cLFV Z and Higgs decays: Leptonic CPV phases and CP asymmetries

Jonathan Kriewald

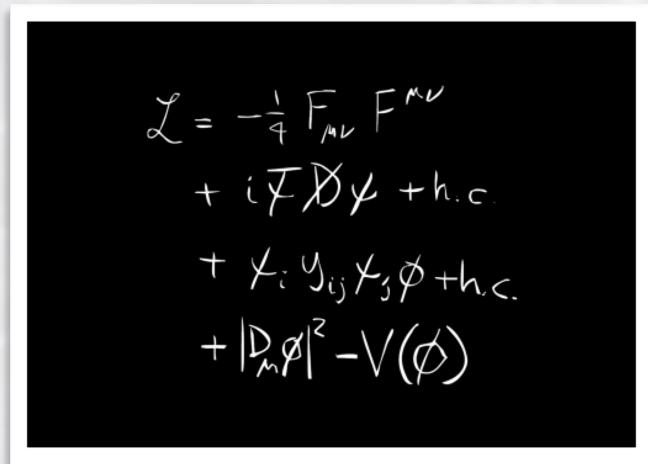
Jožef Stefan Institute

Invisibles'23 (Göttingen) 1/9/2023

Based on: [2107.06313] and [2207.10109] with A. Abada, E. Pinsard, S. Rosauro-Alcaraz and A. M. Teixeira

Flavour and CP violation: SM

Flavour in the **Standard Model:** interactions (and transitions) between fermion families



Gauge interactions are **flavour universal**

Yukawas Y^u_{ij}, Y^d_{ij} and Y^ℓ_{ij} encode all **flavour dynamics**

(Masses, mixings and **CP violation**)

SM quark sector:

6 massive states

flavour violated in charged current interactions $V^{ij}_{\text{CKM}} W^\pm \bar{q}_i q_j$

total **baryon number** is conserved in **SM** interactions

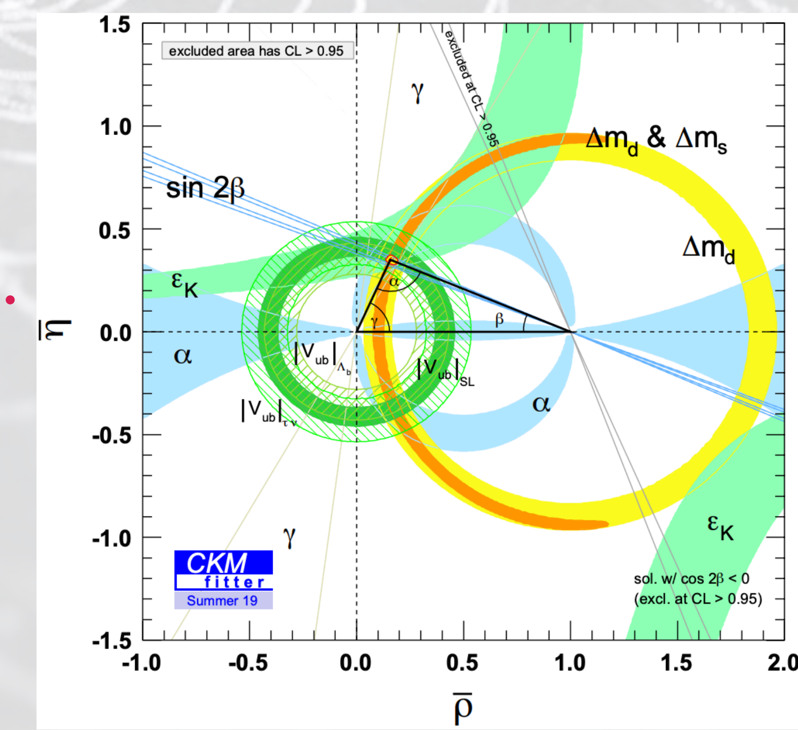
CP violation: δ_{CKM} and θ_{QCD}

(not enough to explain BAU from baryogenesis)

CKM paradigm extensively probed:

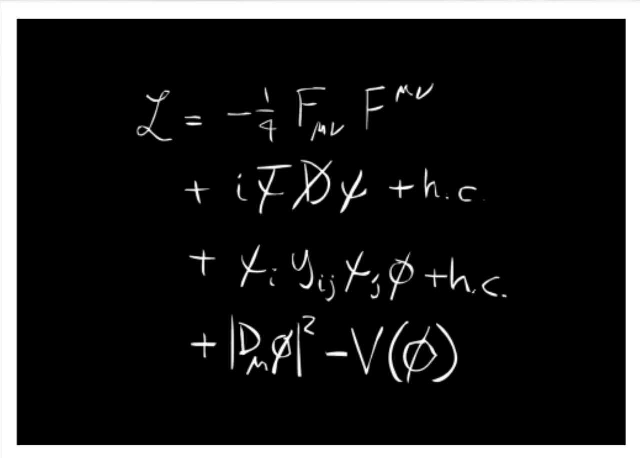
Meson oscillations & decays, β decays, CP violation...

Few tensions, CAA, V_{cb}, V_{ub}, ...



Flavour and CP violation: SM

Flavour in the **Standard Model:** interactions (and transitions) between fermion families



Gauge interactions are **flavour universal**

Yukawas Y^u_{ij}, Y^d_{ij} and Y^ℓ_{ij} encode all **flavour dynamics**

(Masses, mixings and **CP violation**)

SM quark sector:

6 massive states

flavour violated in charged current interactions $V^{ij}_{\text{CKM}} W^\pm \bar{q}_i q_j$

total **baryon number** is conserved in **SM** interactions

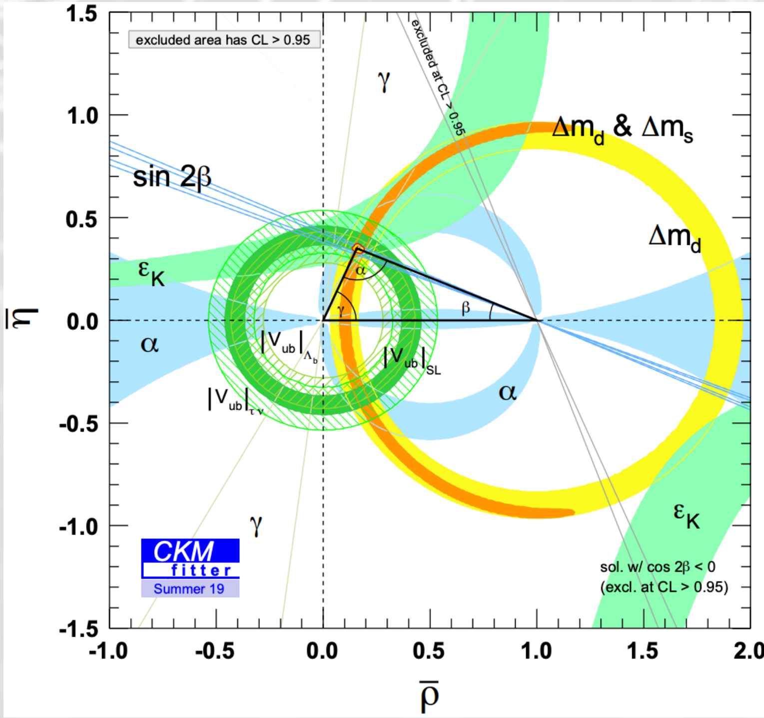
CP violation: δ_{CKM} and θ_{QCD}

(not enough to explain BAU from baryogenesis)

CKM paradigm extensively probed:

Meson oscillations & decays, β decays, CP violation…

Few tensions, CAA, V_{cb}, V_{ub}, …



SM lepton sector: neutrinos are strictly massless

- **Conservation of** (total) **lepton number** and **lepton flavour**
- **Lepton flavour universality** only broken by **Yukawas**
- No intrinsic **CPV sources** — (tiny) lepton **EDMs** @ 4-loop

Strong arguments in f(l)avour of New Physics!

Observations unaccounted for in SM: ν-oscillations, Dark matter, baryon asymmetry of the Universe (also some theoretical caveats…)

How to unveil the NP model at work?

⇒Test SM symmetries with flavour observables:

(c)LFV, lepton flavour universality violation, …

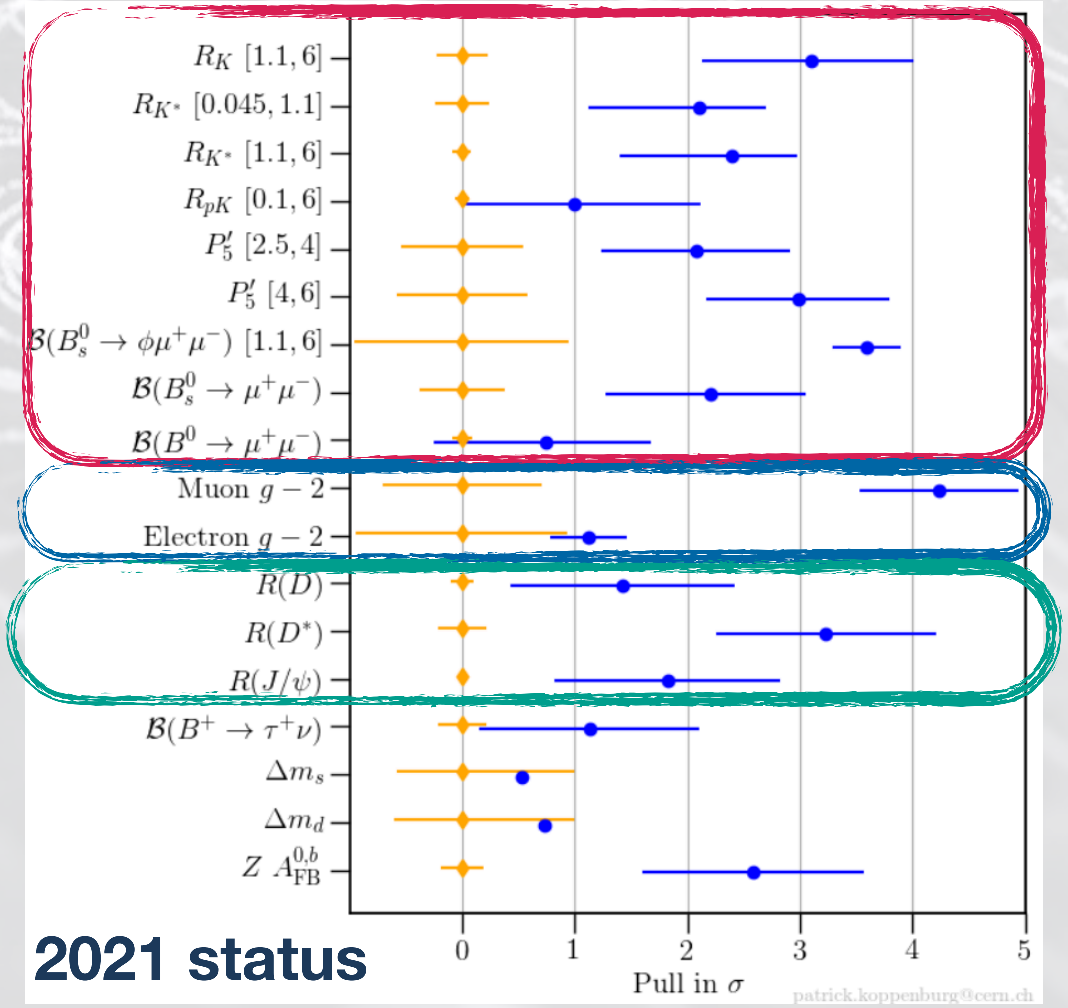
Strong arguments in f(l)avour of New Physics!

Observations unaccounted for in SM: ν-oscillations, Dark matter, baryon asymmetry of the Universe (also some theoretical caveats…)

How to unveil the NP model at work?

⇒Test SM symmetries with flavour observables: (c)LFV, lepton flavour universality violation, …

- $R_{K^{(*)}} \equiv \dfrac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$ ~ **SM-like** (before ~ 3σ tension)
- $R_{D^{(*)}} \equiv \dfrac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$ ~ 3σ tension (before ~ 4σ)
- $(g_\mu - 2)/2$ ~ 5σ tension (possibly) **reduced** to ~ 2σ (Lattice QCD)



Strong arguments in f(l)avour of New Physics!

Observations unaccounted for in SM: ν-oscillations, Dark matter,

baryon asymmetry of the Universe (also some theoretical caveats…)

How to unveil the NP model at work?

⇒Test SM symmetries with flavour observables:

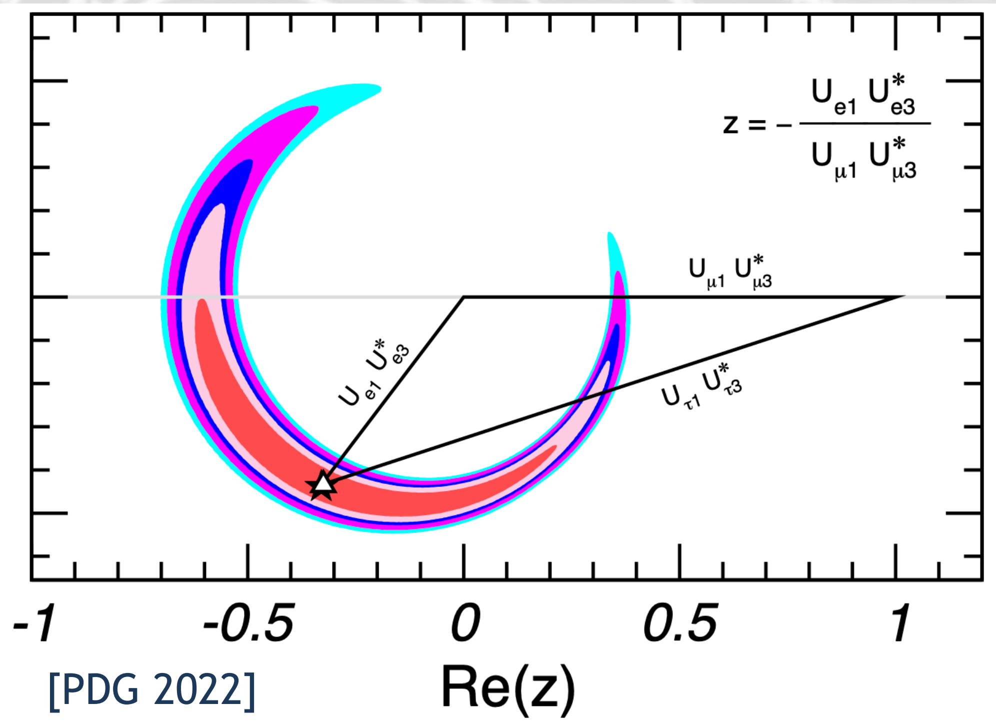
(c)LFV, lepton flavour universality violation, …

ν-oscillations 1st laboratory *evidence* of New Physics!

- New mechanism of mass generation? **Majorana fields?**
- New sources of CP violation?

Several puzzles remain:

- Absolute mass scale?
- Mass ordering? (NO vs IO)
- CP violation maximal?



[PDG 2022]

Lepton flavour probes of New Physics

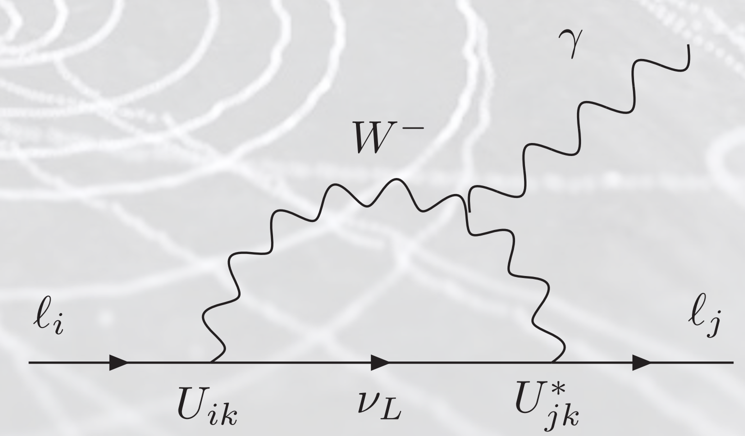
Neutrinos oscillate ⇒ **neutral lepton flavour violated, neutrinos are massive,**
new sources of **CPV?**

Extend SM to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$: ad-hoc 3 ν_R ⇒ Dirac masses, "**SM**$_{m_\nu}$", $U_{\mathbf{PMNS}}$

In **SM**$_{m_\nu}$: **flavour-universal** lepton couplings, lepton number conserved

cLFV possible ... but not observable! $\mathrm{BR}(\mu \to e\gamma) \propto |\sum U^*_{\mu i} U_{ei} m^2_{\nu_i} / m^2_W| \simeq 10^{-54}$

EDMs still tiny... (2-loop from δ_{CP}, $|d_\ell| \sim 10^{-35} e\mathrm{cm}$)



⇒ any **cLFV signal** would imply **non-minimal New Physics!**
(Not necessarily related to m_ν generation)

Lepton flavours offer a plethora of observables and **probes of New Physics**

⇒**Negative search results:** allow to place **tight bounds** on **New Physics**

Neutrino mass 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)

Realised at very different scales $\Lambda_{\text{EW}} \rightsquigarrow \Lambda_{\text{GUT}}$

$\Rightarrow$ Expect *very* different phenomenological impact

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

High scale: $\mathcal{O}(10^{10-15}$ GeV)	Low scale: $\mathcal{O}$(MeV - TeV)
Theoretically **"natural"** $Y^\nu \sim 1$	Finetuning of Y^ν (or approximate LN conservation)
"Vanilla" leptogenesis	Leptogenesis possible (resonant, ...)
Decoupled new states	New states within experimental reach!
	Collider, high-intensities ("leptonic observables")

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

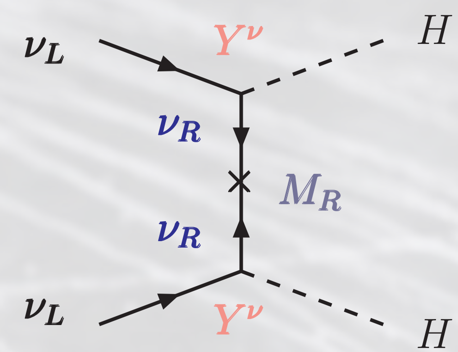
$\Rightarrow$ rich phenomenology at **colliders, high intensities** and low energies

testability!!

