CP violation and (heavy) Neutrinos

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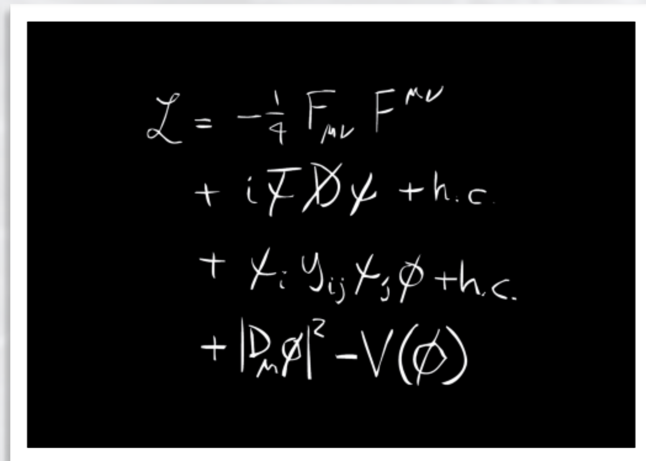
Flavour and CP violation: SM

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**)

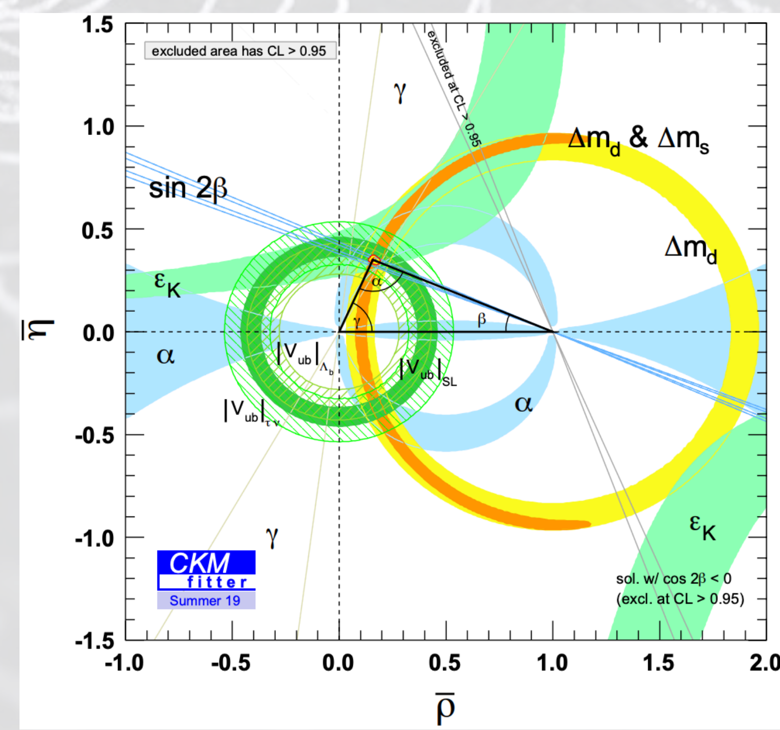
SM quark sector:

- 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}, …



See talks by Stéphane, Francesca and Radek

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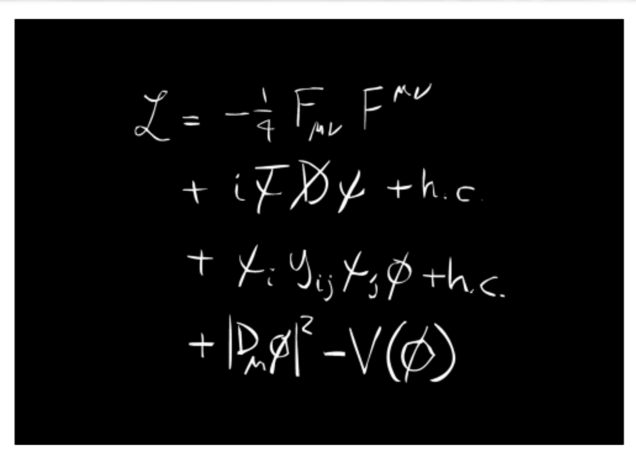

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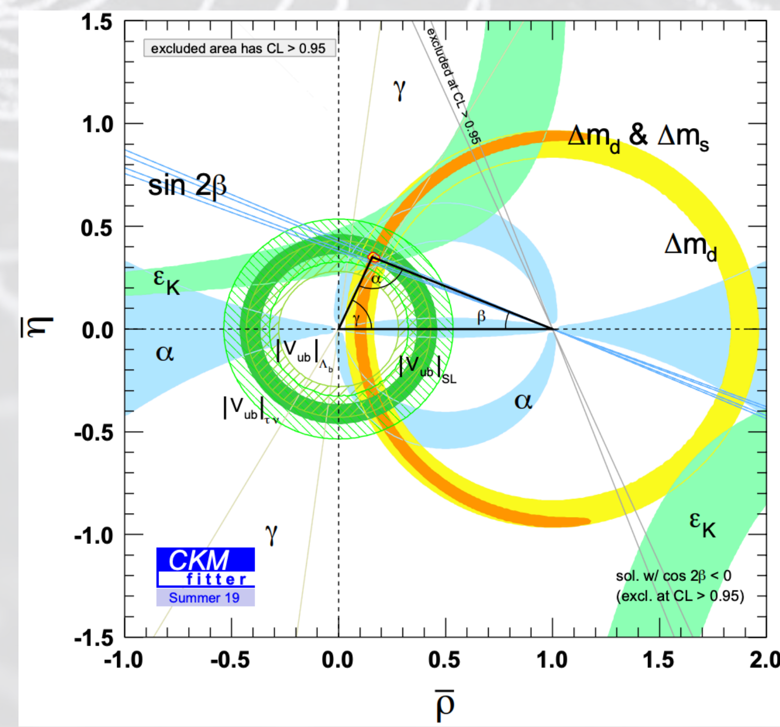
SM lepton sector: neutrinos are strictly massless

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



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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, …

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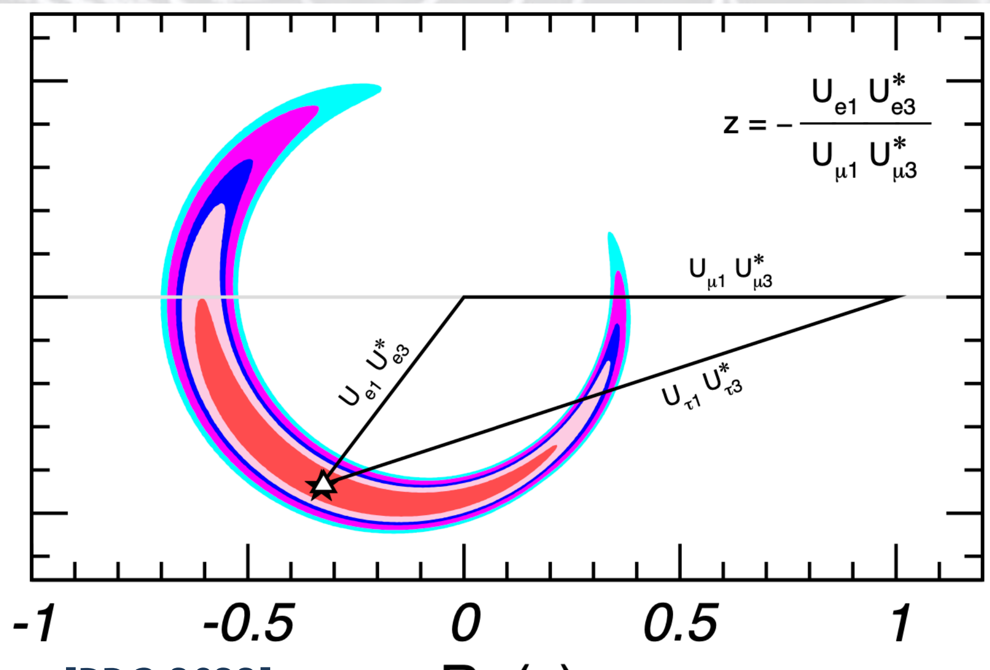
⇒Test SM symmetries with flavour observables:
(c)LFV, lepton flavour universality violation, …

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

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

See talks by Sara, Pierre and Evan



[PDG 2022]

Several puzzles remain:

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

Lepton flavour probes of New Physics

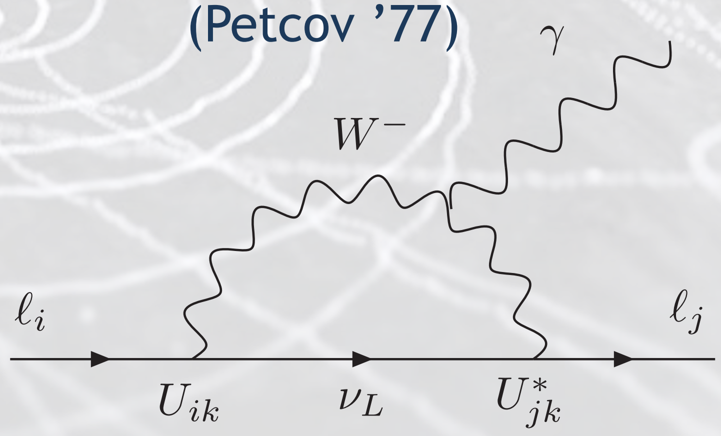
Neutrinos oscillate ⇒ **neutral lepton flavour violated, neutrinos are massive,**
new sources of **CPV?**

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

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

cLFV possible … but not observable! $\text{BR}(\mu \to e\gamma) \propto |\sum U^*_{\mu i} U_{ei} m^2_{\nu_i}/m^2_W| \simeq 10^{-54}$
(Petcov '77)

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



⇒ 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** $\Lambda_{\mathrm{EW}} \rightsquigarrow \Lambda_{\mathrm{GUT}}$

$\Rightarrow$ 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)

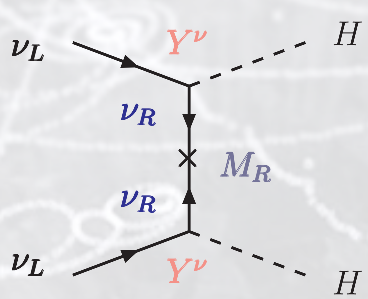
Disentangle seesaw mass models — more correlations

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

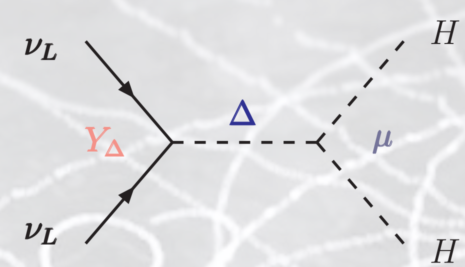
  In the absence of direct NP discovery - **correlations** might allow to disentangle models and provide important **complementary information** to direct searches!

