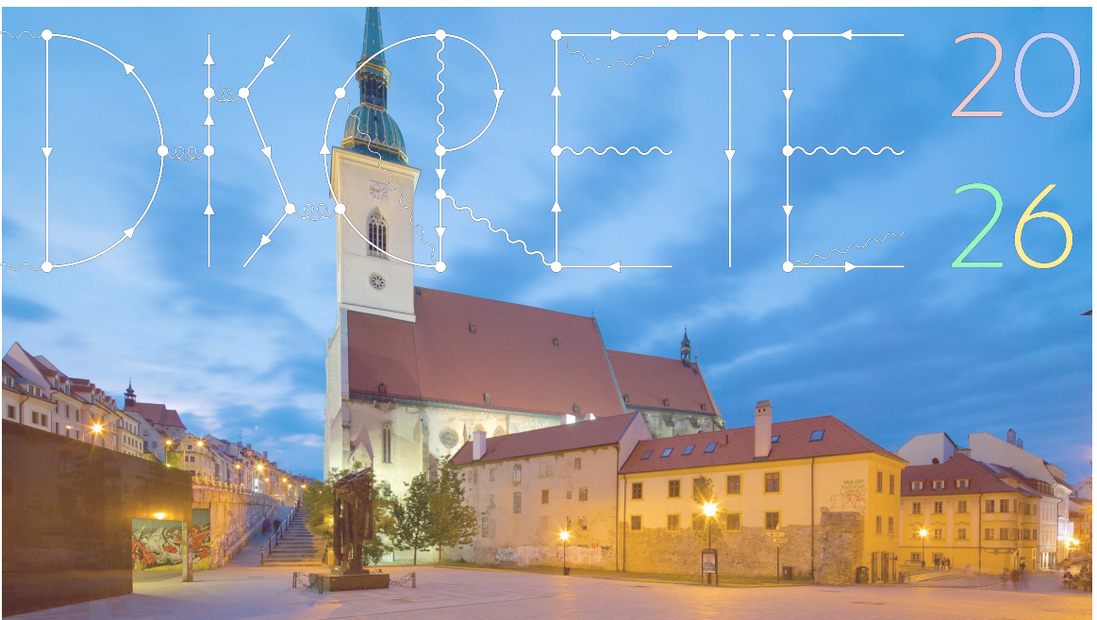


cLFV in HNL extensions of the SM: the role of CP violation

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CNRS / IN2P3



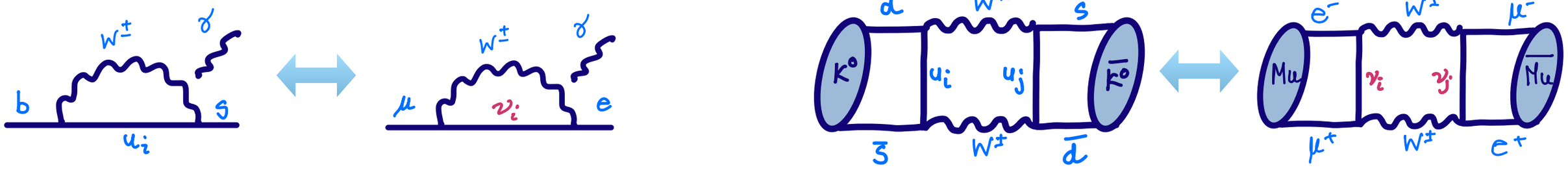
Discrete 2026

Bratislava, 13 November 2026

Lepton flavours: from ν oscillations...

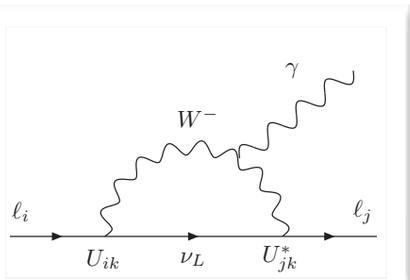
Neutrino oscillations: 1st laboratory **evidence of NP!** SM description **insufficient...**

Violation of lepton flavour in the neutral lepton sector opens a wide door to **flavour violation in the charged lepton sector!**



How general is this once we extend the SM to accommodate $\nu_\alpha \nleftrightarrow \nu_\beta$ *?*

In the most **minimal extension** SM_{m_ν} [SM_{m_ν} = "ad-hoc" m_ν (Dirac), U_{PMNS}]



total **lepton number** still **conserved**

lepton EDMs beyond observation (2-loop contributions from δ_{CP})

cLFV possible... but **not observable!!** **BR**$(\mu \to e\gamma) \sim 10^{-54}$