(Also expect tight constraints)

Type I seesaw

(Heavy) right-handed **Majorana** neutrinos
coupled via Higgs to SM-like neutrinos



$$M_\nu = \begin{pmatrix} 0 & vY_\nu \\ vY_\nu^T & M_N \end{pmatrix}$$

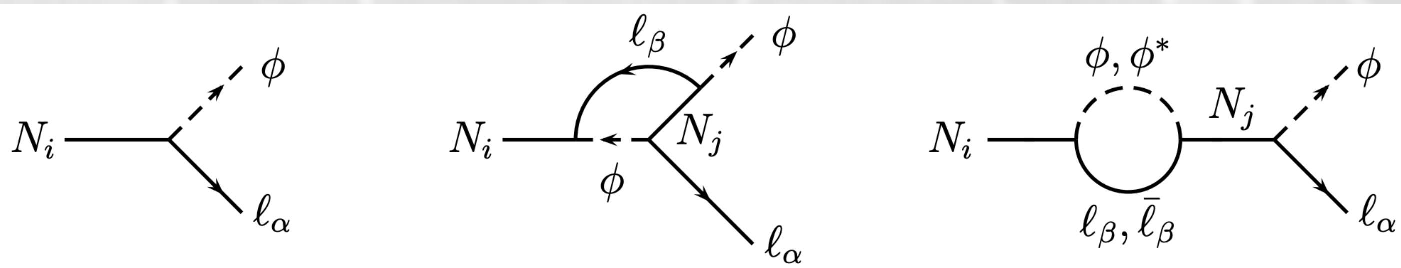
Generate "naturally" small masses of the active neutrinos

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

$$U_{\nu N} \simeq v Y_\nu^* M_N^{-1\dagger} \quad \mathcal{U} = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} , \quad U_{\nu\nu} \simeq (1-\eta)\, U_{\text{PMNS}}$$

Leptogenesis in a nutshell: generate lepton asymmetry $\Rightarrow$ convert into baryon asymmetry

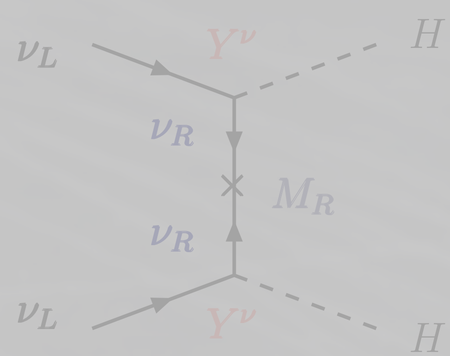
CP-violating out of equilibrium decay $\Rightarrow$ create lepton asymmetry (at a high scale)



Interference of tree & loop diagrams

$$\epsilon_i^\alpha \equiv \frac{\Gamma(N_i \to \phi \ell_\alpha) - \Gamma(N_i \to \phi^\dagger \bar{\ell}_\alpha)}{\sum_\beta [\Gamma(N_i \to \phi \ell_\beta) + \Gamma(N_i \to \phi^\dagger \bar{\ell}_\beta)]} \propto \sum_{j \neq i} \mathrm{Im}[Y_{\alpha i}^{\nu *} (Y^{\nu\dagger} Y^\nu)_{ij} Y_{\alpha j}^\nu]$$

(Heavy) right-handed Majorana neutrinos
coupled via Higgs to SM-like neutrinos



$$M_\nu = \begin{pmatrix} 0 & vY_\nu \\ vY_\nu^T & M_N \end{pmatrix}$$

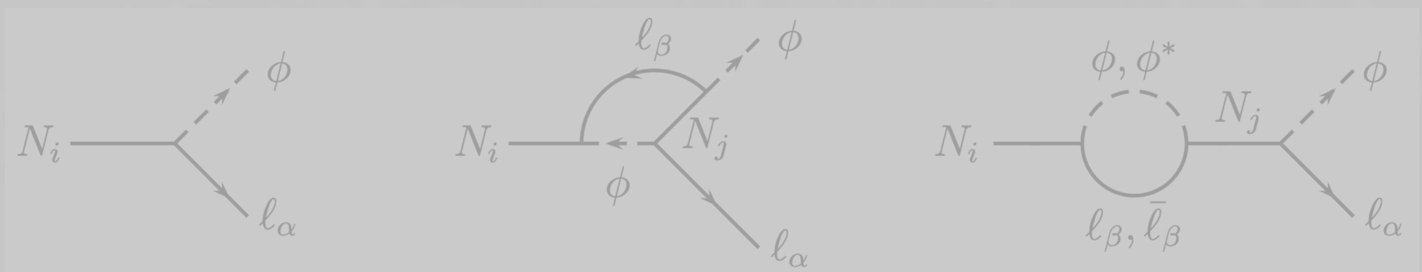
Generate "naturally" small masses of the active neutrinos

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

What is the phenomenological impact of these CPV phases?

Leptogenesis in a nutshell: generate lepton asymmetry ⇒ convert into baryon asymmetry

CP-violating out of equilibrium decay ⇒ create lepton asymmetry (at a high scale)



Interference of tree & loop diagrams

$$\epsilon_i^\alpha \equiv \frac{\Gamma(N_i \to \phi \ell_\alpha) - \Gamma(N_i \to \phi^\dagger \bar{\ell}_\alpha)}{\sum_\beta [\Gamma(N_i \to \phi \ell_\beta) + \Gamma(N_i \to \phi^\dagger \bar{\ell}_\beta)]} \propto \sum_{j \neq i} \mathrm{Im}[Y^{\nu *}_{\alpha i} (Y^{\nu\dagger} Y^\nu)_{ij} Y^\nu_{\alpha j}]$$

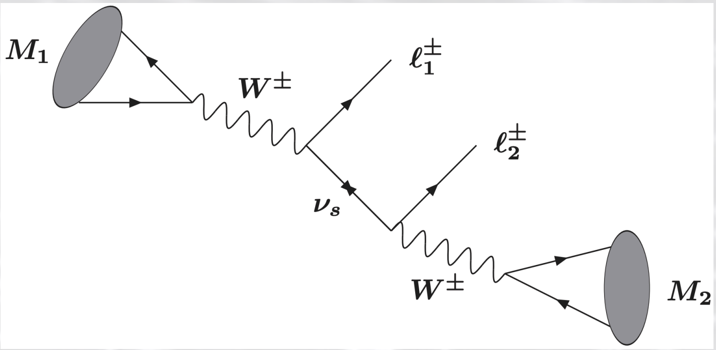
LNV and CP violation

CPV phases and LNV

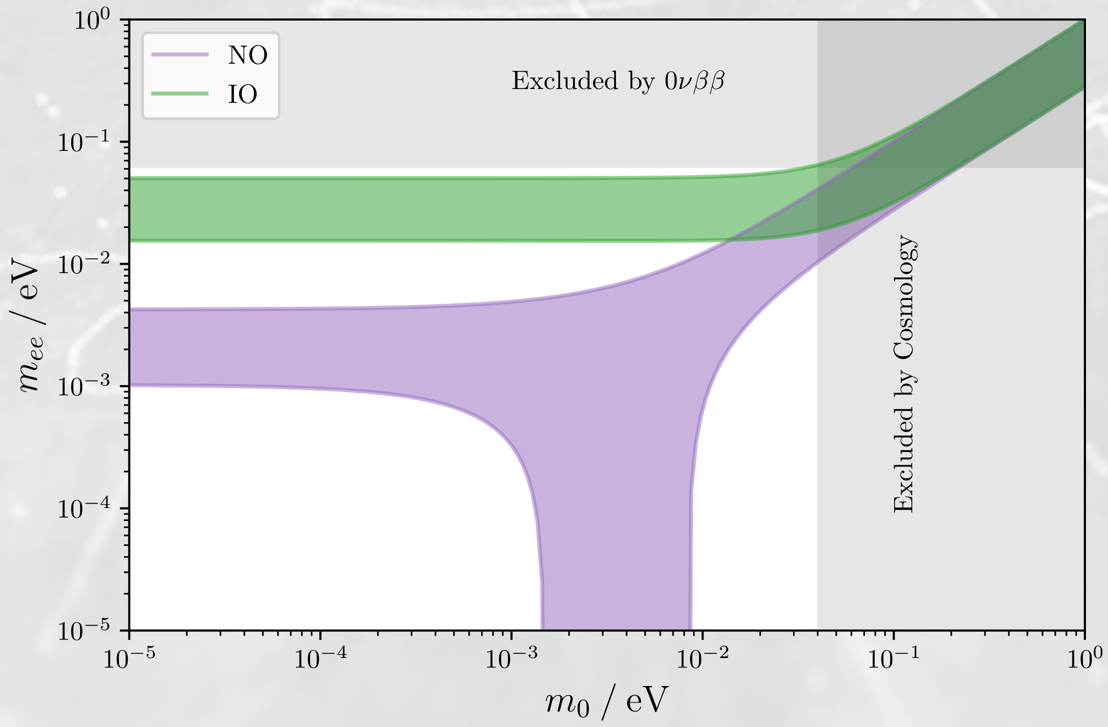
If neutrinos are **Majorana**, total **lepton number** is violated @ tree-level

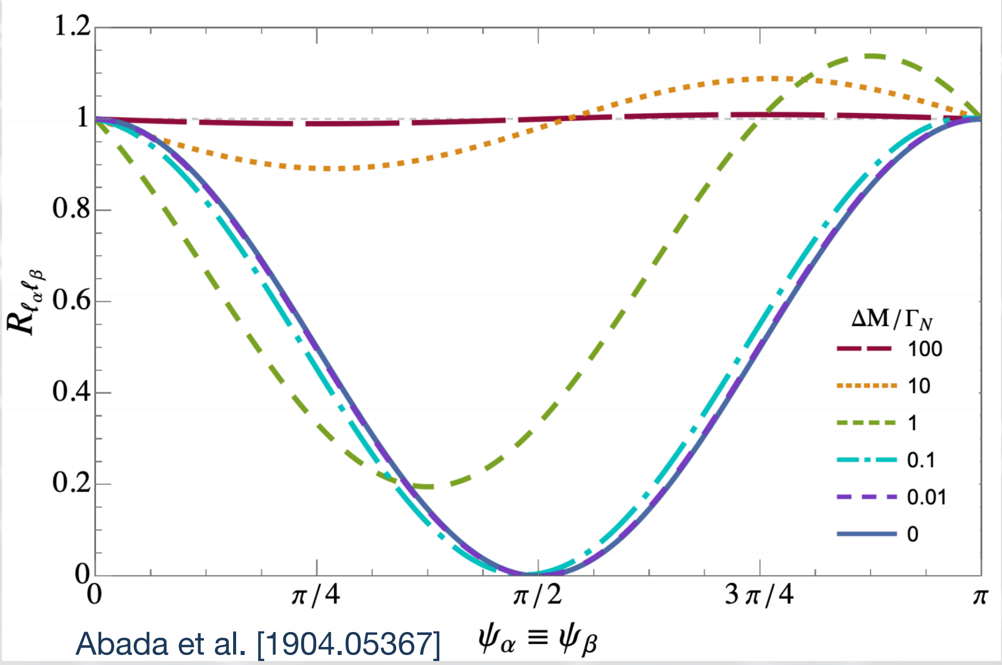
$\Rightarrow$ Expect $0\nu\beta\beta$, **LNV meson decays**, SS di-lepton tails, …

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



CP violating phases are known to play a crucial role:





Abada et al. [1904.05367]

PMNS phases lead to "neck" in $0\nu\beta\beta$, sterile states can interfere in **LNV meson decays**

(Similar interference effects in SS vs OS di-lepton production)

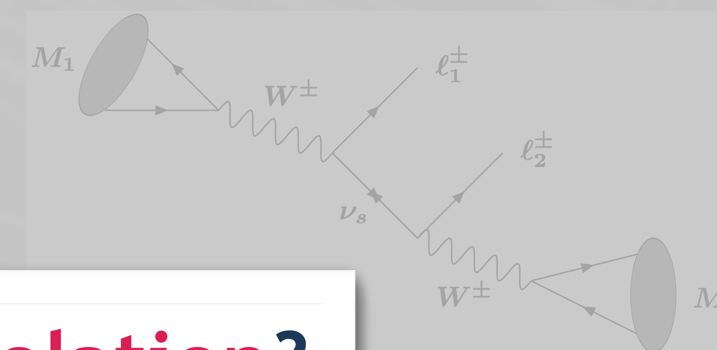
e.g. Abada et al. [2208.13882]

CPV phases and LNV

If neutrinos are **Majorana,** total **lepton number** is violated @ tree-level

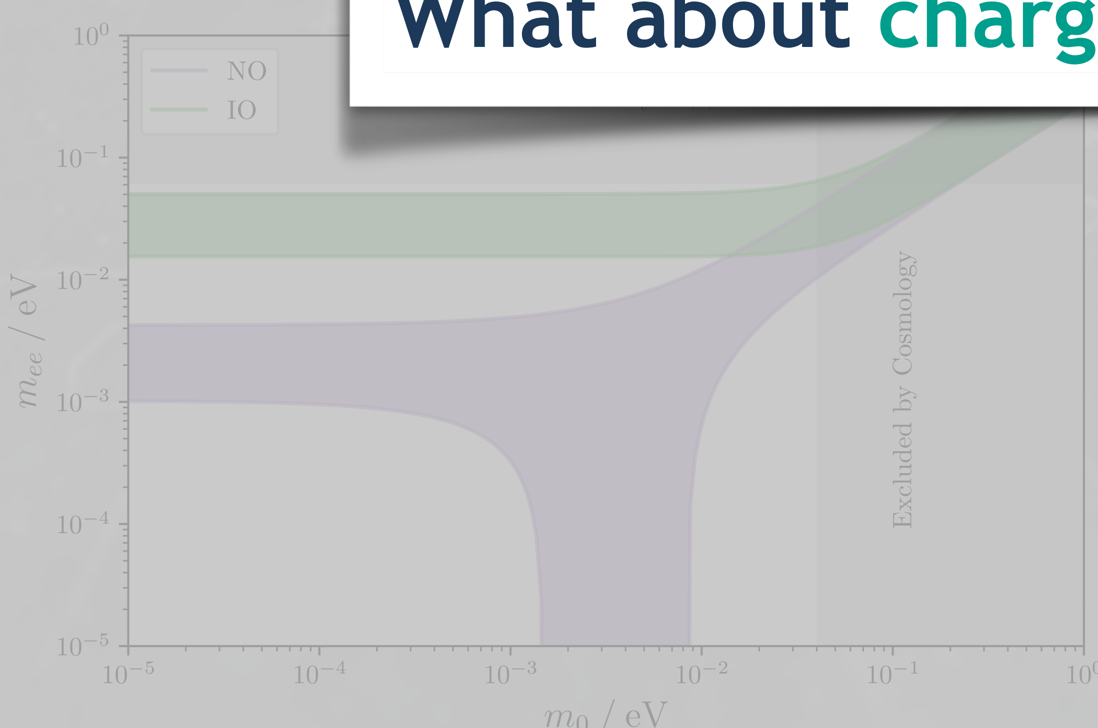
$\Rightarrow$ Expect $0\nu\beta\beta$, **LNV meson decays,** SS di-lepton tails, ...

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



CP violating phases are known to play a crucial role:

What about charged lepton flavour violation?