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

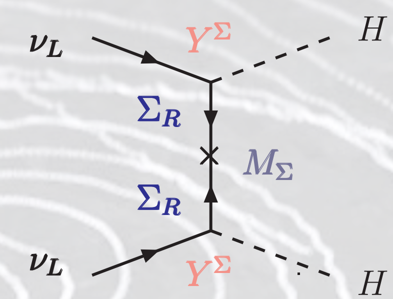
  ratios of observables to **identify seesaw mediators** & constrain their **masses!**



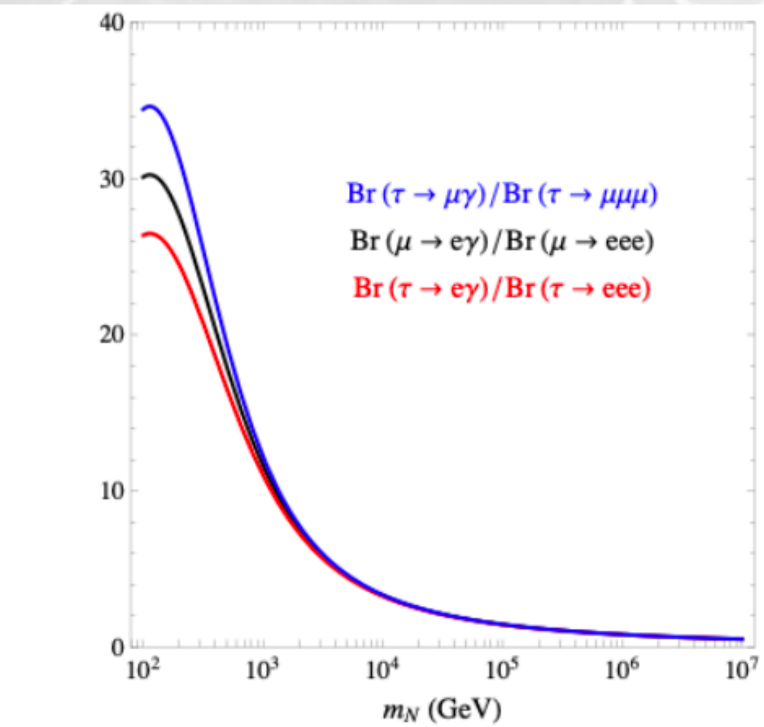
Type I (fermion singlet)

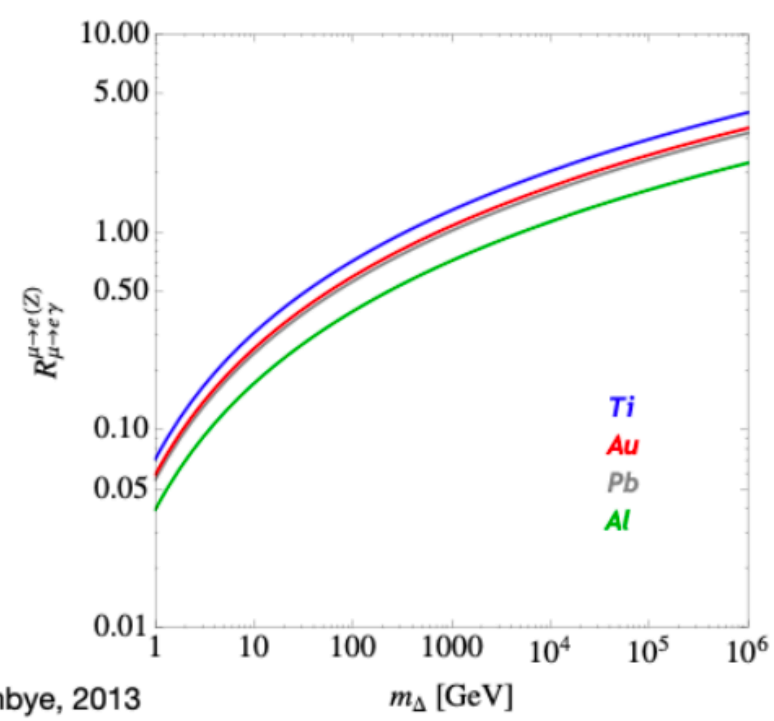


Type II (scalar triplet)



Type III (fermion triplet)





Hambye, 2013

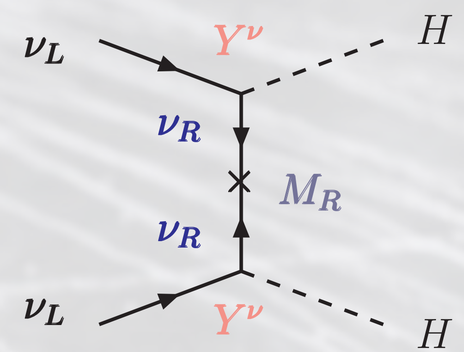
$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{BR}(\mu\to 3e)} = 1.3\times 10^{-3}$$

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

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

Type I seesaw

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



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

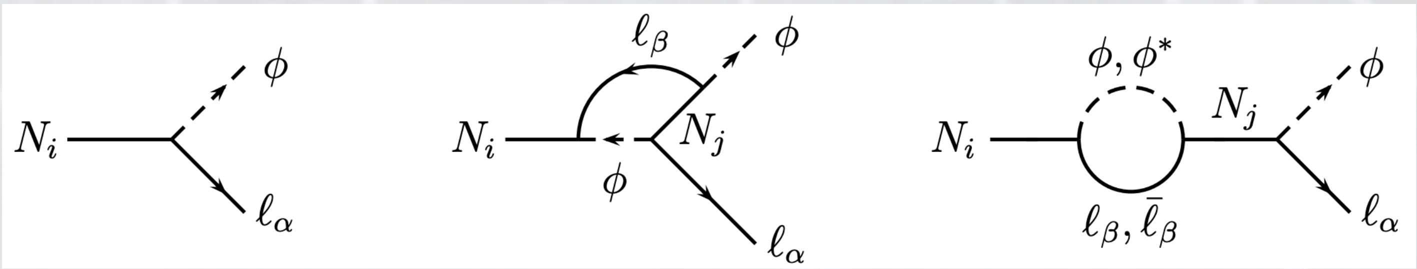
Generate "naturally" small masses of the active neutrinos

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

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

Leptogenesis in a nutshell: generate lepton asymmetry ⇒ convert into baryon asymmetry
(See talk by Stéphane Lavignac and lectures by Julia Harz)

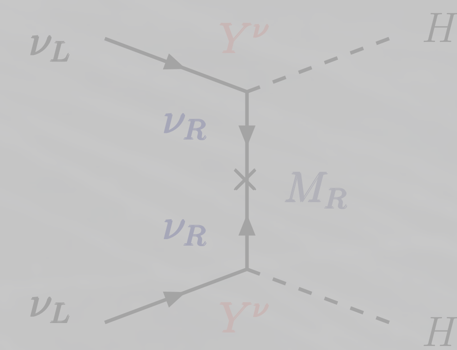
CP-violating out of equilibrium decay ⇒ create lepton asymmetry (at a high scale)



Interference of tree & loop diagrams

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

Heavy right-handed Majorana neutrinos
Coupled via Higgs to SM-like neutrinos



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What is the phenomenological impact of these phases?

