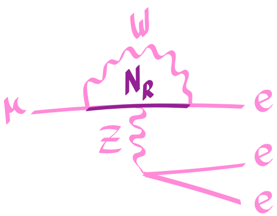
cLFV signals - correlations matter

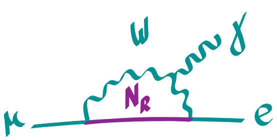
Synergy of cLFV observables very important: **Probe** different operators/topologies

$\mathrm{BR}(\mu \to e\gamma)$, $\mathrm{BR}(\mu \to eee)$ and $\mathrm{CR}(\mu - e, \mathrm{N})$ correlated by **common topologies**:

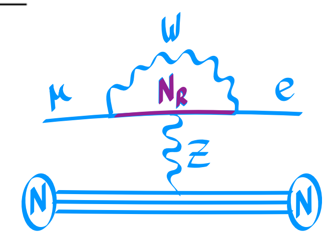
γ dipoles & anapoles, Z penguins, tree-level contributions,... $\Rightarrow$ 4-fermion operators

Model-dependent: certain topologies dominate, tree-level contributions might be present





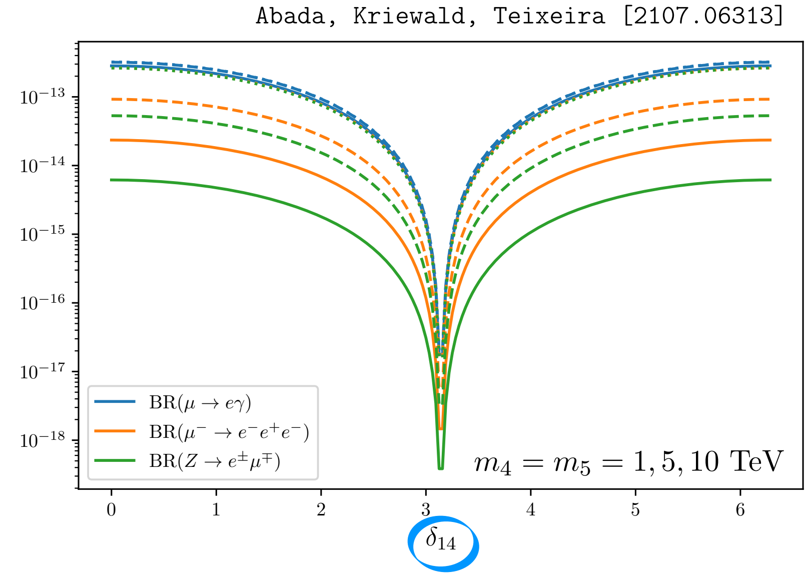
Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop* †	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$



$\Rightarrow$ study **correlations/ratios** of **cLFV observables, might find peculiar cLFV patterns**

$\Rightarrow$ **provide complementary information to direct searches**

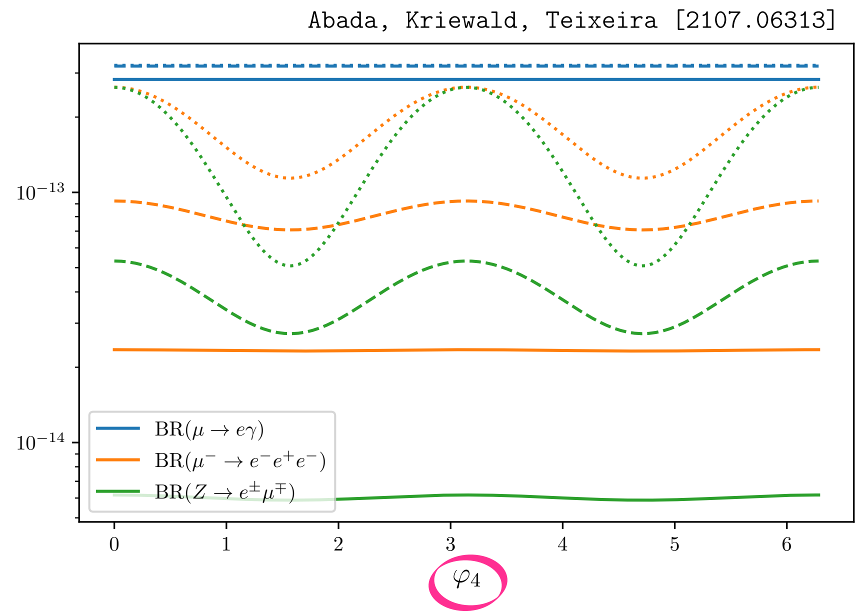
More on cLFV & CPV phases



Full cancellation of the rates for

$$\delta_{14} = \pi$$

Similar results for other **Dirac phases**

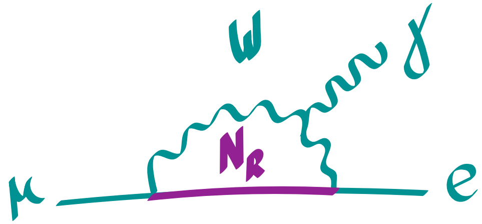


Milder dependence, γ-penguin independent of **Majorana phases**

$\mu \to e\gamma$ and CPV phases

Radiative decays:

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

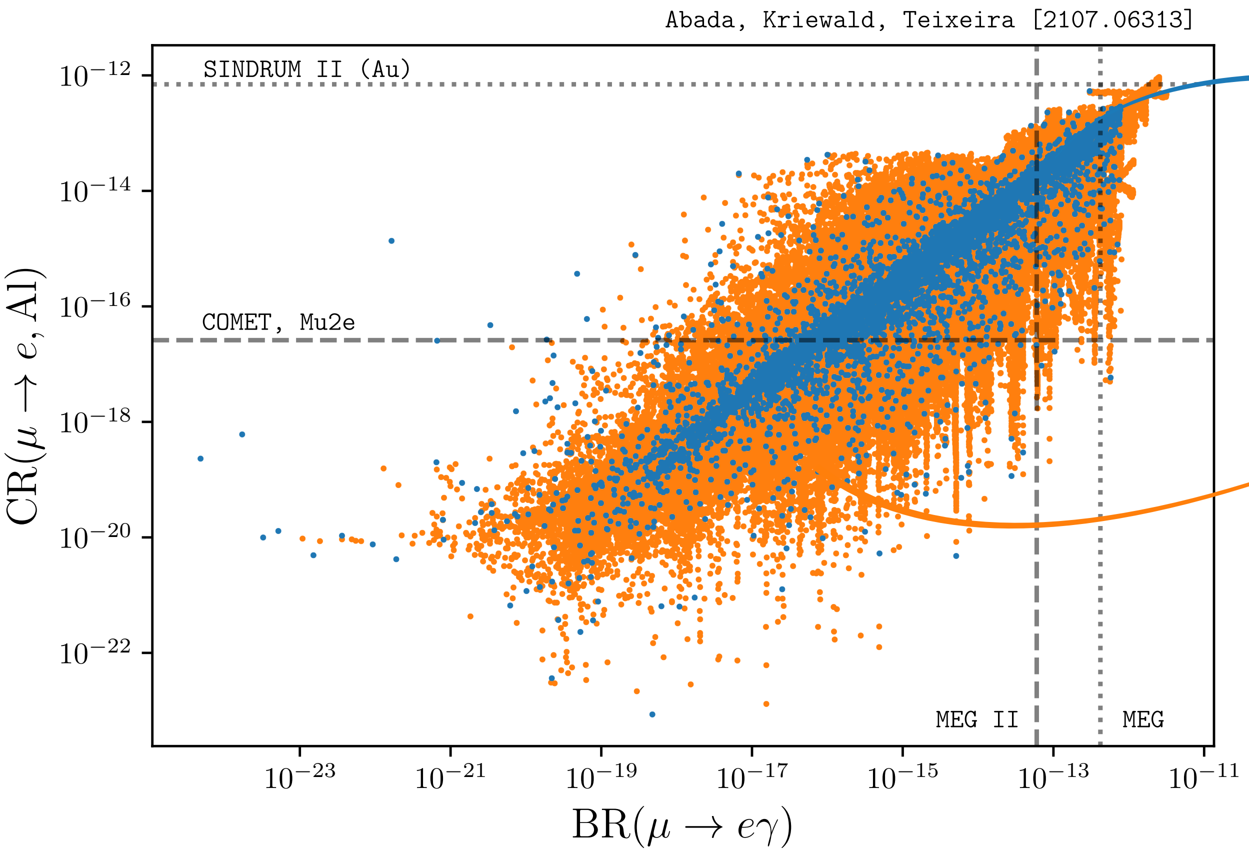


Assume (for *simplicity & illustrative purposes*): $m_4 \approx m_5, \quad \sin\theta_{\alpha 4} \approx \sin\theta_{\alpha 5} \ll 1$

$$|G_\gamma^{\mu e}|^2 \approx 4\ \sin^2\theta_{e4}\ \sin^2\theta_{\mu 4}\ \cos^2\left(\frac{\delta_{14}+\delta_{25}-\delta_{15}-\delta_{24}}{2}\right) G_\gamma\left(\frac{m^2_{N_i}}{m^2_W}\right)$$

$\Longrightarrow$ **Radiative decays: rate** depends **only on Dirac phases**;

full cancellation for $\Sigma\delta = \pi$



Strong correlation

(CP conserving)

Loss of correlation!

(CP violating)