Abada et al. [1904.05367]

PMNS phases lead to "neck" in $0\nu\beta\beta$, sterile states can interfere in **LNV meson decays**

(Similar interference effects in SS vs OS di-lepton production)

e.g. Abada et al. [2208.13882]

cLFV observables across all sectors and energies

Any **cLFV** signal necessarily implies the presence of **New Physics!**

- **"Purely" leptonic cLFV observables:** $\ell_\beta \to \ell_\alpha \gamma, \ell_\beta \to \ell_\alpha \ell_\gamma \ell_{\gamma'}$

  Most stringent exp. bounds: $\mathrm{BR}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$, $\mathrm{BR}(\mu \to eee) \lesssim 10^{-12}$

- **Muonic atoms (and bound states):** many **"nuclear-assisted"** cLFV observables

  e.g. neutrinoless $\mu - e$ conversion $(\mu^- N \to e^- N)$: $\mathrm{CR}(\mu - e, \mathrm{Au}) \lesssim 7 \times 10^{-13}$

- **Semi-leptonic cLFV τ decays:** $\tau \to P\ell', \tau \to V\ell'$; $\mathrm{BR}(\tau \to \phi\mu) \lesssim 8.4 \times 10^{-8}$

- **(Semi-) leptonic cLFV meson decays:** $M \to \ell_\alpha^\pm \ell_\beta^\mp, M \to M' \ell_\alpha^\pm \ell_\beta^\mp$;

  $\mathrm{BR}(K_L \to \mu^\pm e^\mp) \lesssim 4.7 \times 10^{-12}$, $\mathrm{BR}(B_{(s)} \to \ell_\alpha^\pm \ell_\beta^\mp) \lesssim \mathcal{O}(10^{-5})$

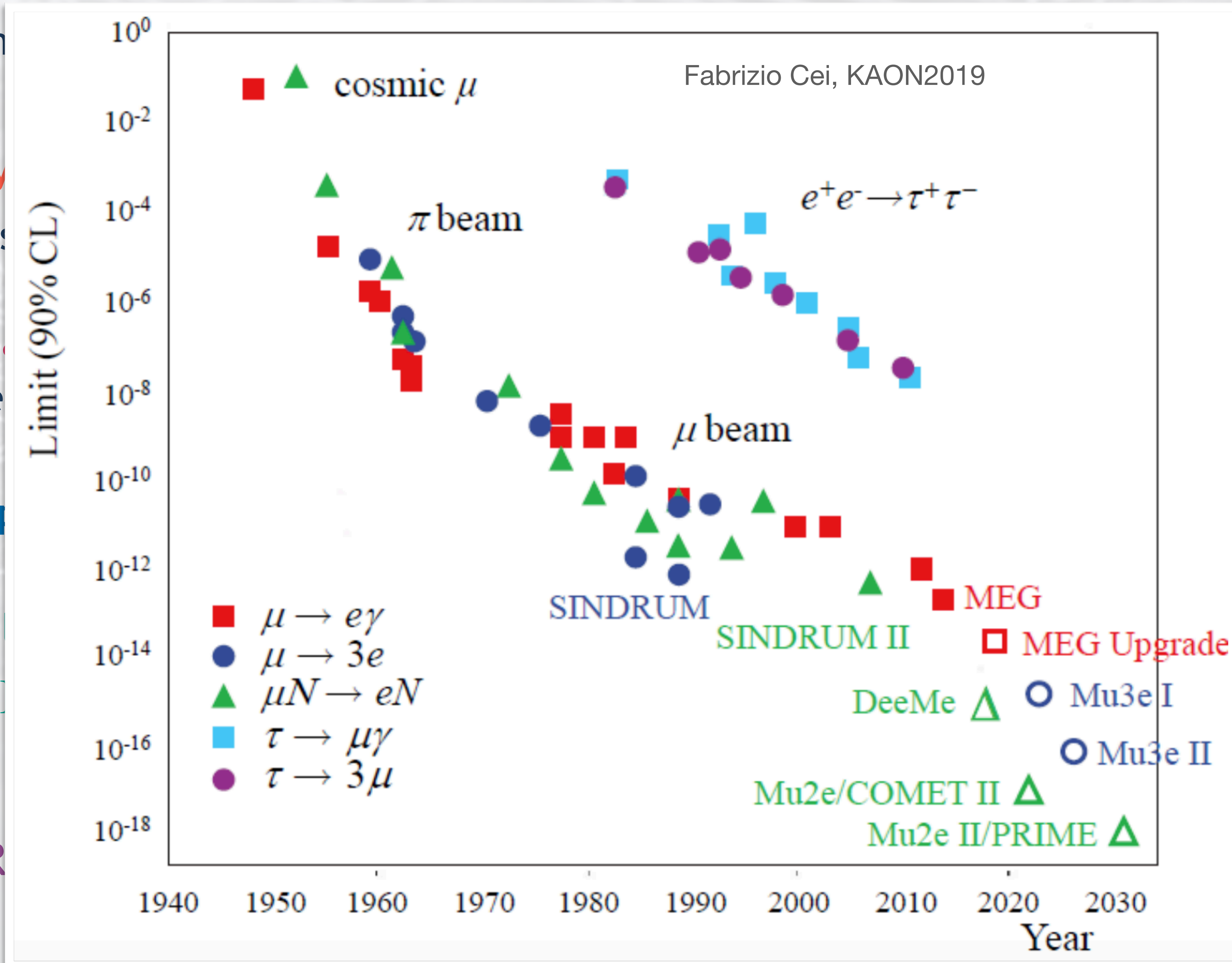
- **cLFV @ higher energies:** $Z \to \ell_\alpha^\pm \ell_\beta^\mp, H \to \ell_\alpha^\pm \ell_\beta^\mp$, high-p_T di-lepton tails $pp \to \ell_\alpha^\pm \ell_\beta^\mp$,

  $\mathrm{BR}(Z \to \ell_\alpha^\pm \ell_\beta^\mp) \lesssim \mathcal{O}(10^{-6})$

cLFV observables across all sectors and energies

Any **cLFV** sign

- "Purely
  Mos $e) \lesssim 10^{-12}$
- Muonic es
  e.g. ne 10^{-13}
- Semi-lep 0^{-8}
- (Semi-)
- cLFV @ $p \to \ell^{\pm}_{\alpha}\ell^{\mp}_{\beta}$,
  BR



A “3+2” neutrino toy model

Simplified "toy models" for phenomenological analyses: SM + ν_s

- **Ad-hoc** (low-energy) **constructions: SM** extended via n_S **Majorana massive** states

No assumption on **mechanism of mass generation**

Well-defined interactions in physical basis

Phenomenological low-energy limit of complete constructions (type I seesaw, ISS, ...)

Hypotheses: 3 active neutrinos + 2 sterile states

$$n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s^c, \nu_{s'}^c)^T$$

interaction basis ⇜⇝ **physical** basis

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

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

3×3 sub-block, **non-unitary!**

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

3×5 rectangular matrix

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

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

Would-be **PMNS** no longer unitary, leptonic W and Z vertices modified

- **Physical parameters: 5** masses [3 light (mostly active) & **2 heavier (mostly sterile) states]**

10 mixing angles, **10 CPV phases** (6 **Dirac** δ_{ij}, 4 **Majorana** φ_i)

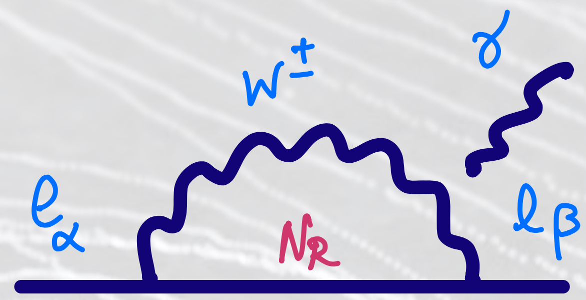
The impact of CP violating phases

cLFV processes mediated by HNL at loop-level

Consider "3+2" toy model (addition of 2 heavy sterile states; leptonic mixing $\mathcal{U}_{5\times 5}$, CPV phases)

- **Radiative decays:** $\mathrm{BR}(\mu \to e\gamma) \propto |G_\gamma^{\mu e}|^2$

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



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

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

$\Rightarrow$ **Radiative decays: rate** depends **only on Dirac phases**; full cancellation for $\Sigma\delta = \pi$

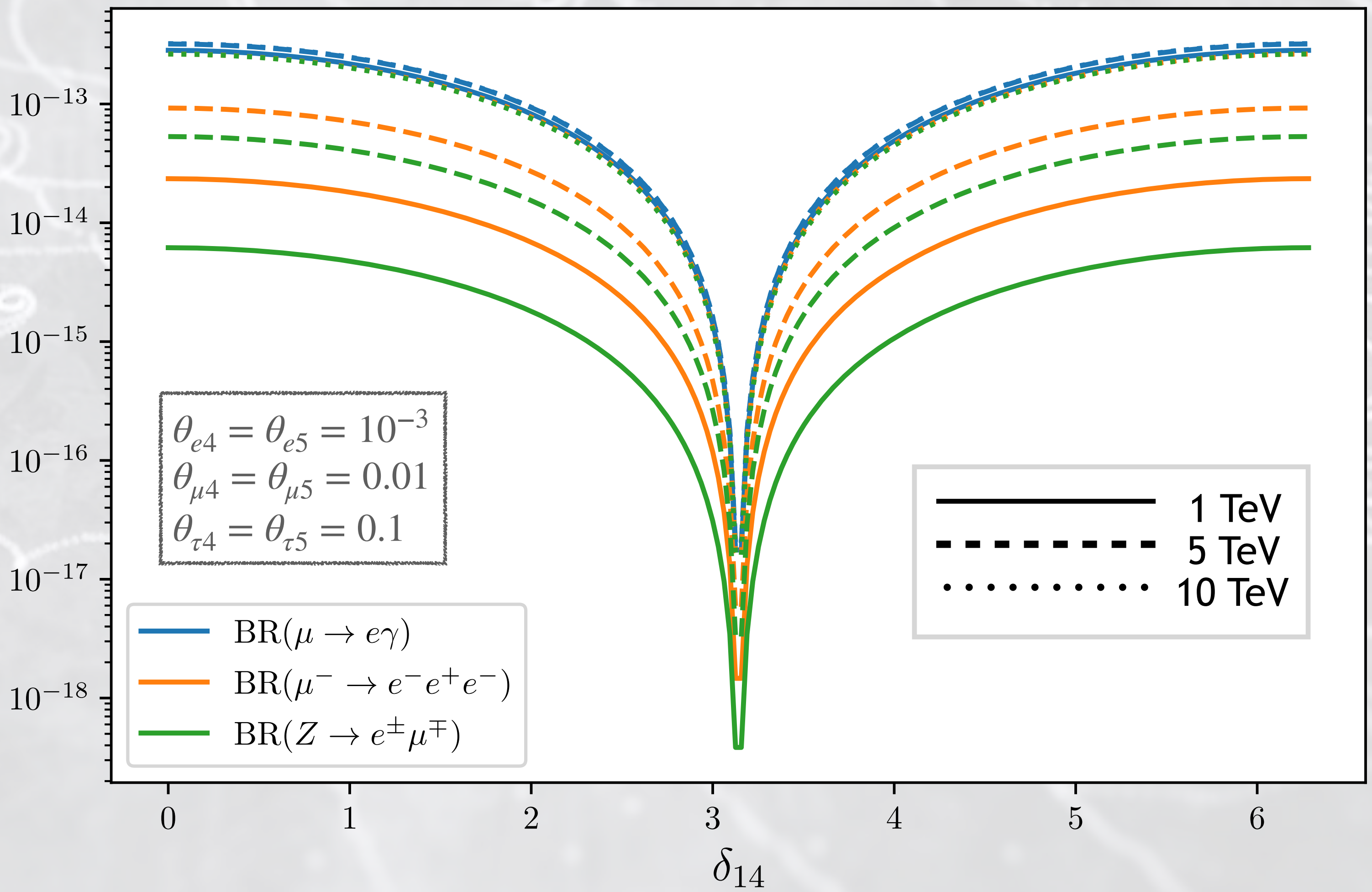
(Other form factors - more involved expressions, depend also on Majorana phases $\varphi_{4,5}$)

The impact of CP violating phases: Dirac

cLFV processes mediated by HNL at loop-level

Consider **"3+2" toy model** (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)

Abada, **JK,** Teixeira [2107.06313]



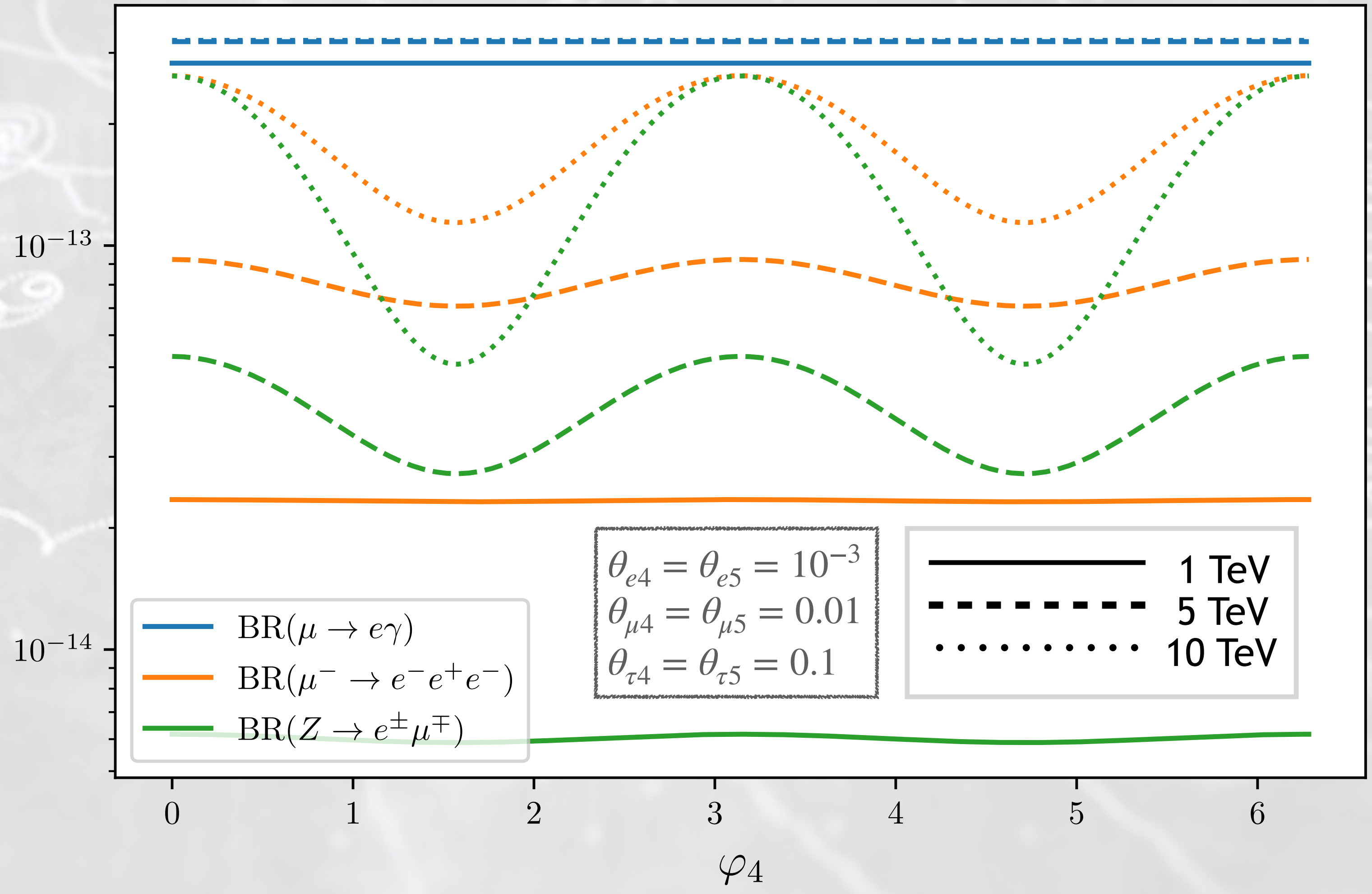
$\Rightarrow$ **Full cancellation of the rates for $\delta_{14} = \pi$, similar results for other (Dirac) phases**

The impact of CP violating phases: Majorana

cLFV processes mediated by HNL at loop-level

Consider **"3+2" toy model** (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)

Abada, **JK,** Teixeira [2107.06313]



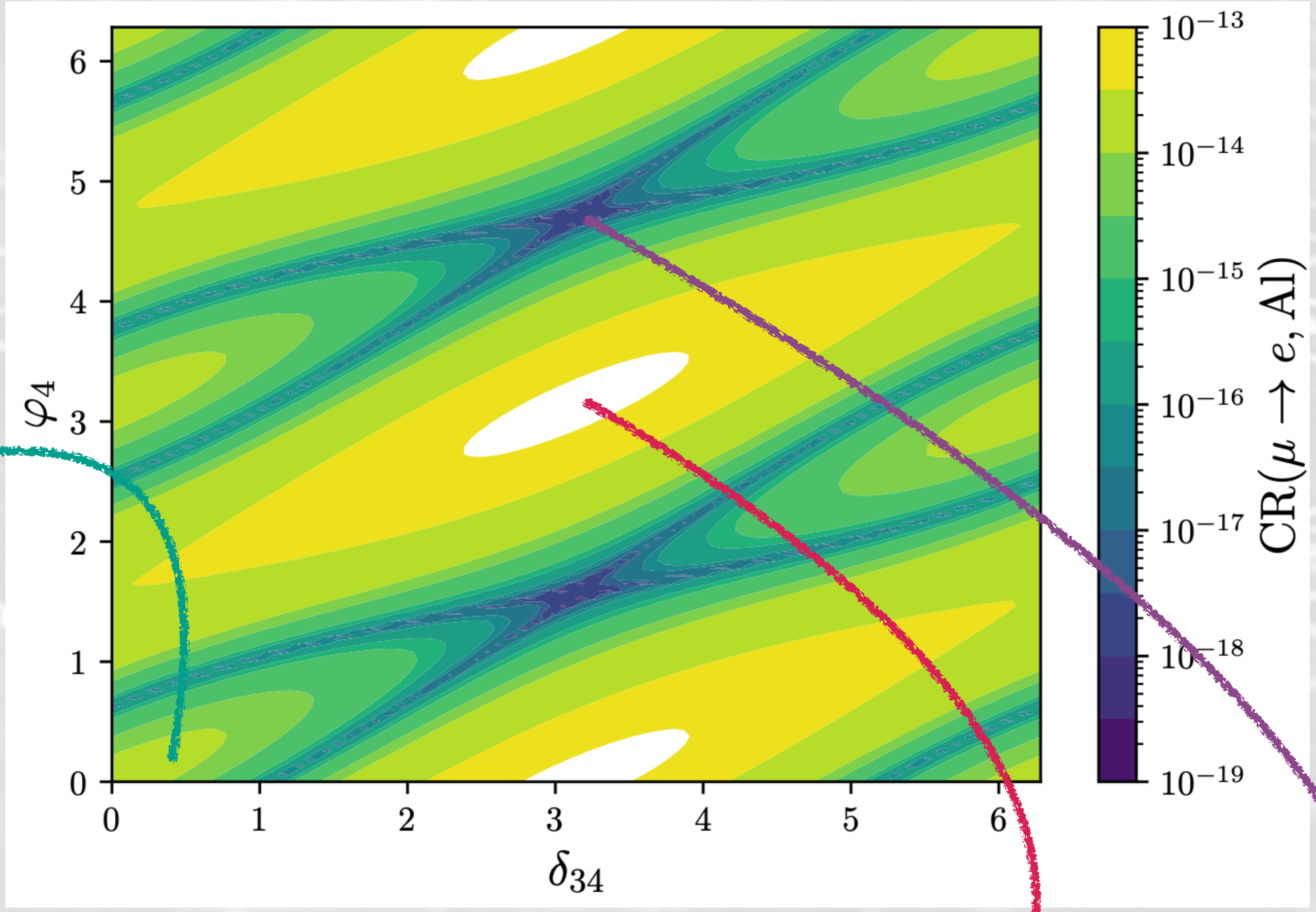
⇒Milder dependence, γ-penguin independent of Majorana phases