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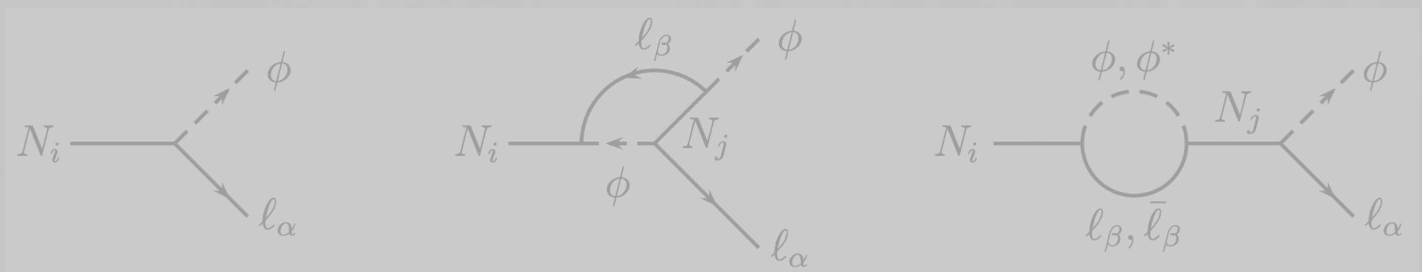

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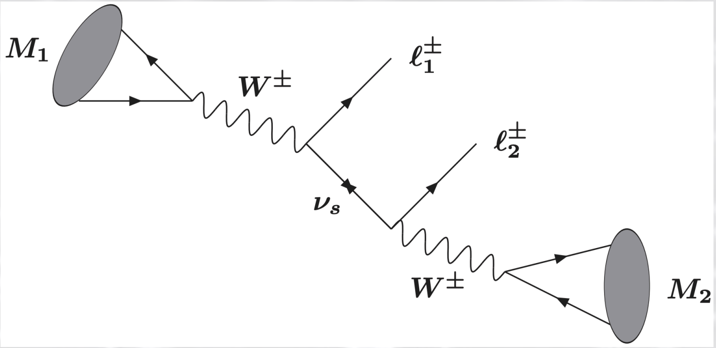
CPV phases and LNV

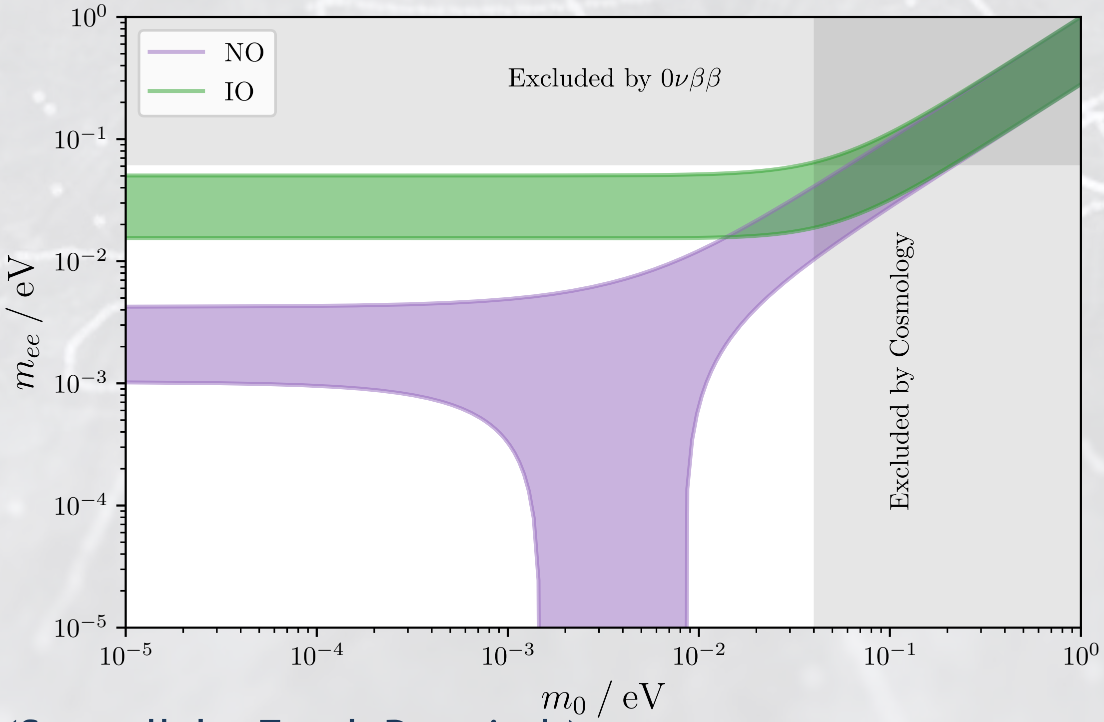
If neutrinos are **Majorana**, total **lepton number** is violated @ tree-level

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

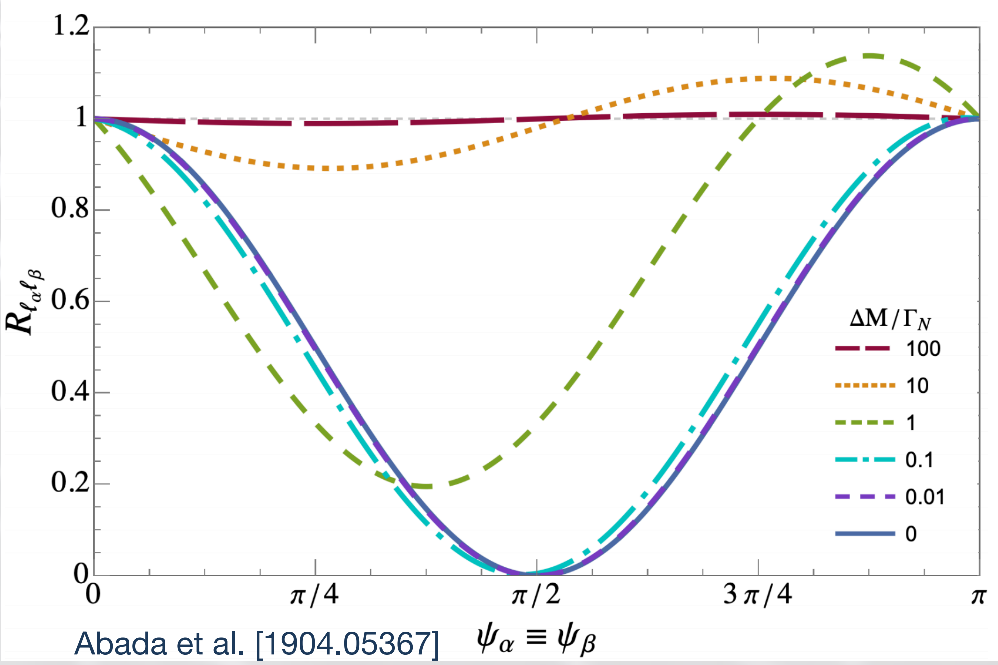
Massive (and mixing) neutrinos: new sources of **CP violation**



CP violating phases are known to play a crucial role:



(See talk by Frank Deppisch)



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]

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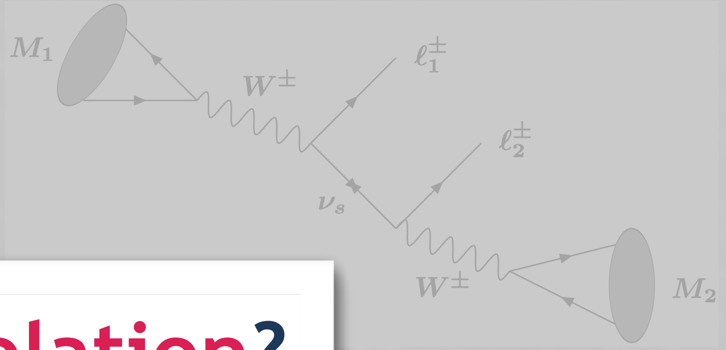
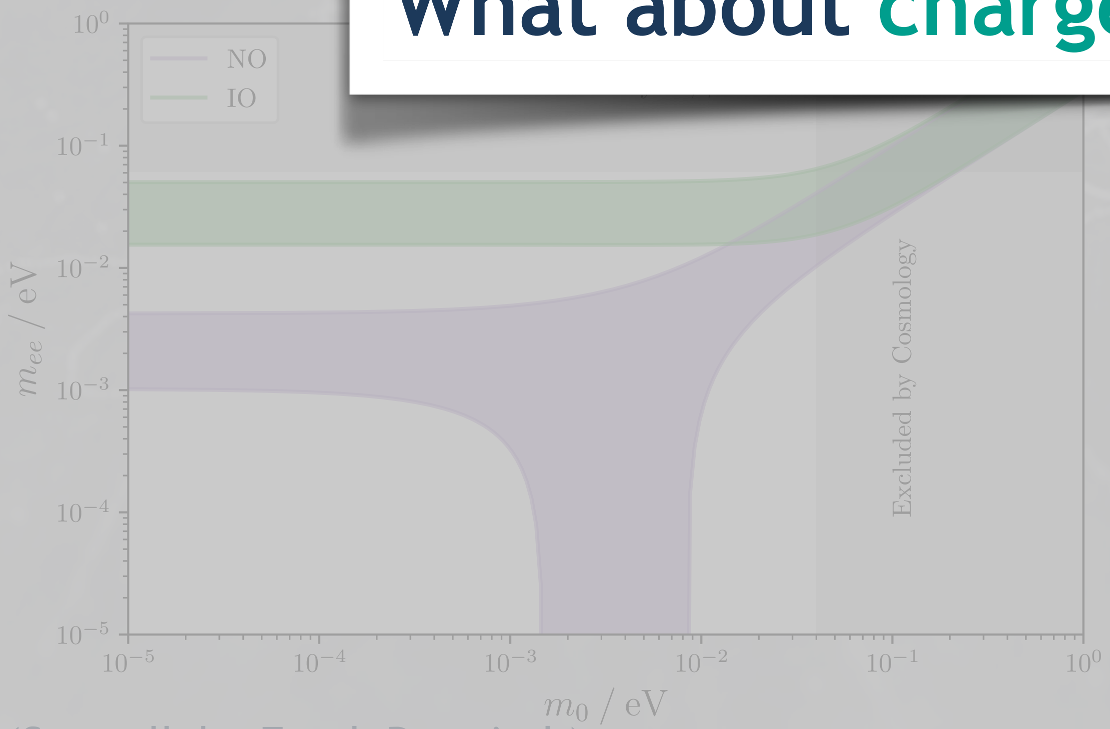


What about charged lepton flavour violation?