The impact of CP violating phases: Majorana

cLFV processes mediated by HNL at loop-level

Consider "3+2" toy model (addition of 2 heavy sterile states; leptonic mixing $\mathcal{U}_{5\times5}$, CPV phases)

CP conserving



Abada, **JK,** Teixeira [2107.06313]

⇒Interplay of non-vanishing CP phases can lead to enhancements…

… or strong suppressions of the rates

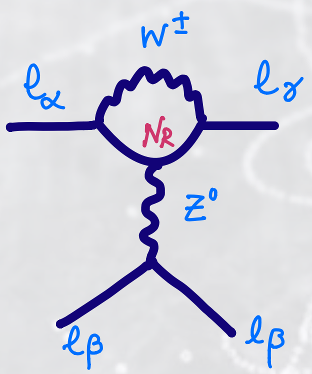
cLFV signals — correlations matter

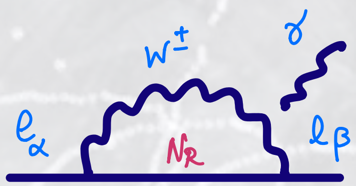
Synergy of **cLFV observables very important:** probe different operators/topologies

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

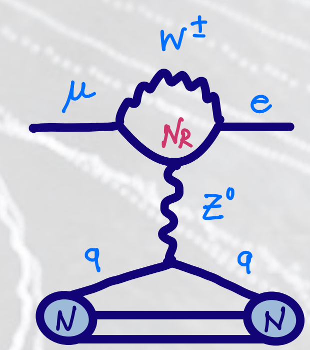
γ **dipoles & anapoles**, Z **penguins**, **tree-level contributions,... ⇒4-fermion operators**

Model-dependent: certain topologies **dominate**, tree-level cont. 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$^{*\,\dagger}$	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$



⇒ study correlations/ratios of cLFV observables, **might find** peculiar cLFV patterns

⇒ **provide complementary information to direct searches**

In **EFT: RGE** leads to operator mixing, **need to consider as many** observables as possible

to constrain $\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \frac{\mathscr{C}^5\,\mathscr{O}^5}{\Lambda_{\text{LNV}}}(m_\nu) + \frac{\mathscr{C}^6\,\mathscr{O}^6}{\Lambda^2_{\text{cLFV}}}(\ell_i \leftrightarrow \ell_j) + \ldots + \frac{\mathscr{C}^9\,\mathscr{O}^9}{\Lambda'^5_{\text{LNV}}}(0\nu 2\beta) + \ldots$

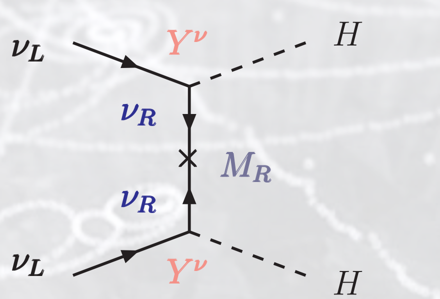
Disentangle seesaw mass models — more correlations

- **Models of m_ν** (and leptonic LFV) predict/accommodate **extensive ranges for cLFV...**

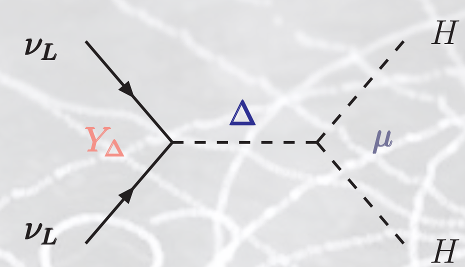
  In the absence of direct NP discovery - **correlations** might allow to disentangle models and provide important **complementary information** to direct searches!

- **Seesaw realisations:** distinctive signatures for numerous **cLFV observables**

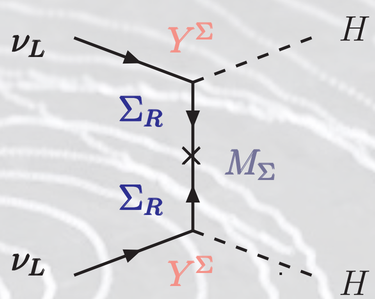
  ratios of observables to **identify seesaw mediators** & constrain their **masses!**



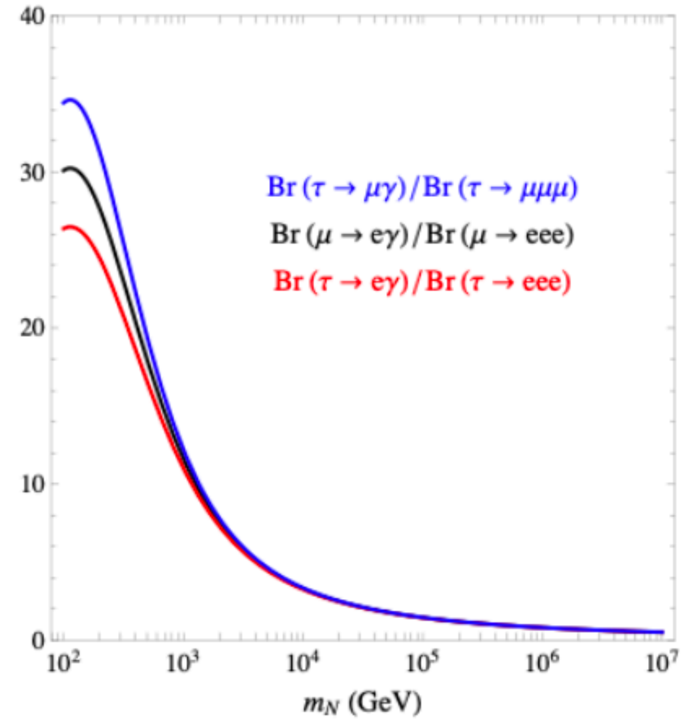
Type I (fermion singlet)

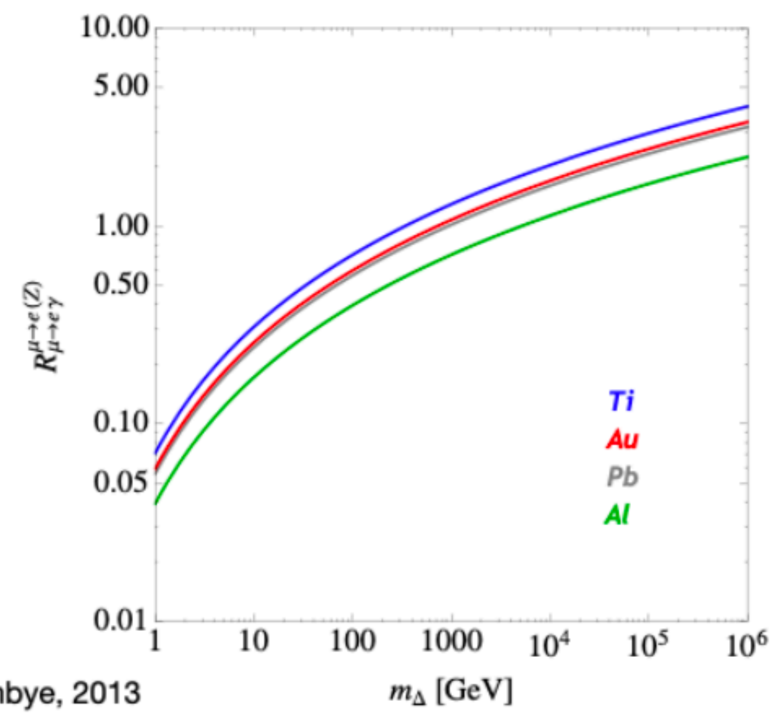


Type II (scalar triplet)



Type III (fermion triplet)





Hambye, 2013

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

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

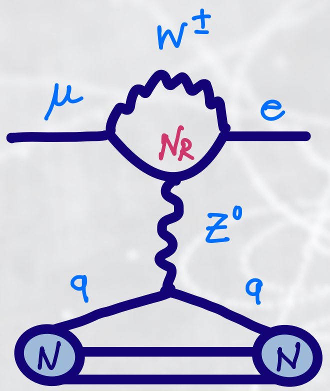
$$\frac{\text{BR}(\mu\to e\gamma)}{\text{CR}(e-\mu,\text{Ti})} = 3.1\times 10^{-4}$$

The impact of CP violating phases — breaking correlations

cLFV signatures: **ratios of observables** to **identify mediators** & constrain their **masses!**

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

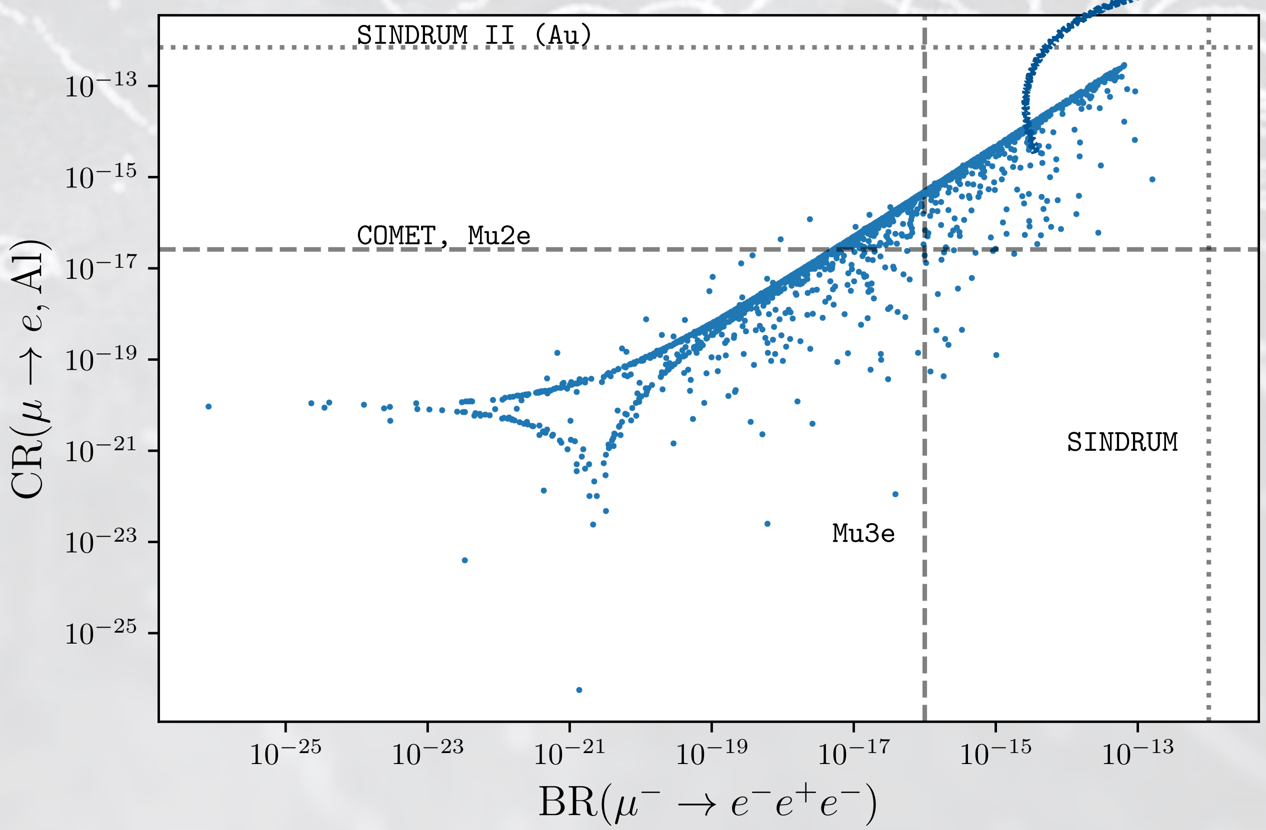
Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)



Observables dominated by **common topology: Z-penguins**

$\mu - e$ **conversion in nuclei**

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



Abada, **JK**, Teixeira [2107.06313]

Strong correlation
(CP conserving)

$m_4 = m_5 = 1$ TeV

- CP conserving

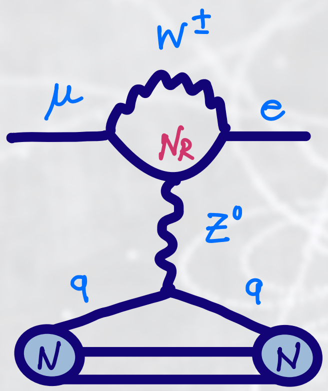
***Observation** of $\mu \to 3e$*
$\Rightarrow$ observation of
$\mu - e$ conversion

The impact of CP violating phases — breaking correlations

cLFV signatures: ratios of observables to **identify mediators** & constrain their **masses!**

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

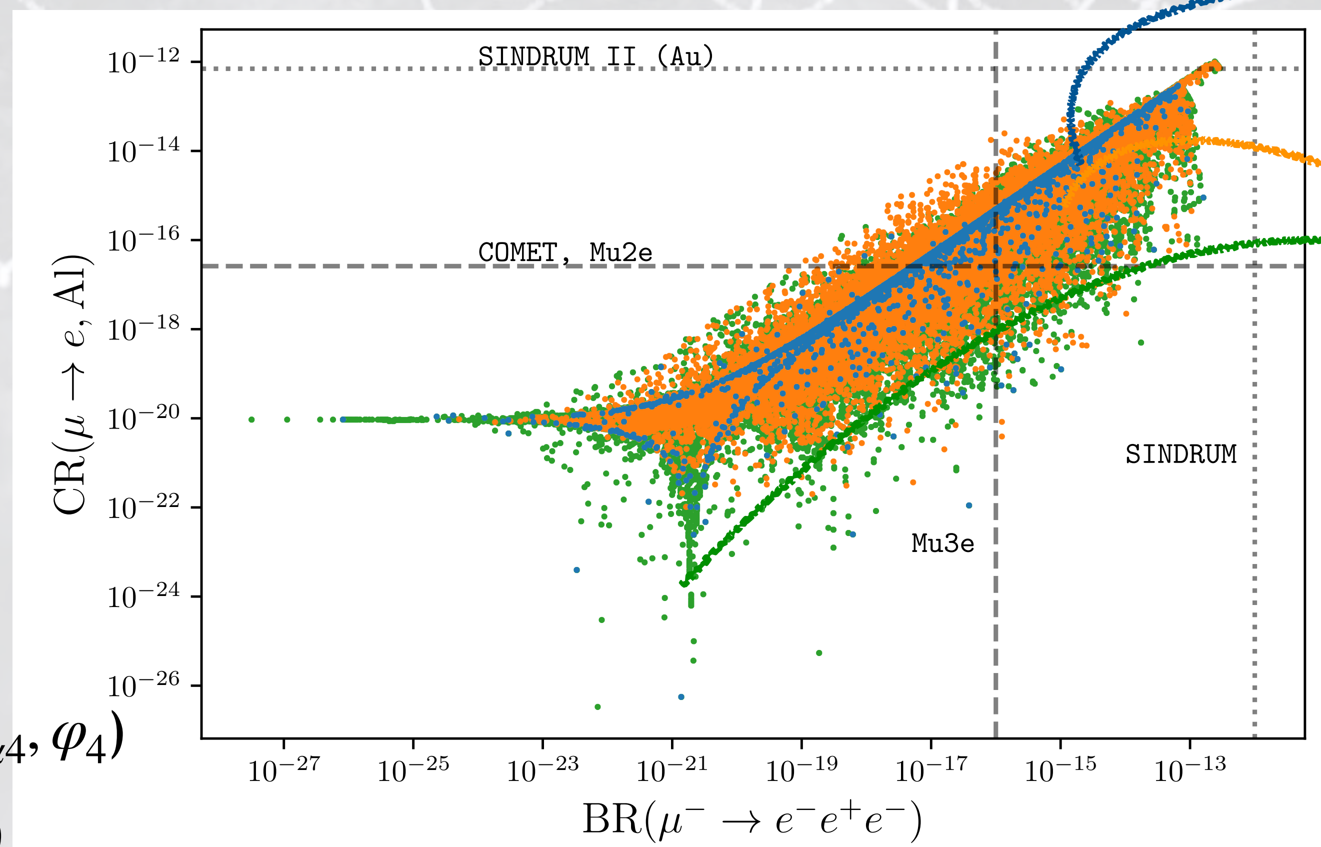
Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)



Observables dominated by **common topology: Z-penguins**

$\mu - e$ **conversion in nuclei**

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



Abada, **JK**, Teixeira [2107.06313]

Strong correlation (CP conserving)

Loss of correlation! (CP violating)

$m_4 = m_5 = 1$ TeV

- CP conserving
- CPV phases (random $\delta_{\alpha 4}, \varphi_4$)
- CPV phases (grid $n\pi/4$)

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

$\not\Rightarrow$ *observation of*

$\mu - e$ conversion

The impact of CP violating phases — no more correlations

cLFV signatures: ratios of observables to **identify mediators** & constrain their **masses!**

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

Some *illustrative* **benchmark points** - CP conserving (P_i) and CPV variants (P_i')

	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} ✓

Abada, **JK**, Teixeira [2107.06313]

P_3: only cLFV τ decays in allowed region; cLFV μ transitions already experimentally disfavoured

Regime of large mixing angles excluded?