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Abada et al. [1904.05367]

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

interaction basis ⇝ **physical** basis $\quad |n_L\rangle = \mathcal{U}_{5\times5}|\nu_i\rangle$

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 $\boldsymbol{W}$ and $\boldsymbol{Z}$ 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)

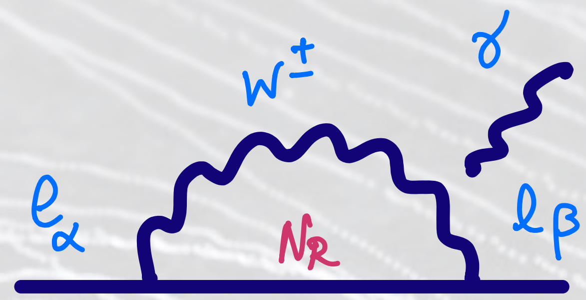
The impact of CP violating phases

cLFV processes mediated by HNL at loop-level

Consider **"3+2" toy model** (addition of **2 heavy sterile** states; leptonic mixing $\mathcal{U}_{5\times5}$, **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 $\sin\theta_{\alpha 4} \approx \sin\theta_{\alpha 5} \ll 1$

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

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

(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

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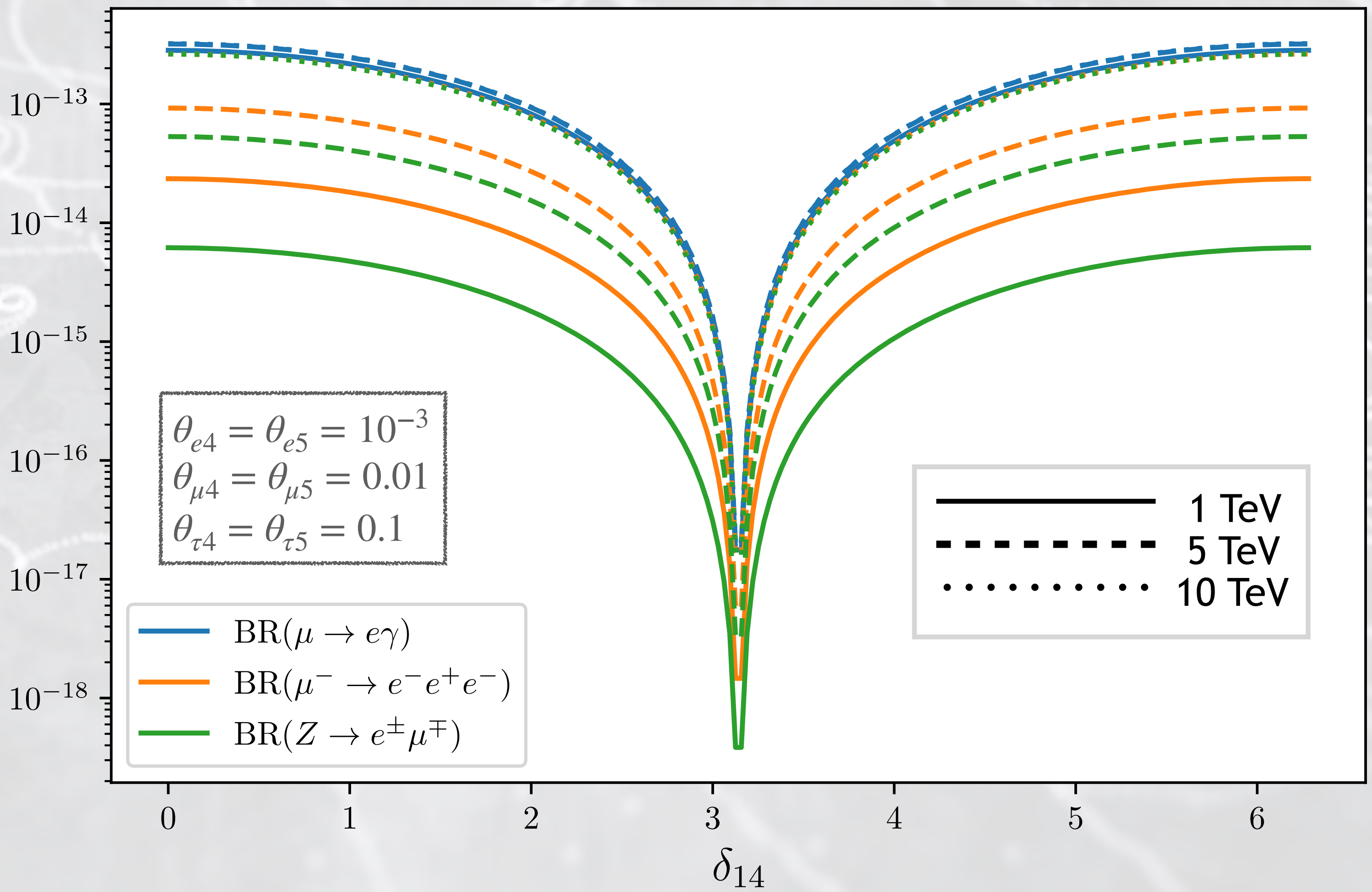
Abada, **JK,** Teixeira [2107.06313]



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

IJS

The impact of CP violating phases: Majorana

cLFV processes mediated by HNL at loop-level

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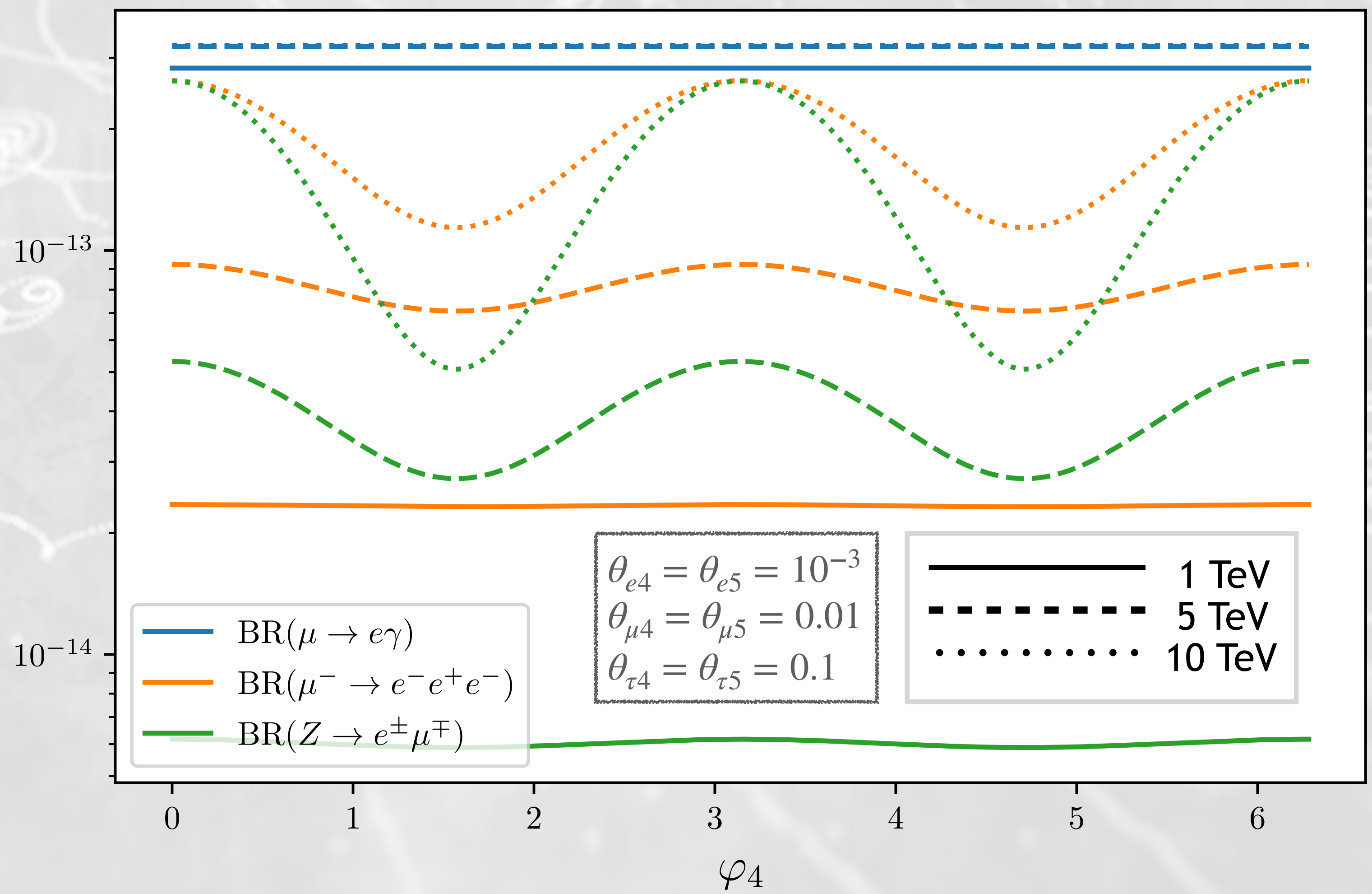

⇒Milder dependence, γ-penguin independent of Majorana phases

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...*

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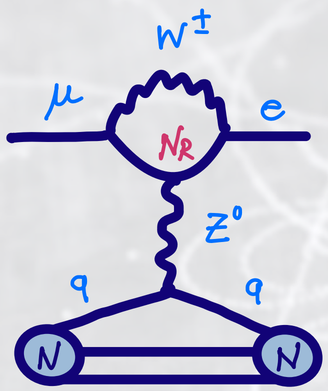
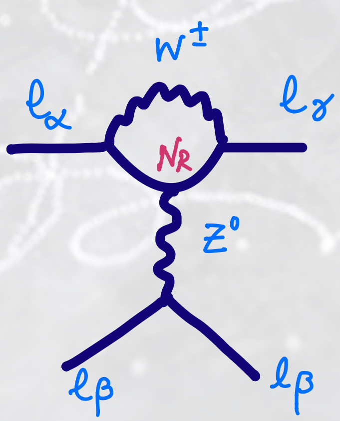


Observables dominated by **common topology: Z-penguins**

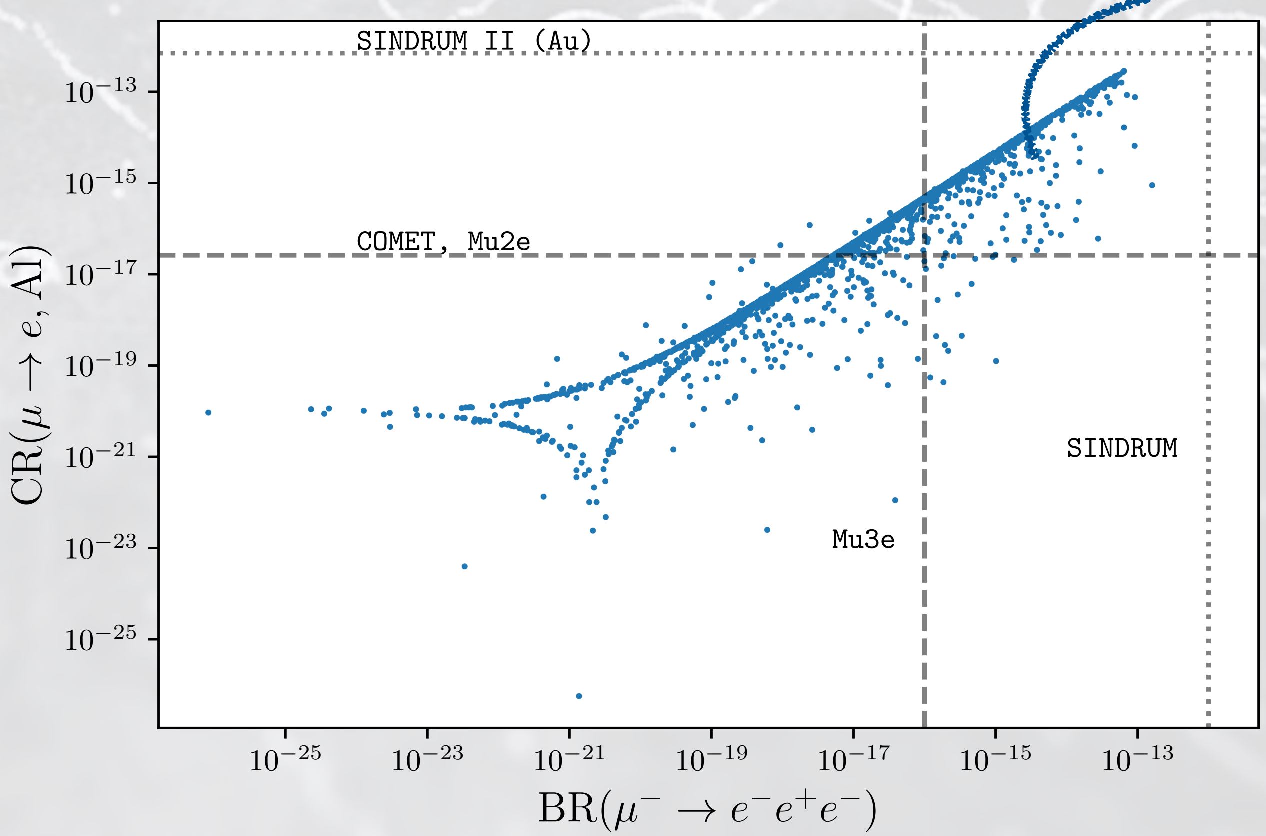
$\mu - e$ **conversion in nuclei**

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



$m_4 = m_5 = 1$ TeV

- CP conserving



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

Strong correlation (CP conserving)

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

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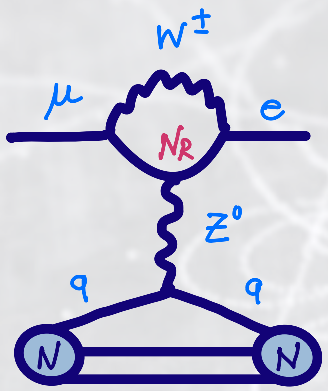

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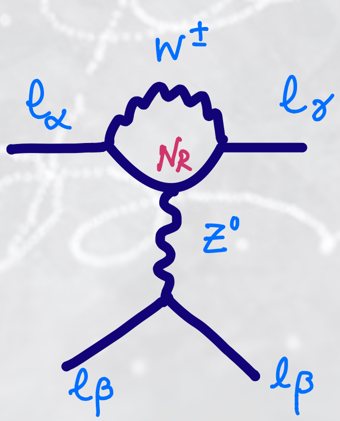
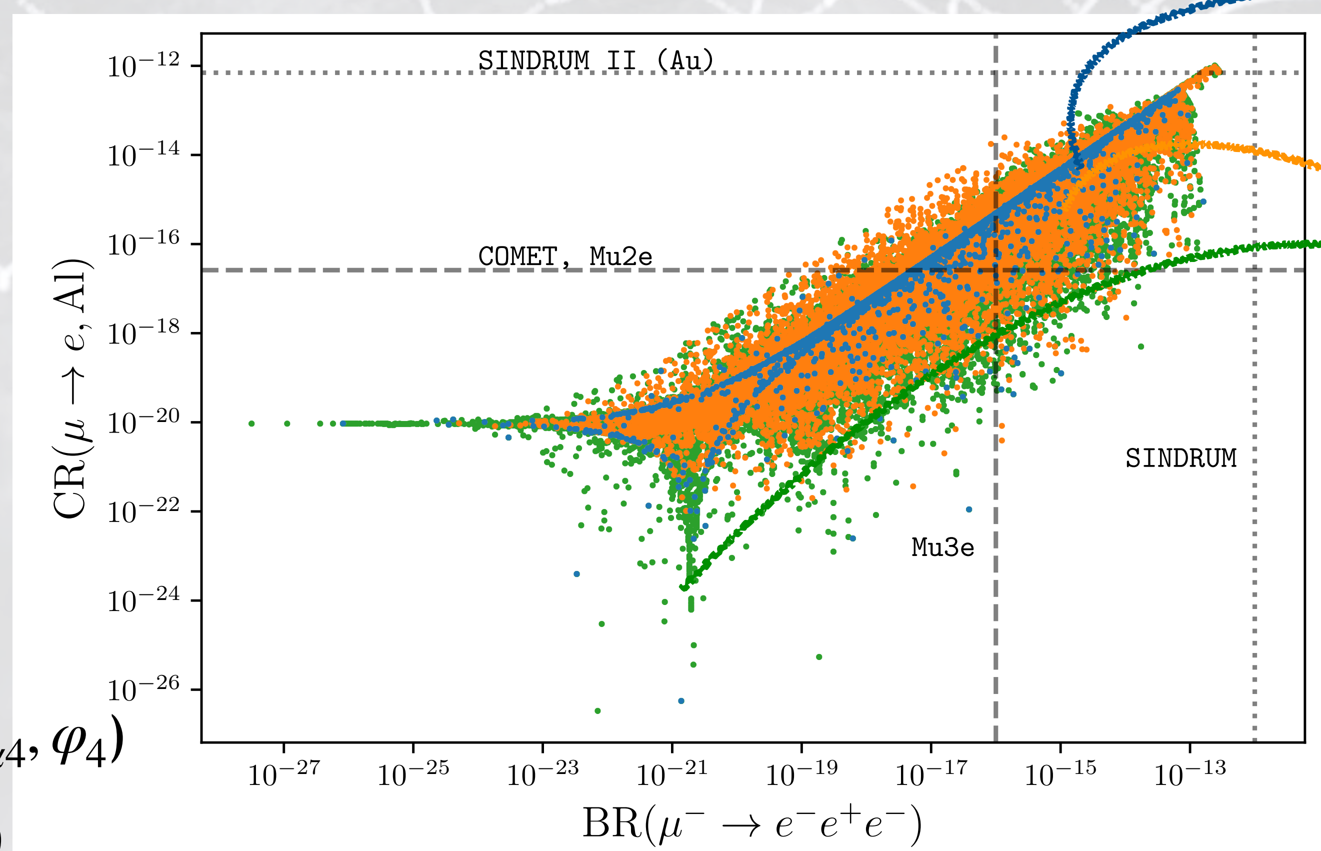


$m_4 = m_5 = 1$ TeV

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



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

Strong correlation
(CP conserving)

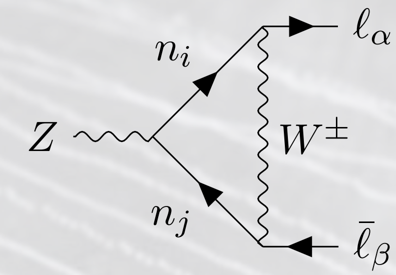
Loss of correlation!
(CP violating)