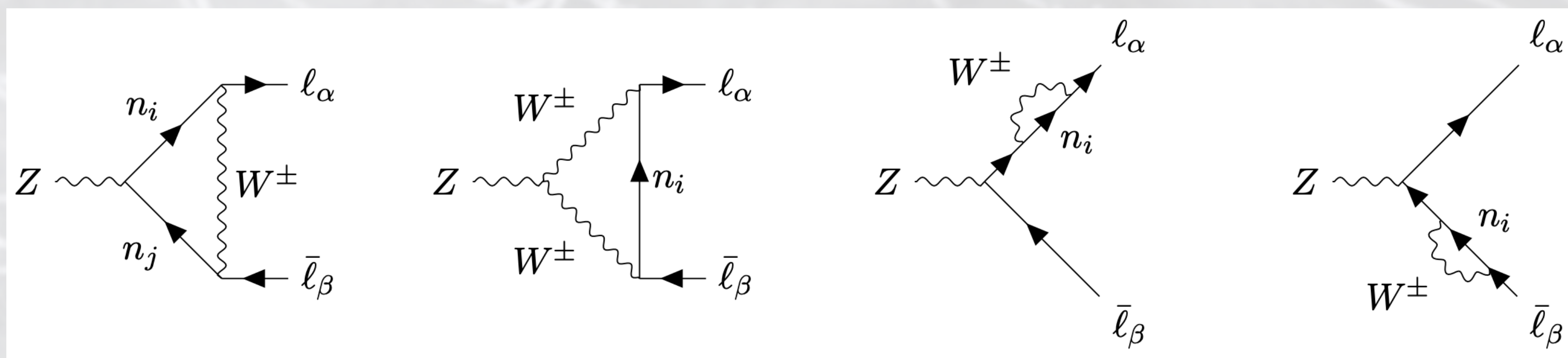
P_3': ***all*** considered **cLFV transitions currently allowed, $\mu \to e\gamma$ beyond sensitivity!**

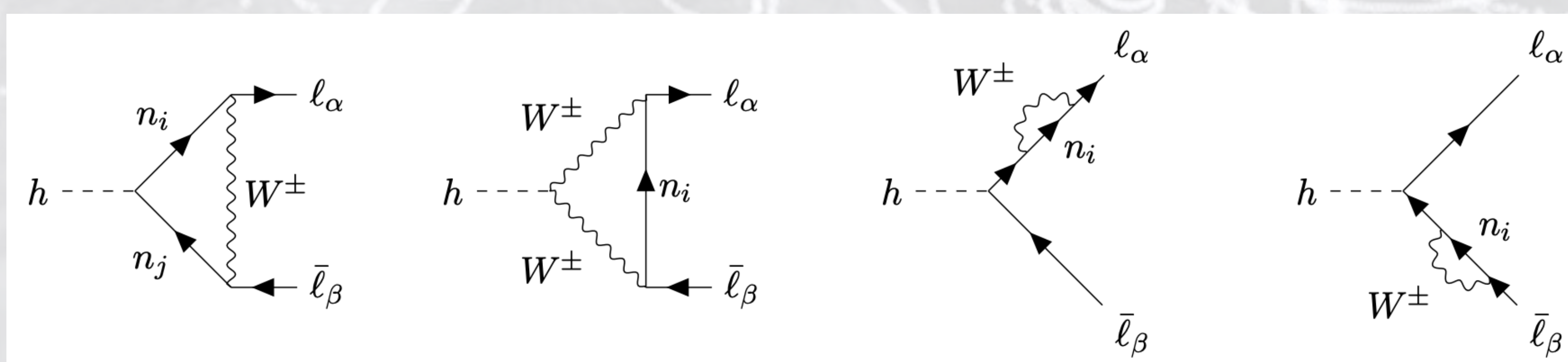
(Non)-observation of cLFV observable(s) $\Rightarrow$ *not* necessarily *disfavour* HNL extension!

cLFV Z & Higgs decays

cLFV $Z \to \ell_\alpha^\pm \ell_\beta^\mp$ and $h \to \ell_\alpha^\pm \ell_\beta^\mp$ can be induced by the presence of HNL:

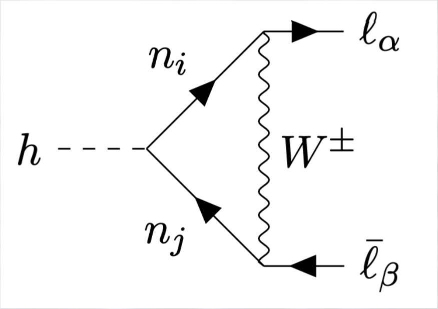
See also many contributions by several groups: [9403398], …, [1405.4300], [1412.6322], [1503.04159], [1607.05257], [1612.0929], [1703.00896], [1710.02510], [1807.01698], [1912.13327], [2005.11234], …



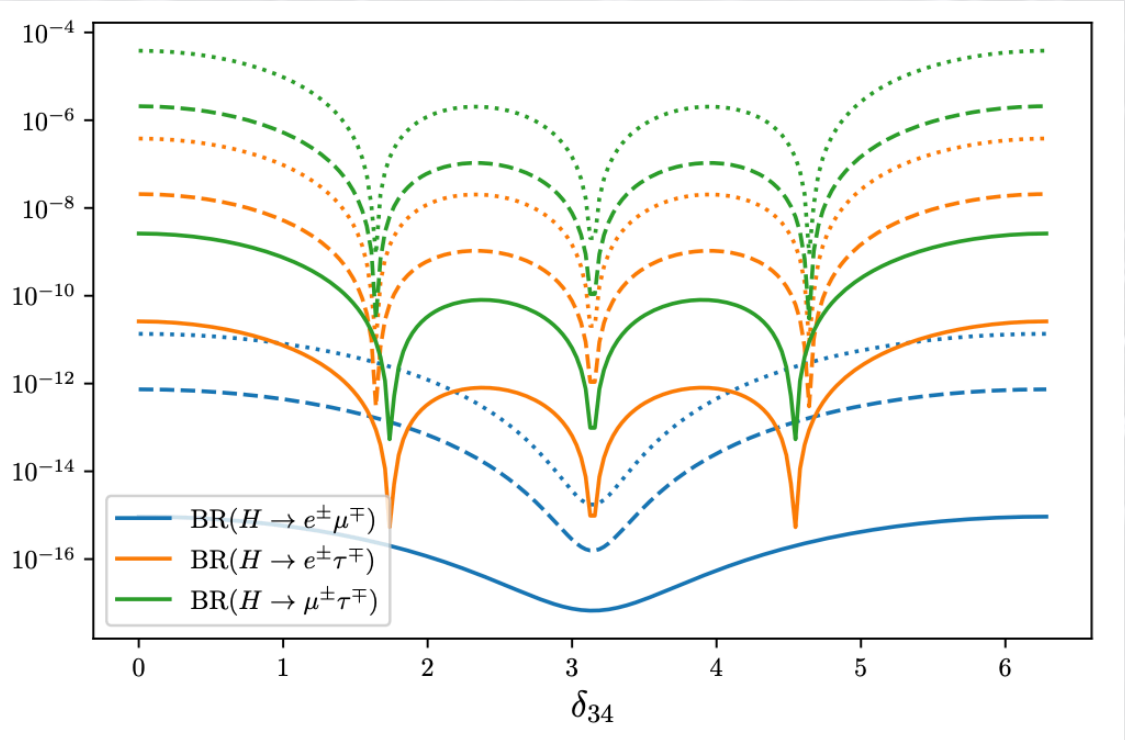


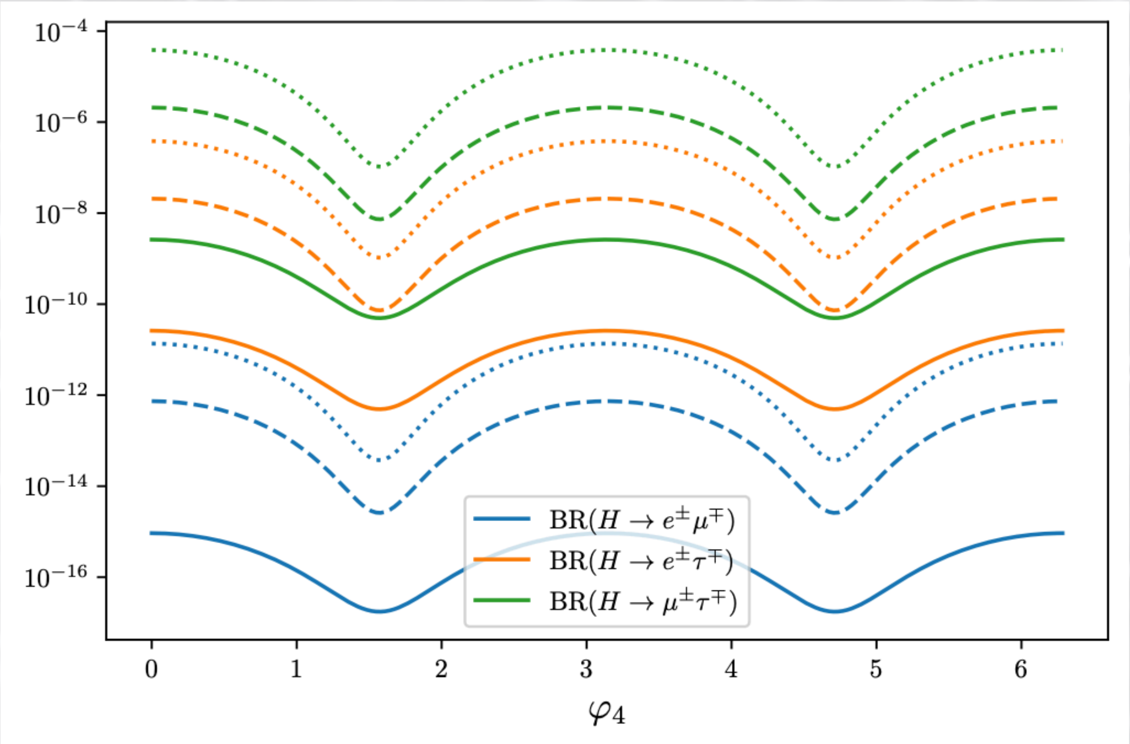
$\Rightarrow$ Study in detail effects of CP violating Dirac and Majorana phases

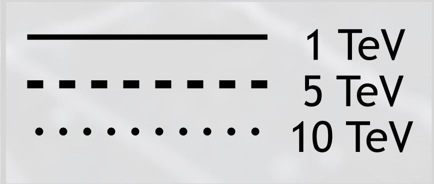
The impact of CP violating phases



Abada, JK, Pinsard, Rosauro, Teixeira [2207.10109]







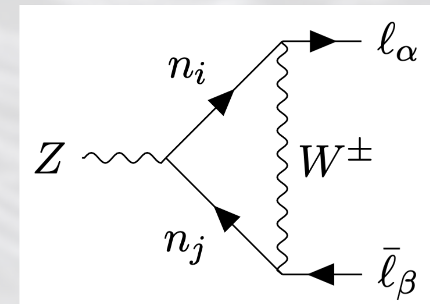
$$\theta_{e4} = \theta_{e5} = 10^{-3}$$
$$\theta_{\mu 4} = \theta_{\mu 5} = 0.01$$
$$\theta_{\tau 4} = \theta_{\tau 5} = 0.1$$

⇒ Several points of strong suppression with Dirac phases

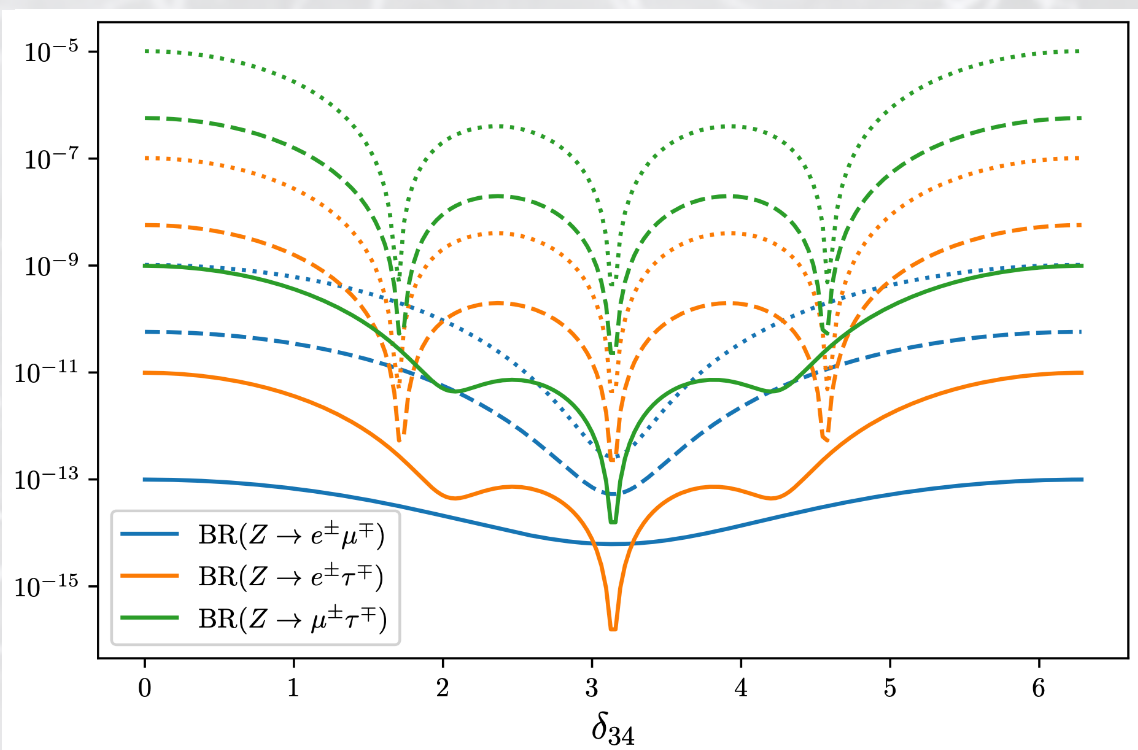
⇒ Milder suppression with Majorana phases

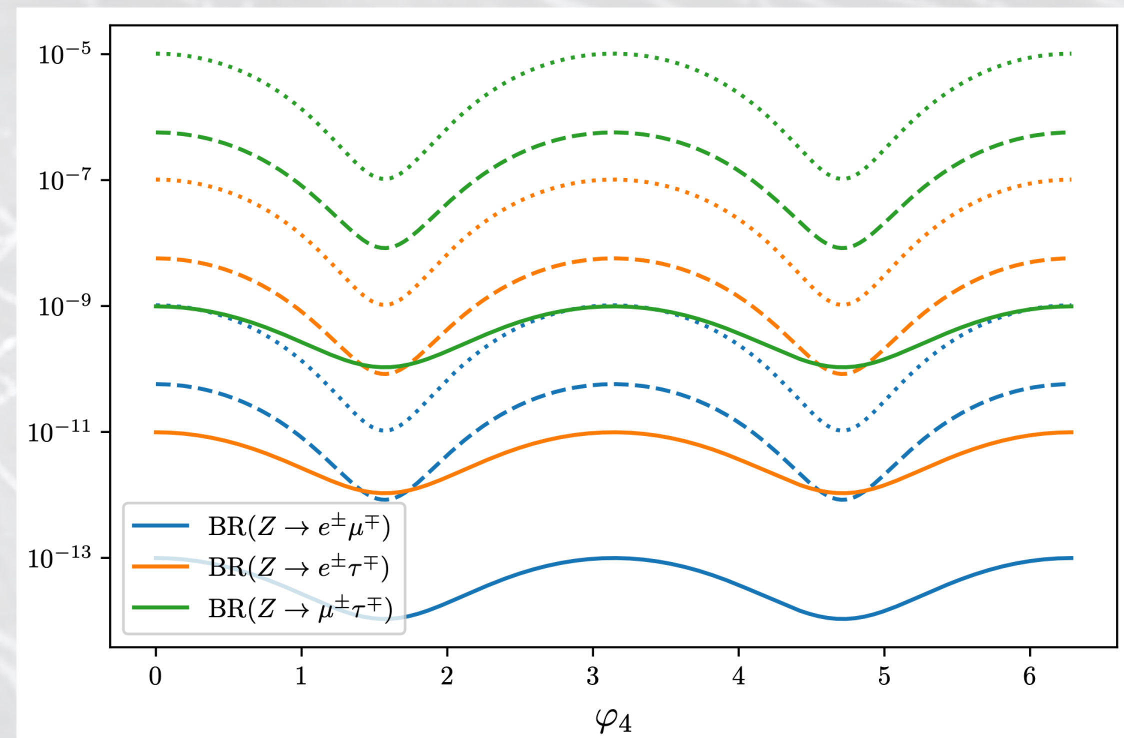
⇒Both mainly due to 2-neutrino vertex diagram

The impact of CP violating phases



Abada, JK, Pinsard, Rosauro, Teixeira [2207.10109]





$$\theta_{e4} = \theta_{e5} = 10^{-3}$$
$$\theta_{\mu 4} = \theta_{\mu 5} = 0.01$$
$$\theta_{\tau 4} = \theta_{\tau 5} = 0.1$$

$\Rightarrow$ Several points of strong suppression with Dirac phases

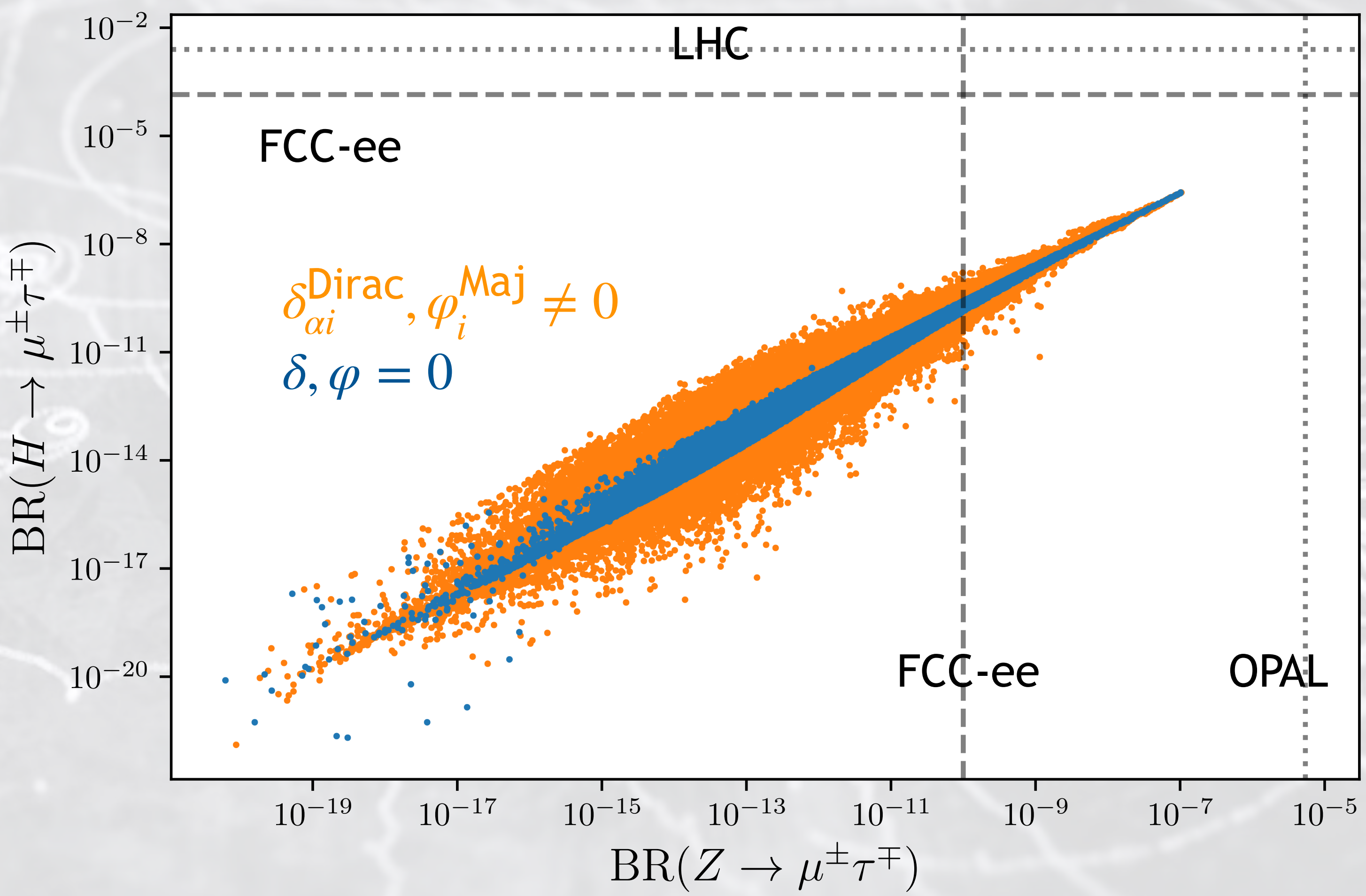
$\Rightarrow$ Milder suppression with Majorana phases

$\Rightarrow$ Both mainly due to 2-neutrino vertex diagram

cLFV processes: $H \to \ell_\alpha \ell_\beta$, $Z \to \ell_\alpha \ell_\beta$ and CPV Dirac / Majorana phases

Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)

All angles & CPV phases *randomly* (independently) varied; **non-degenerate heavy states (TeV)**



Abada, **JK**, Pinsard, Rosauro, Teixeira [2207.10109]

$\Rightarrow$ **Important contributions** of sterile fermions to **cLFV Higgs and Z decays!**

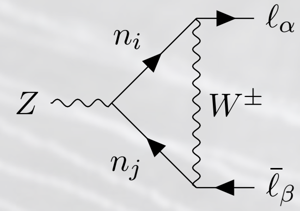
($H \to \mu\tau$ most promising, but still beyond "observation", even FCC-ee...)

$\Rightarrow$ **Effect** of **Majorana and Dirac phases** on cLFV **rates:** *constructive and destructive interferences*

Milder **loss of correlation** with respect to CP conserving case than **cLFV leptonic decays**

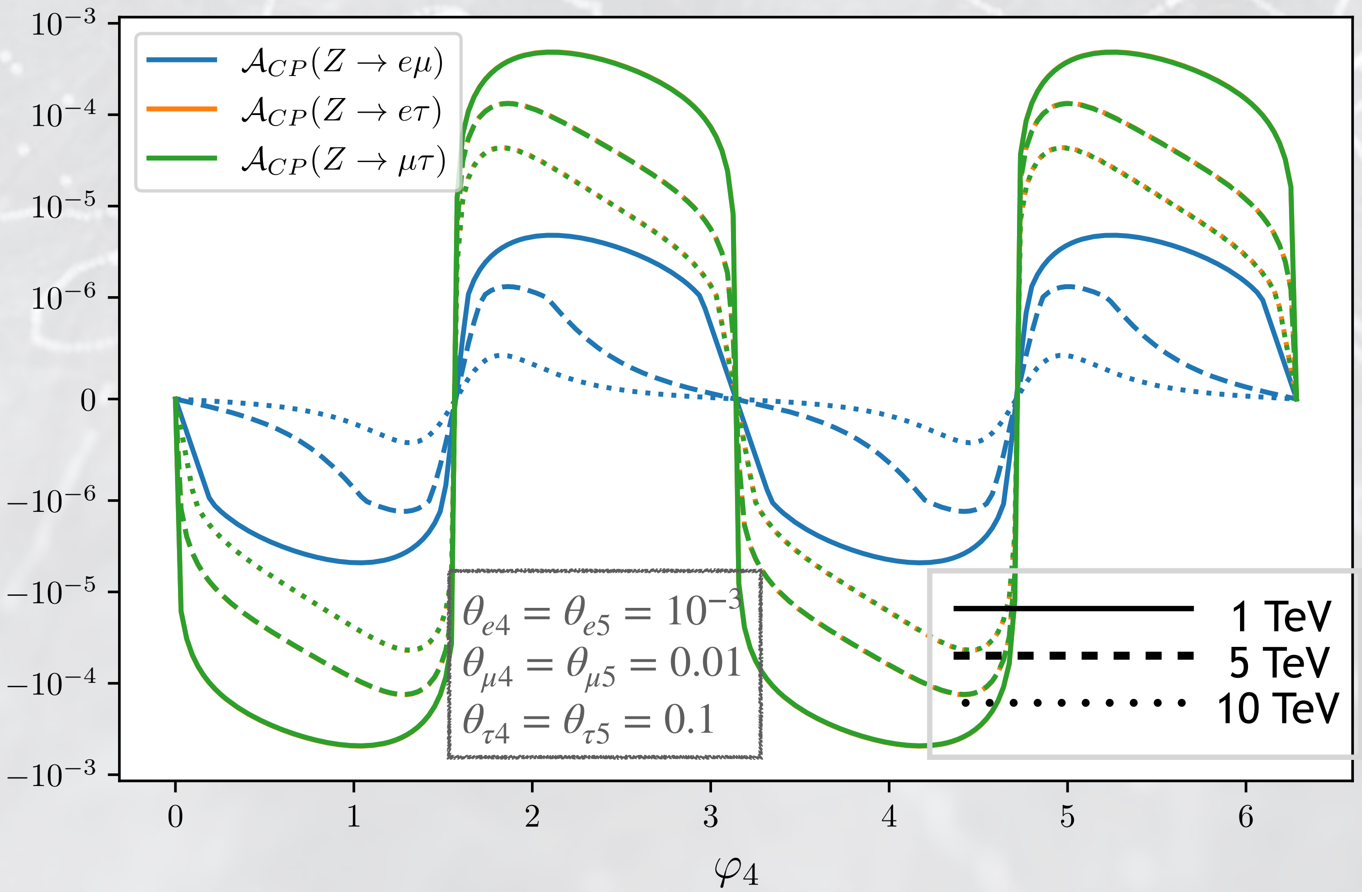
CP-asymmetries

Correlations **broken**, large mixing angles still possible, how do we “tag” the presence of **CPV**?



Introduce **CP-asymmetries:** $\mathscr{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \dfrac{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) - \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) + \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}$

Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathscr{U}_{5\times 5}$, **CPV** phases)
Simplified approach: $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$; $m_4 = m_5 = (1, 5, 10)$ TeV



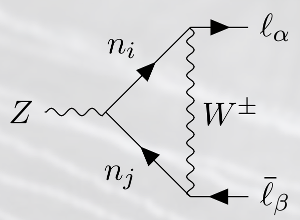
Abada, JK, Pinsard, Rosauro, Teixeira [2207.10109]

- **Impact** of **Majorana** CPV phases (per mile - per cent effect)

(Higgs decay asymmetries accidentally negligible)

CP-asymmetries

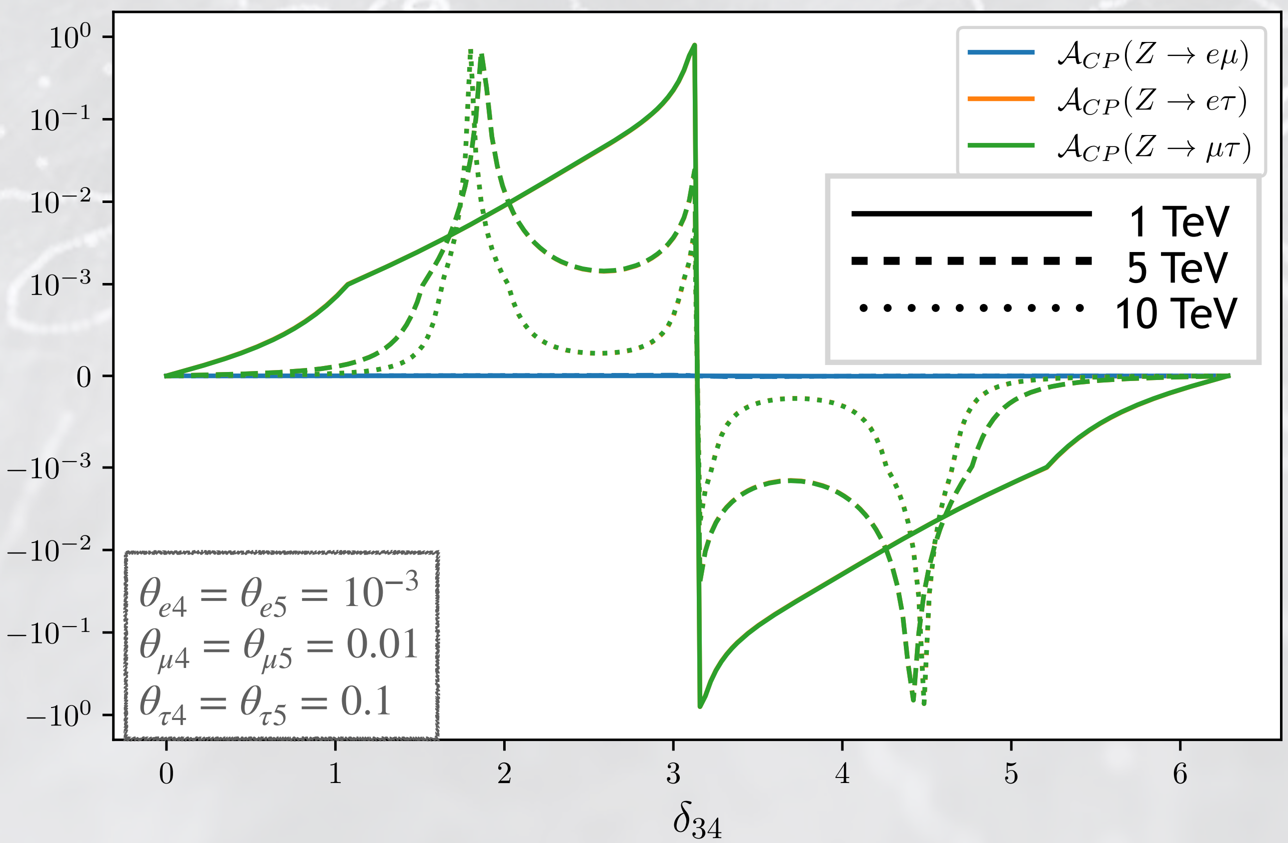
Correlations **broken**, large mixing angles still possible, how do we “tag” the presence of **CPV**?



Introduce **CP-asymmetries:** $\mathscr{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \dfrac{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) - \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) + \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}$

Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathscr{U}_{5\times5}$, **CPV** phases)

Simplified approach: $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$; $m_4 = m_5 = (1, 5, 10)$ TeV



Abada, JK, Pinsard, Rosauro, Teixeira [2207.10109]

- **Impact** of **Majorana** CPV phases (per mile - per cent effect)
- **Dirac:** sensitivity of $\mathscr{A}_{CP}$ to **all phases**

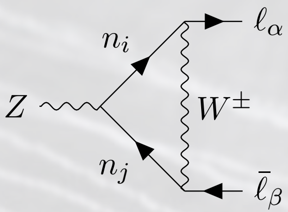
$\boldsymbol{\delta_{34}}$ **- at the source of very large** $\boldsymbol{\mathscr{A}_{CP}(Z \to \mu\tau)}$

$\Rightarrow$ amplified with **increasing** $\boldsymbol{m_{4,5}}$

(Higgs decay asymmetries accidentally negligible)

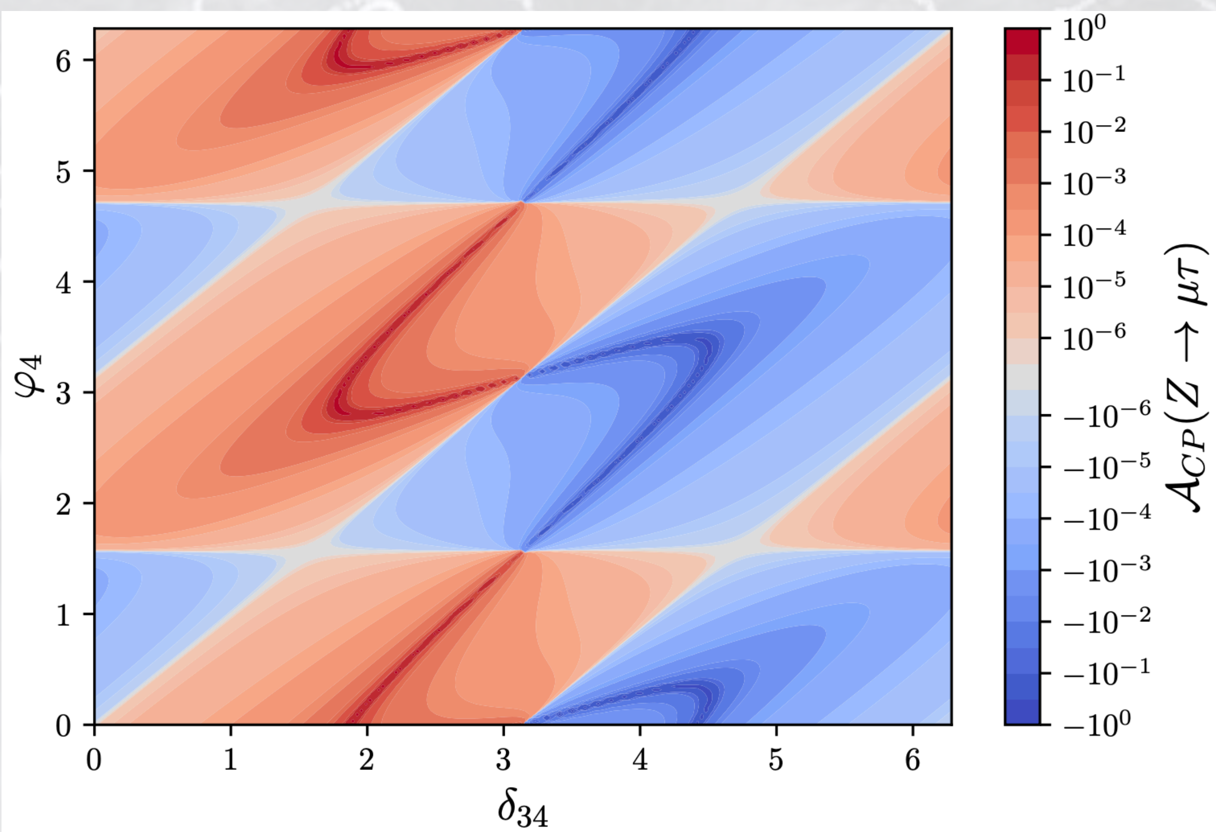
CP-asymmetries

Correlations **broken**, large mixing angles still possible, how do we “tag” the presence of **CPV**?