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

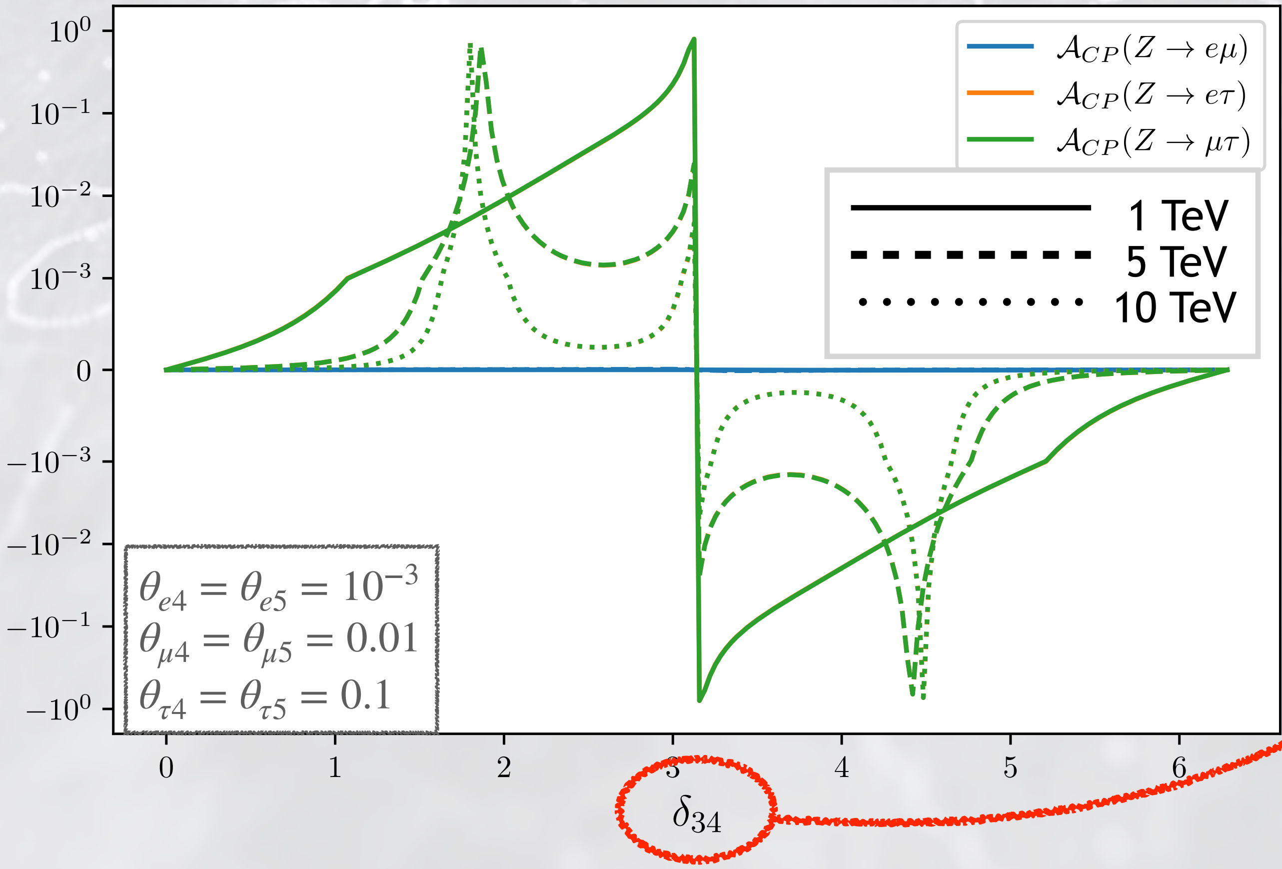
CP-asymmetries

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

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



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

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

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

(Higgs decay asymmetries accidentally negligible)

CP-asymmetries

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

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]

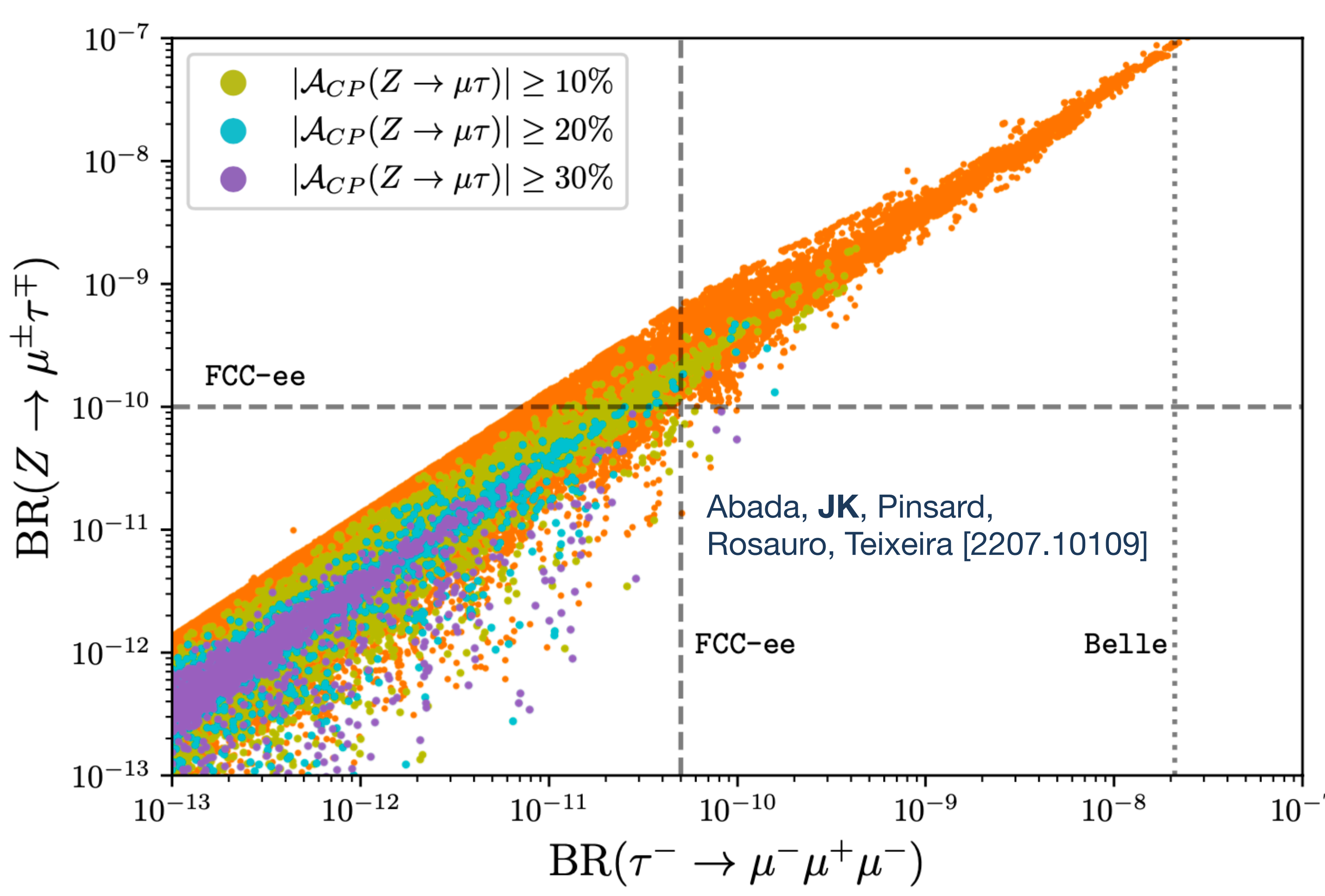
Consider **CP-asymmetries:** $\mathscr{A}_{CP}(Z \to \ell_\alpha \ell_\beta) = \dfrac{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) - \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}{\Gamma(Z \to \ell_\alpha^+ \ell_\beta^-) + \Gamma(Z \to \ell_\alpha^- \ell_\beta^+)}$

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

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

Strong phenomenological impact!

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

See also Ema's poster :)

IJS

Conclusion

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

⇒ massive and oscillating neutrinos open the door to LFV and

new sourc... f CPV

New CPV phases from HNL play a cr... s:

⇒ Inte...

...s can be broken

Strong pheno... ...ological 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!