Introduce **CP-asymmetries:** $\mathscr{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \dfrac{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) - \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) + \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}$

Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathscr{U}_{5\times5}$, **CPV** phases)
Simplified approach: $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$; $m_4 = m_5 = (1, 5, 10)$ TeV



- **Interesting** interplay of **Majorana** and Dirac **CPV phases**

(Higgs decay asymmetries accidentally negligible)

Abada, JK, Pinsard, Rosauro, Teixeira [2207.10109]

CP-asymmetries

Correlations **broken**, large mixing angles still possible, how do we "tag" the presence of CPV?

Benchmark points (with different mixing)
P_1 (CP-conserving), P_2 (CP-violating)
lead to identical cLFV predictions!

Observable	$\mu \to eee$	$\mu - e$ (Al)	$\tau \to \mu\mu\mu$	$Z \to \mu\tau$
$P_{1,2}$ prediction	2×10^{-15}	5×10^{-14}	1×10^{-10}	2×10^{-10}

Abada, **JK**, Pinsard, Rosauro, Teixeira [2207.10109]

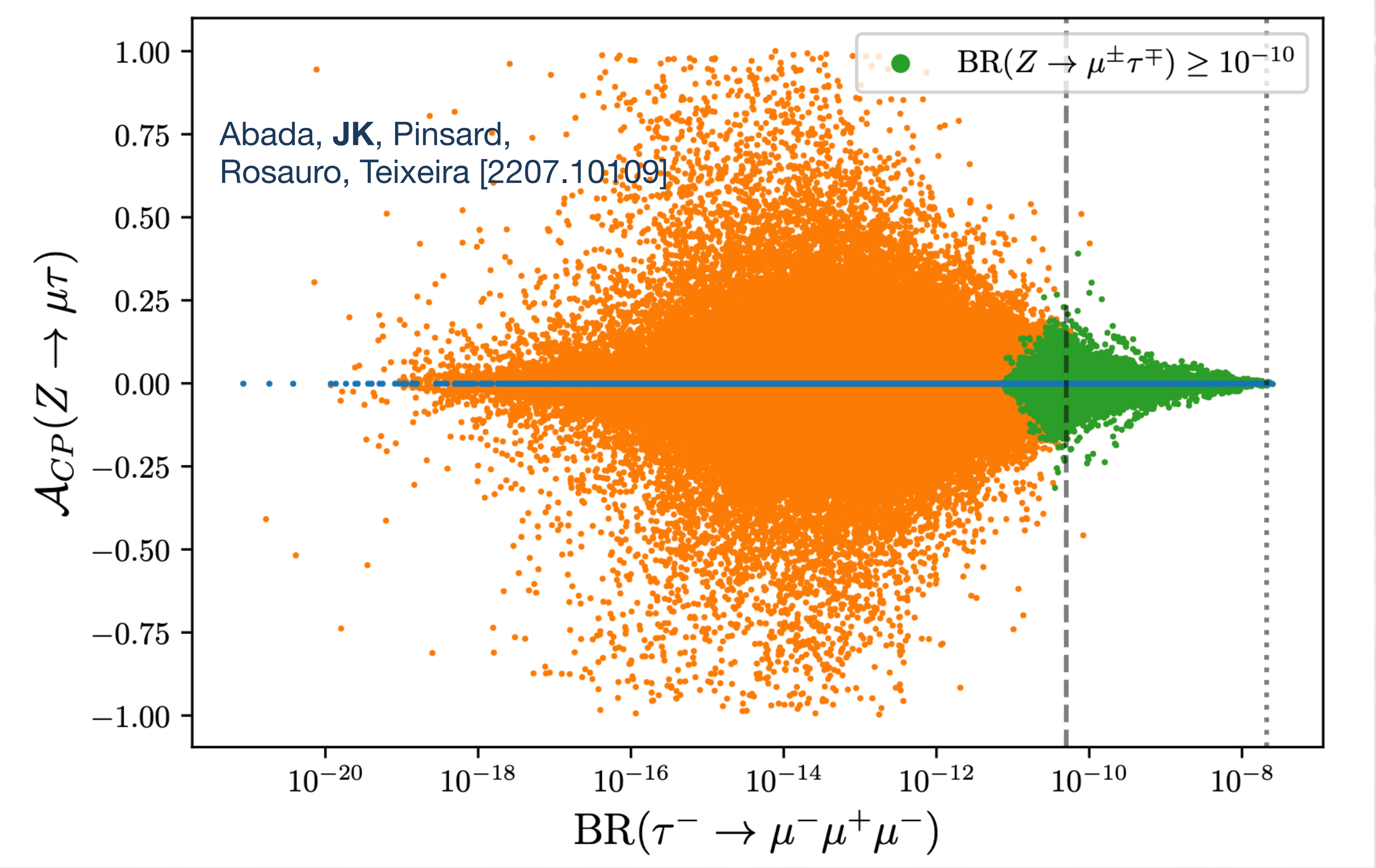
Consider CP-asymmetries: $\mathcal{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \dfrac{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) - \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) + \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}$

$\Rightarrow P_2$: $\mathcal{A}_{CP}(Z \to \mu\tau) \simeq 30\,\%$!

Measuring **CP-asymmetries, i.e.** searching for $Z \to \ell_\alpha^+ \ell_\beta^-$ and $Z \to \ell_\alpha^- \ell_\beta^+$ independently

might allow to constrain CPV phases

and can help to identify the source of cLFV!



CP (T)-asymmetries have also been considered in **angular distributions** of $\mu \to eee$

(see Bolton & Petcov [2204.03468])

CP-asymmetries

Correlations **broken**, large mixing angles still possible, how do we "tag" the presence of CPV?

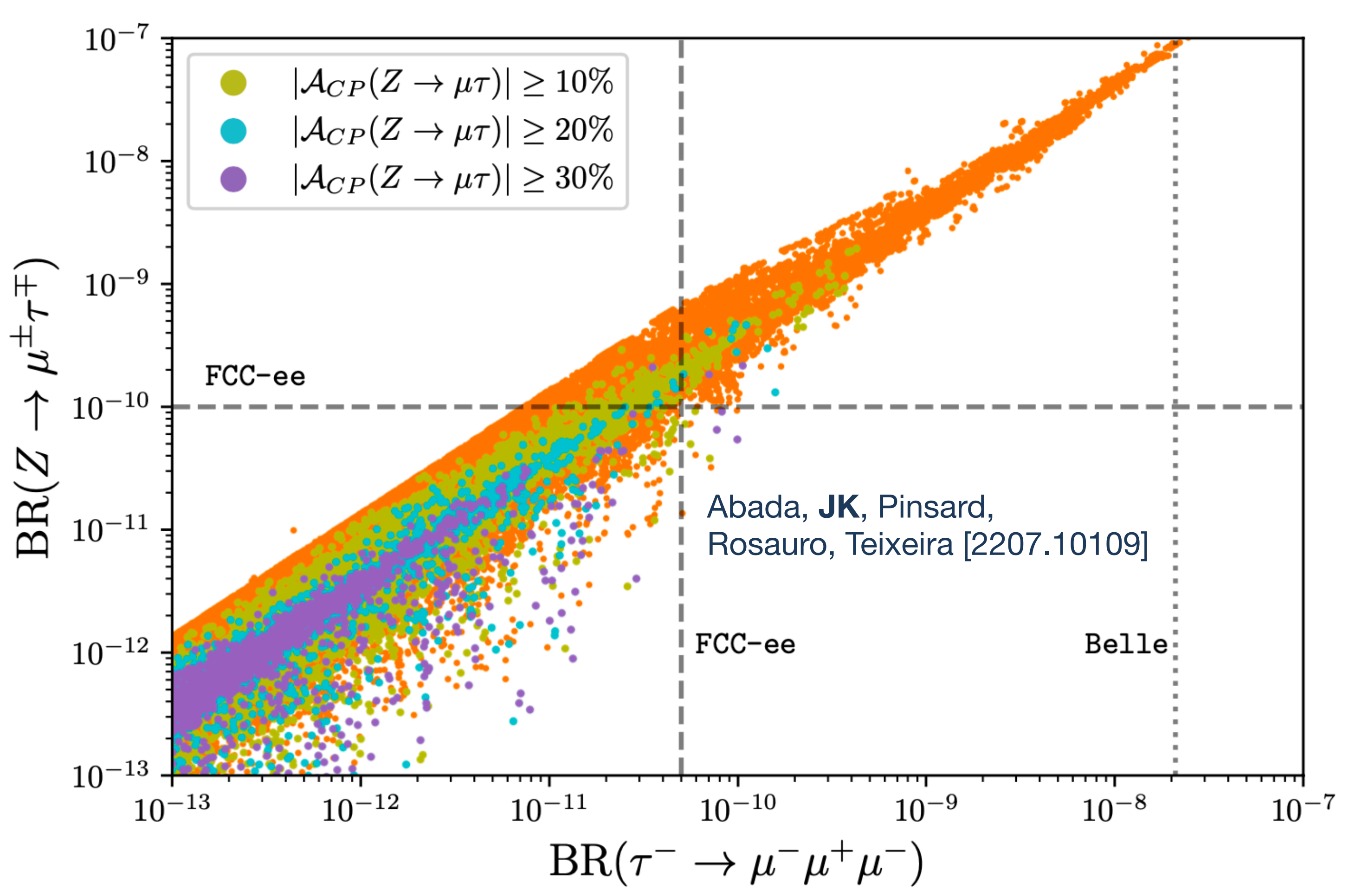
Benchmark points (with different mixing)
P_1 (CP-conserving), P_2 (CP-violating)
lead to identical cLFV predictions!

Observable	$\mu \to eee$	$\mu - e$ (Al)	$\tau \to \mu\mu\mu$	$Z \to \mu\tau$
$P_{1,2}$ prediction	2×10^{-15}	5×10^{-14}	1×10^{-10}	2×10^{-10}

Abada, **JK**, Pinsard, Rosauro, Teixeira [2207.10109]

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

$\Rightarrow P_2$: $\mathscr{A}_{CP}(Z \to \mu\tau) \simeq 30\,\%$!



Measuring CP-asymmetries, i.e. searching for $Z \to \ell_\alpha^+ \ell_\beta^-$ and $Z \to \ell_\alpha^- \ell_\beta^+$ independently might allow to constrain CPV phases and can help to identify the source of cLFV!

CP (T)-asymmetries have also been considered in **angular distributions** of $\mu \to eee$
(see Bolton & Petcov [2204.03468])

Conclusion

Neutrino oscillations are the 1st **laboratory evidence** of **New Physics!**

⇒ massive and oscillating neutrinos open the door to **LFV** and new sources of **CPV**

New **CPV phases** from **HNL** play a crucial role in **LNV** and **cLFV** processes:

⇒ **Interference effects** can enhance or suppress rates

⇒ Correlations between observables can be broken

⇒ Measurements of **CP** asymmetries might help to establish presence of new sources of **CPV**

Strong phenomenological impact!

CP violating phases need to be consistently taken into account in analyses of **HNL** models

Conclusion

Neutrino oscillations are the 1st laboratory evidence of New Physics!

$\Rightarrow$ massive and oscillating neutrinos open the door to LFV and

new sourc... f CPV

New CPV phases from HNL play a crucial role i... es:

$\Rightarrow$ Interferenc...

...broken

$\Rightarrow$ Measu... ...etries might help to establish presence of

new sources of CPV

Strong phenomenological impact!

CP violating phases need to be consistently taken into account in analyses of HNL models

"You cannot spell flaVour without CP Violation"

Phases do really matter!

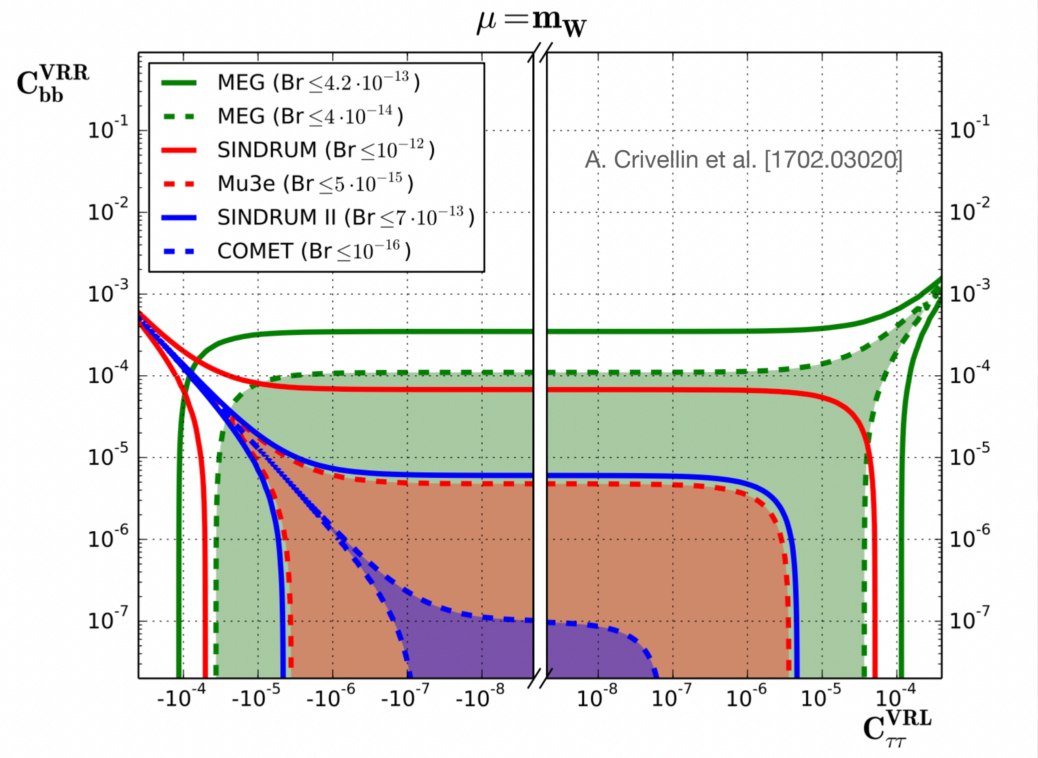
Thank you!

Backup

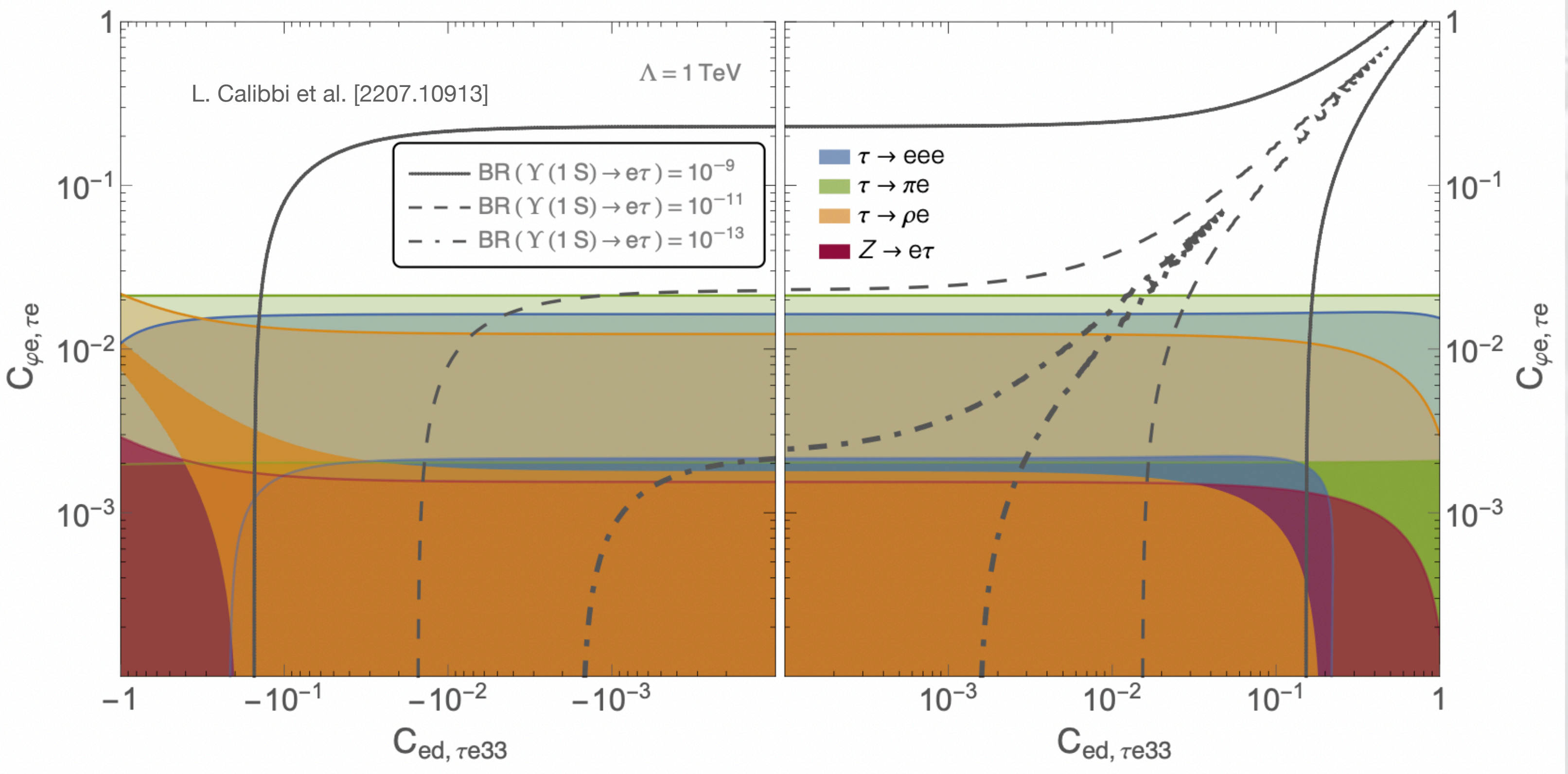
cLFV signals — correlations matter

In **EFT: RGE** leads to **operator mixing, need to consider as many observables** as possible

to constrain $\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \frac{\mathscr{C}^5\,\mathscr{O}^5}{\Lambda_{\text{LNV}}}(m_\nu) + \frac{\mathscr{C}^6\,\mathscr{O}^6}{\Lambda^2_{\text{cLFV}}}(\ell_i \leftrightarrow \ell_j) + \ldots + \frac{\mathscr{C}^9\,\mathscr{O}^9}{\Lambda'^5_{\text{LNV}}}(0\nu2\beta) + \ldots$



Beyond tree-level: interesting connections to semi-leptonic operators



Going beyond 2-operator-limits, see e.g. M. Ardu, S. Davidson and M. Gorbahn [2103.07212, 2202.09246, …]

The probing power of flavour violation

Paving the way to the **SM:** from prediction of charm to the existence of **3 families!**

⇒ **Indirect probes** of much higher scales: e.g. **top mass** in $K^0 - \bar{K}^0$ oscillations

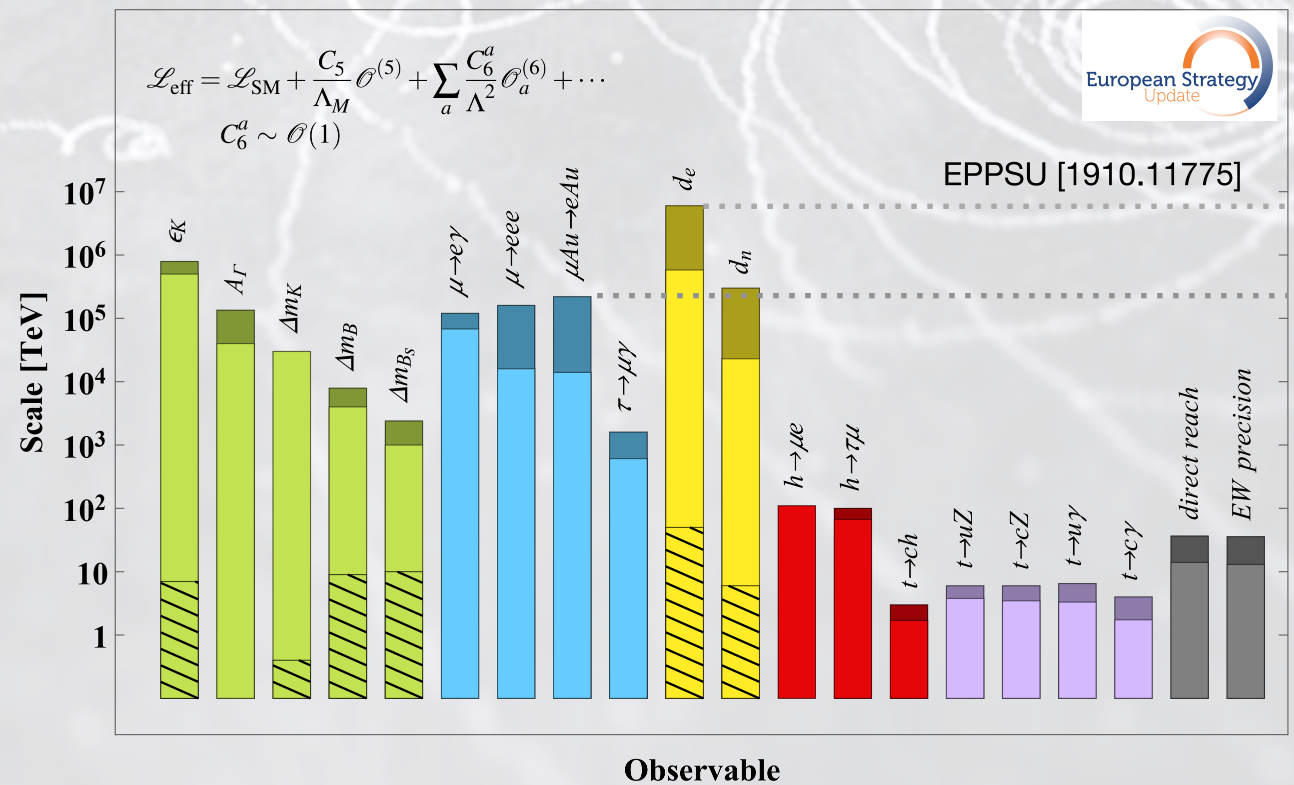
SM interpreted as a **low-energy limit** of a (complete, yet unknown) **NP model**

⇒ Study **various classes** of well-motivated **models**

⇒ **Model-independent**, **effective approach (EFT)**

$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathscr{C}^n(g, Y, \dots)\, \mathscr{O}^n(\ell, q, H, \gamma, \dots)$$

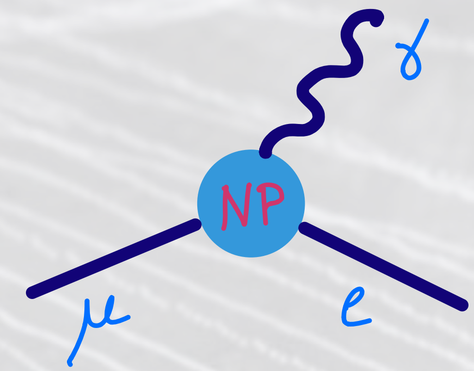
Cast **current data** in terms of $\mathscr{C}^6_{ij}$ and Λ_{NP} : $\mathscr{C}^6_{ij} \approx 1 \Rightarrow$ **bounds on** Λ_{NP}



cLFV decays

Any **cLFV** signal necessarily implies the presence of **New Physics!**

cLFV decay $\mu^+ \to e^+\gamma$:

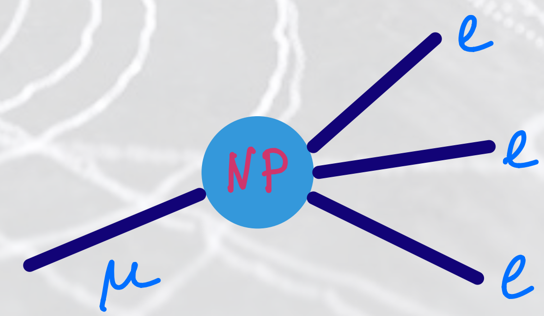


Clean event signature: **back-to-back $e^+\gamma$**, with $E_\gamma = E_{e^+} \simeq m_\mu/2$

Current bound: $\mathrm{BR}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$ (MEG)

Future **prospects:** $\mathrm{BR}(\mu \to e\gamma) \lesssim 6 \times 10^{-14}$ (MEG II)

cLFV decay $\mu^+ \to e^+e^-e^+$:



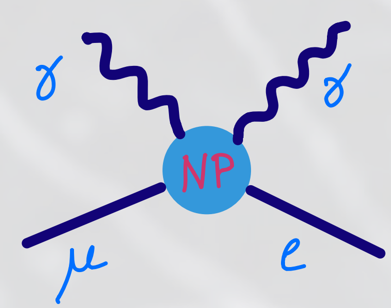
Event signature: **3 electrons in coincidence**, with $\sum p_e = (m_\mu, \vec{0})^T$

Current bound: $\mathrm{BR}(\mu \to eee) \lesssim 1 \times 10^{-12}$ (Sindrum)

Future **prospects:** $\mathrm{BR}(\mu \to eee) \lesssim 10^{-15(16)}$ (Mu3e)

More cLFV decays:

$\mu^+ \to e^+\gamma\gamma$, $\mu^+ \to e^+X(\to \gamma\gamma, e^+e^-)$, $\mu \to ea$ **(ALPs), ...**



Muonic bound states & muonic atoms

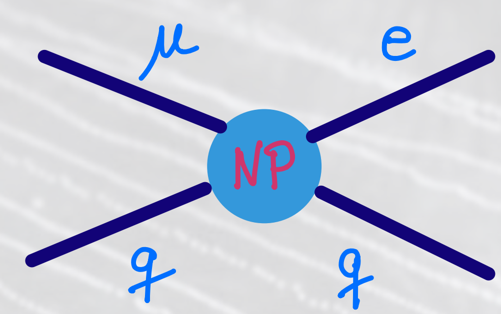
Any **cLFV** signal necessarily implies the presence of **New Physics!**

- **cLFV $\mu^- \to e^-$ conversion:** $\mu^- + (A,Z) \to e^- + (A,Z)^{(*)}$

  Event signature: single **mono-energetic** e^-, with $E_e \simeq \mathcal{O}(100\,\mathrm{MeV})$

  Current bound: $\mathrm{CR}(\mu \to e, \mathrm{Au}) \lesssim 7 \times 10^{-13}$ (Sindrum II)

  Future **prospects:** $\mathrm{CR}(\mu \to e, \mathrm{Al}) \lesssim \mathcal{O}(10^{-17} - 10^{-18})$ **(Mu2e, COMET)** **(also DeeMe)**



- **Coulomb enhanced $\mu^- e^- \to e^- e^-$ decay:** $\Gamma \propto \sigma_{\mu e \to ee} v_{\mathrm{rel}} [(Z-1)\alpha_e m_e]^3$

  Clean event signature: **back-to-back e^- pair,** with $E_e \simeq m_\mu/2$

  Experimental status: **NEW observable!** (to be studied at COMET phase I ?)

  Large Z enhancement, very complementary to $\mu \to eee$ & $\mu \to e\gamma$

  Uesaka et al. [1508.05747]

- **cLFV & LNV $\mu^- - e^+$ conversion:** $\mu^- + (A,Z) \to e^+ + (A, Z-2)^*$

  Complicated event signature, NMEs poorly known… **but: strong correlation with $0\nu 2\beta$!**

- **Muonium:** $\mathrm{Mu}(\mu^+ e^-) \to \overline{\mathrm{Mu}}(\mu^- e^+)$ **oscillation,** $\mathrm{Mu}(\mu^+ e^-) \to e^+ e^-$ **decay**

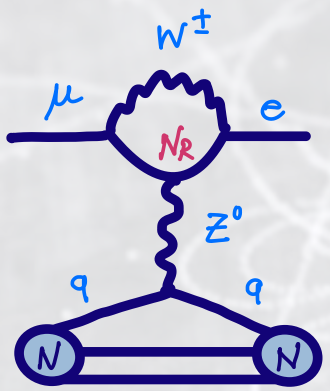
  $P(\mathrm{Mu} \to \overline{\mathrm{Mu}}) \lesssim 8 \times 10^{-11}$ (Willmann et al. '99)

The impact of CP violating phases — no more correlations

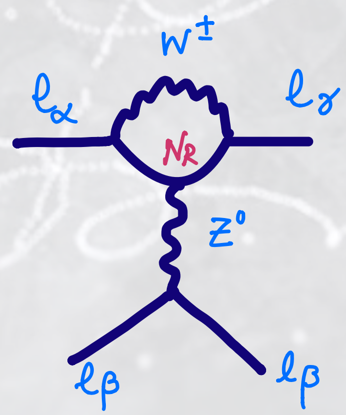
cLFV signatures: ratios of observables to identify mediators & constrain their **masses!**

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

Consider "3+2" toy model (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **CPV** phases)



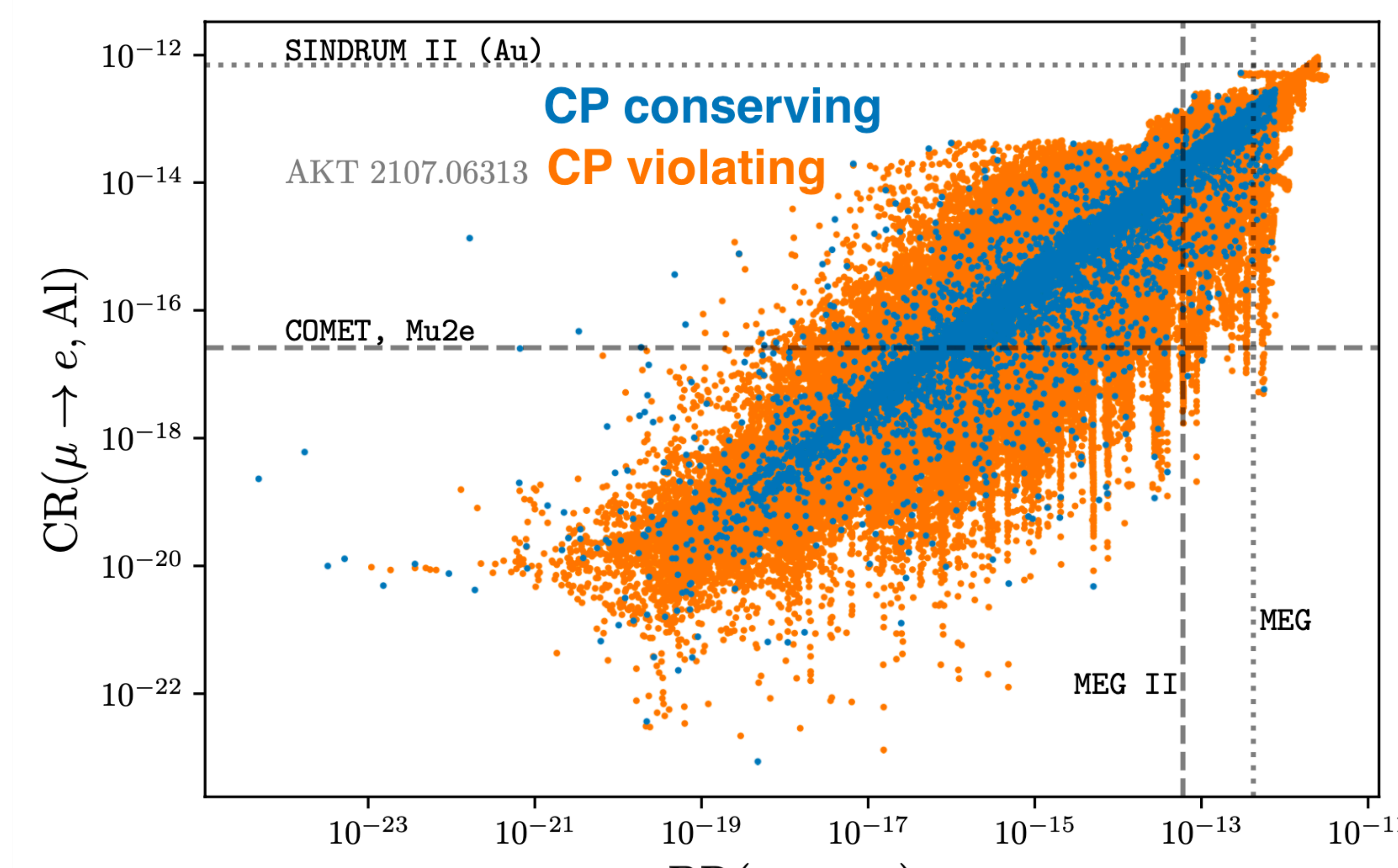
Observables dominated by **common topology: Z-penguins**



Also vary mass splitting,

all angles/phases independently

⇒ Generic effect of **CPV phases!**



Abada, **JK**, Teixeira [2107.06313]

Inverse seesaw model (**ISS**) with Casas-Ibarra parametrisation: $M_R = 5\,\mathrm{TeV}\,, \mu_X = 100\,\mathrm{eV}$