Backup

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:** $M \to \ell_\alpha^\pm \ell_\beta^\mp, M \to M' \ell_\alpha^\pm \ell_\beta^\mp$;

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

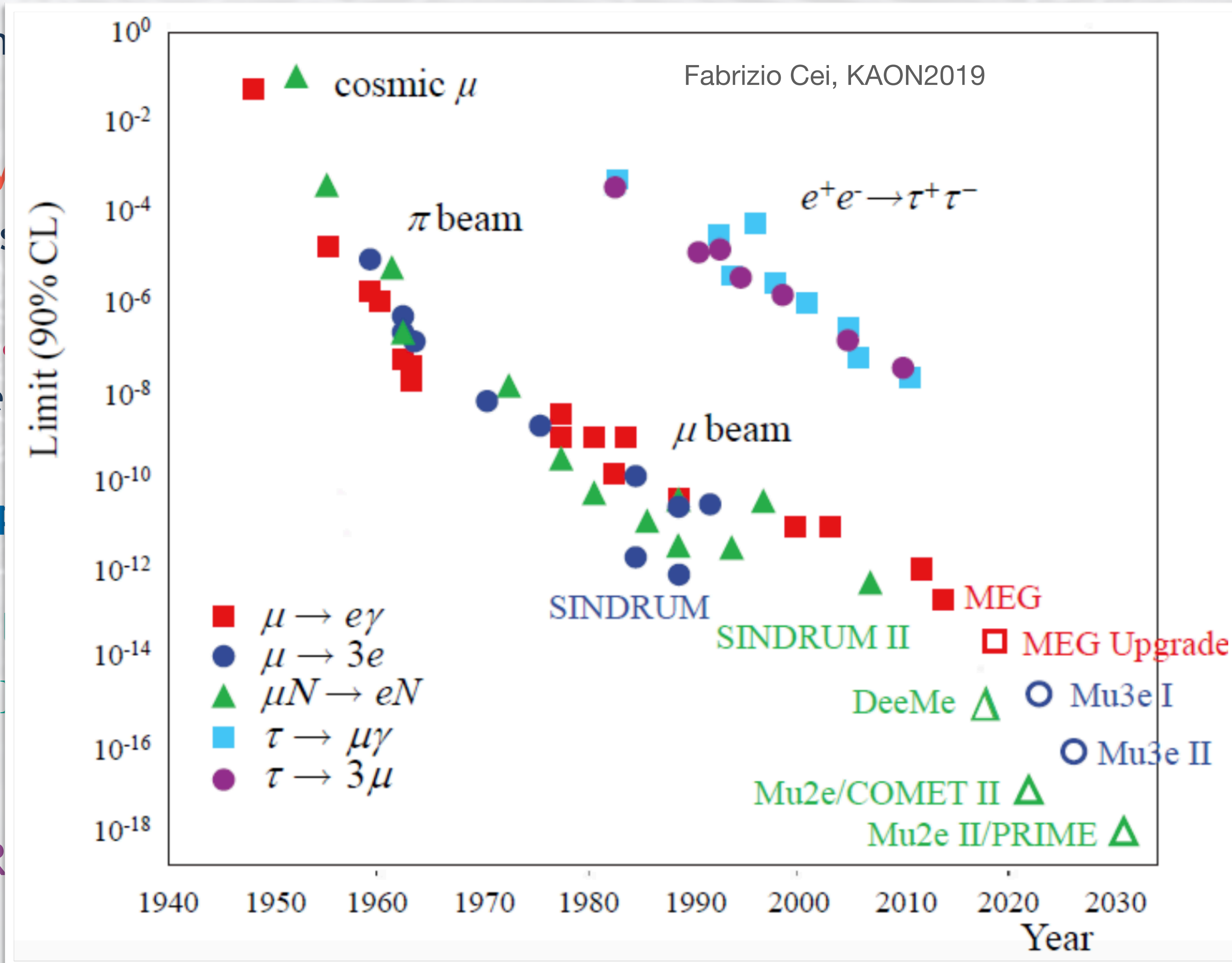
- **cLFV @ higher energies:** $Z \to \ell_\alpha^\pm \ell_\beta^\mp, H \to \ell_\alpha^\pm \ell_\beta^\mp$, high-p_T di-lepton tails $pp \to \ell_\alpha^\pm \ell_\beta^\mp$,

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

cLFV observables across all sectors and energies

Any **cLFV** sign

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



Low-scale type I seesaw

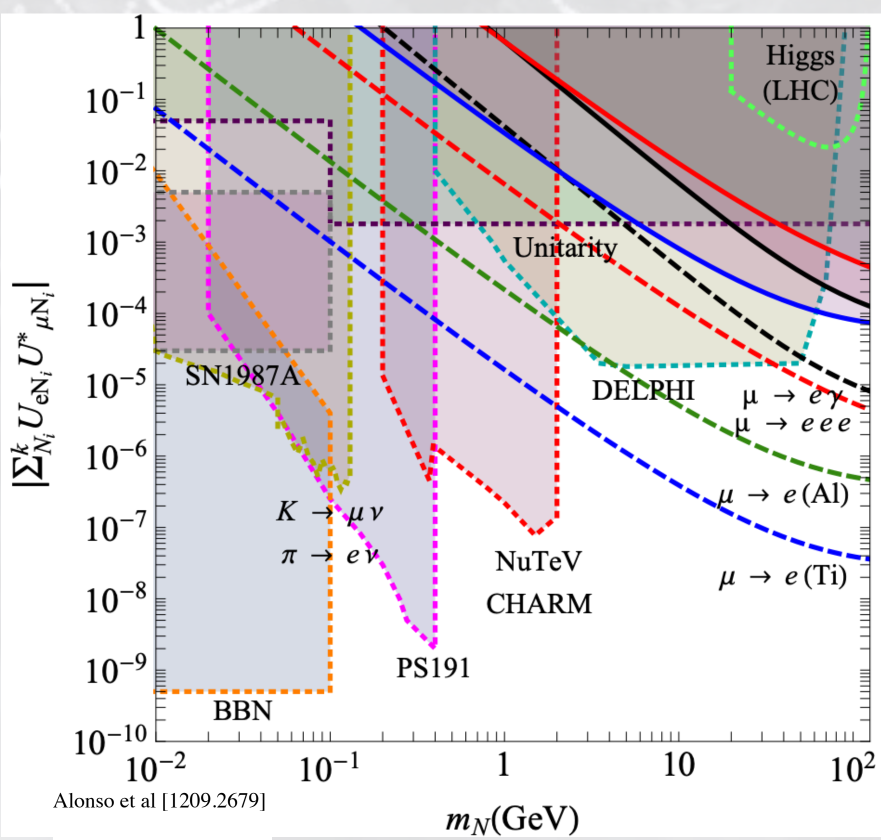
Extend SM with 3 "heavy" **RH Majorana neutrinos:** $\mathrm{MeV} \lesssim m_{N_i} \lesssim 1 - 100\mathrm{TeV}$

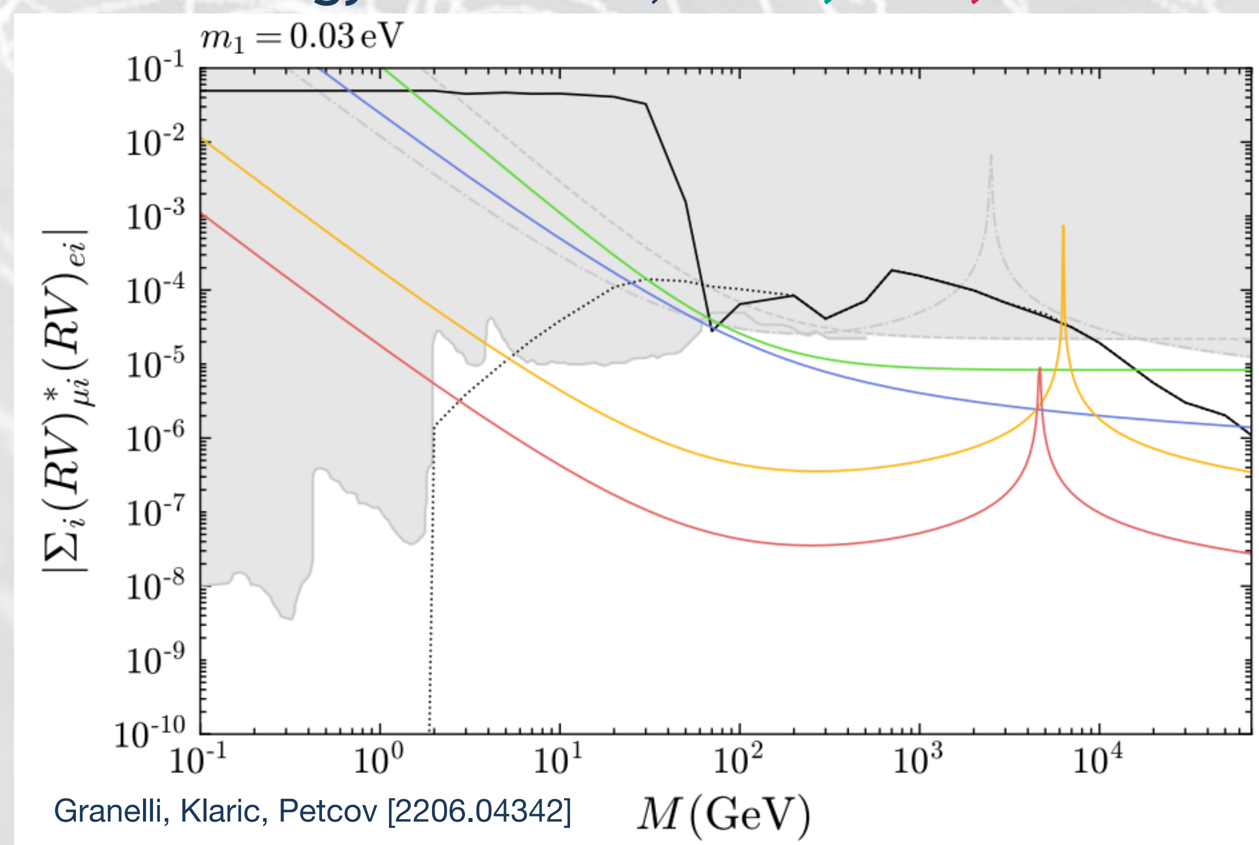
Masses and mixings: $m_\nu \simeq -v^2 Y_\nu^T M_N^{-1} Y_\nu$, $\mathcal{U}^T \mathcal{M}_\nu^{6\times 6} \mathcal{U} = \mathrm{diag}(m_i)$

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

Heavy states not decoupled ⇒ neutral and charged lepton currents modified

⇒ very rich phenomenology: colliders, cLFV, LNV, …



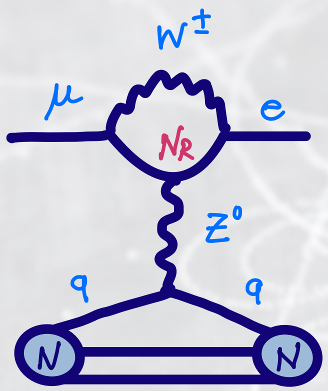


The impact of CP violating phases — no more correlations

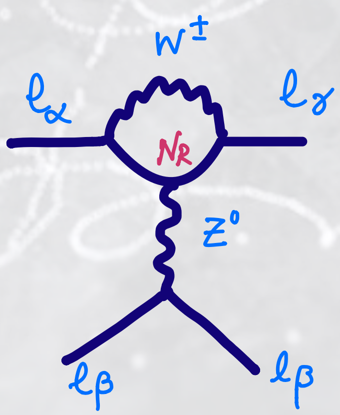
cLFV signatures: ratios of observables to **identify mediators** & constrain their **masses!**

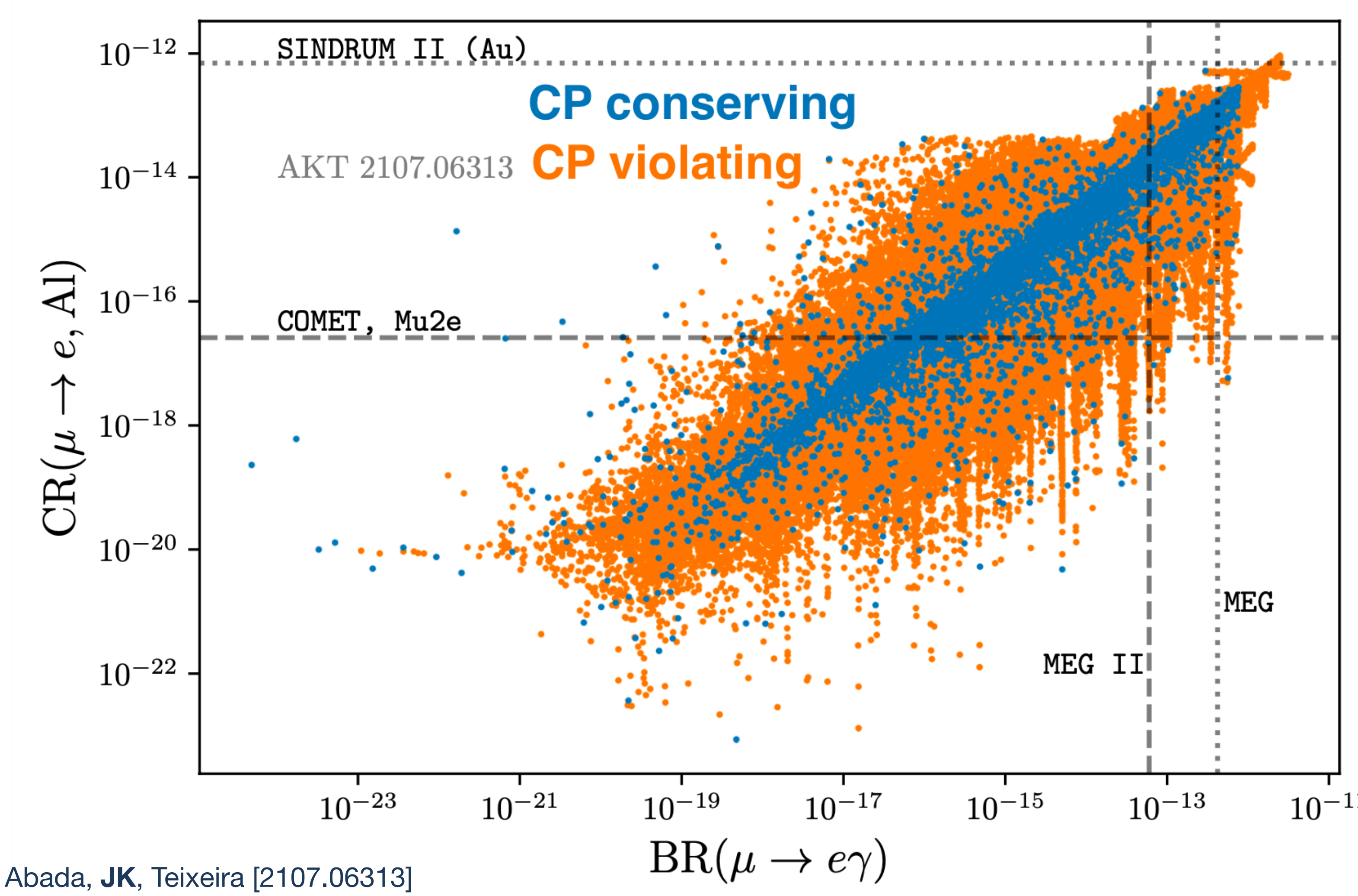
But - CP violating phases do matter! *And impact naïve expectations...*

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





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

Also vary mass splitting,

all angles/phases independently

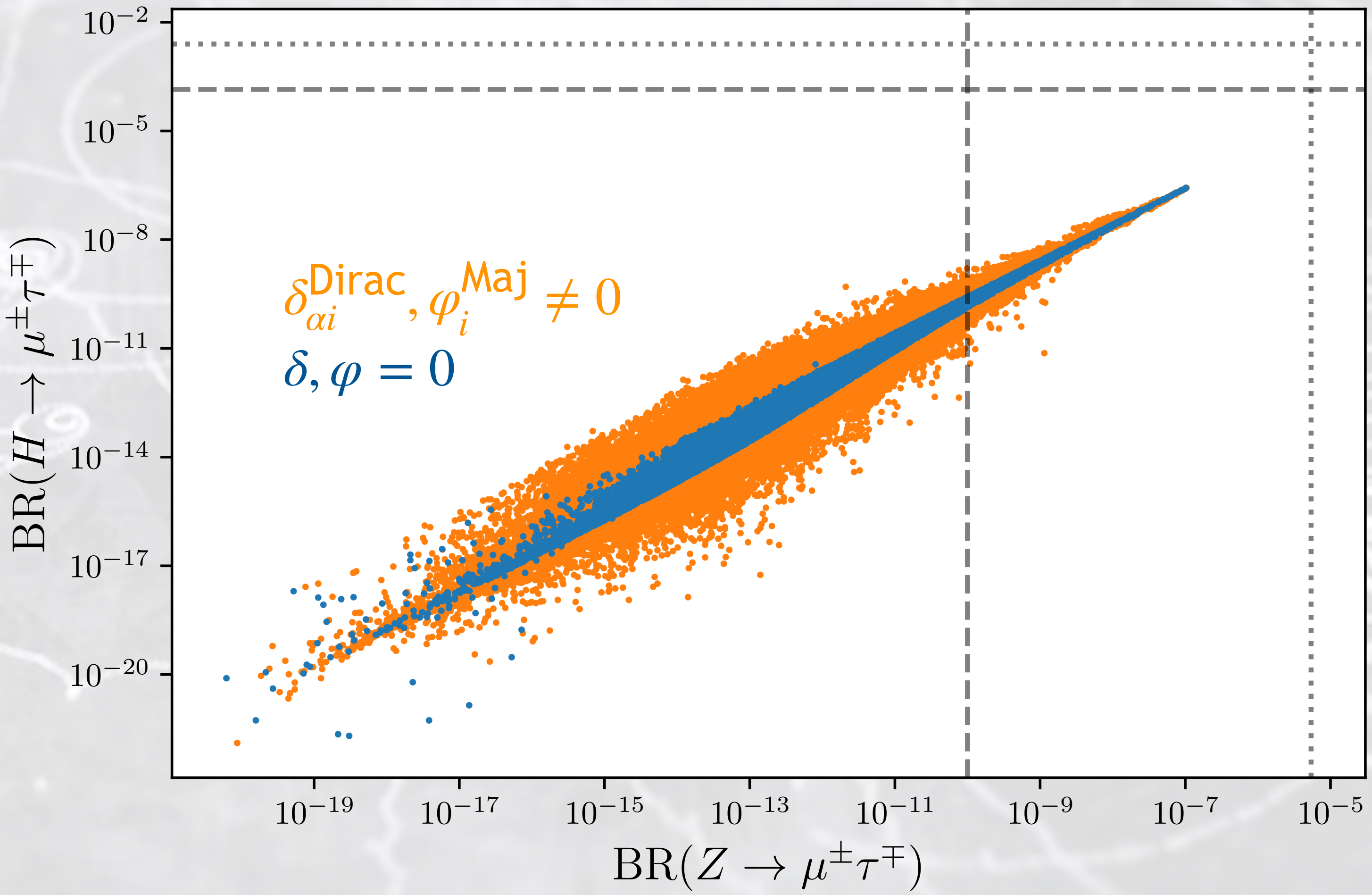
⇒ Generic effect of **CPV phases!**

cLFV: Z and Higgs

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**

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...*

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

	$\mathrm{BR}(\mu \to e\gamma)$	$\mathrm{BR}(\mu \to 3e)$	$\mathrm{CR}(\mu - e,\, \mathrm{Al})$	$\mathrm{BR}(\tau \to 3\mu)$	$\mathrm{BR}(Z \to \mu\tau)$
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) ⇒ *not* necessarily ***disfavour*** **HNL extension!**