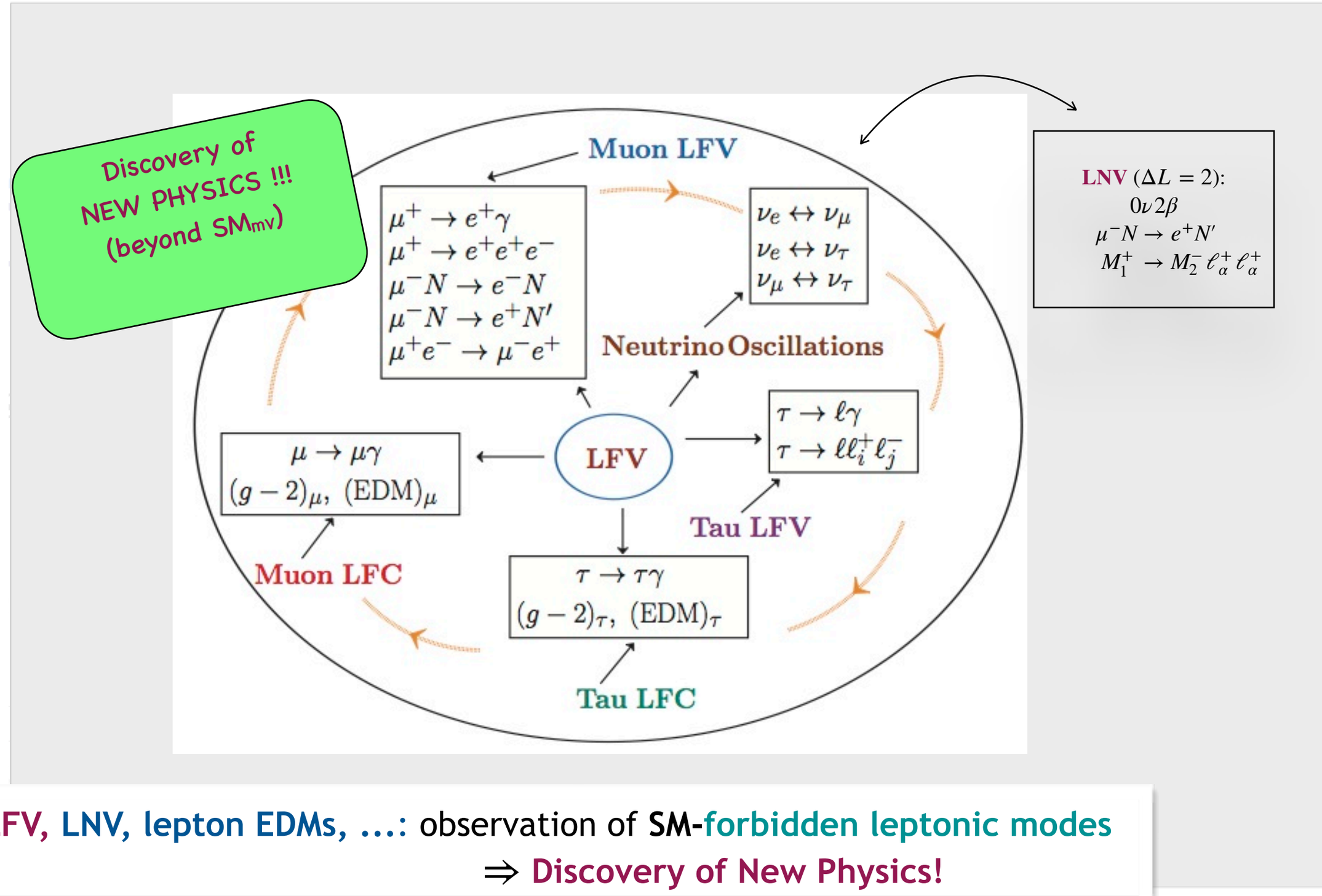
[GIM-like, tiny m_ν...]

cLFV, LNV, lepton EDMs, ...: observation of **SM-forbidden leptonic modes**

$\Rightarrow$ **Discovery of New Physics!**

Lepton flavours: from ν oscillations...

Neutrino oscillations: 1st laboratory **evidence of NP!** SM description **insufficient...**



cLFV, LNV, lepton EDMs, ...: observation of **SM-forbidden leptonic modes**

⇒ **Discovery of New Physics!**

Flavour'ed paths to New Physics

Additional strong arguments in favour of New Physics!

A number of **theoretical** caveats... and **observations unaccounted for in the SM:**

baryon asymmetry of the Universe, viable dark matter candidate,

neutrino oscillations *(and some "tensions"...)*



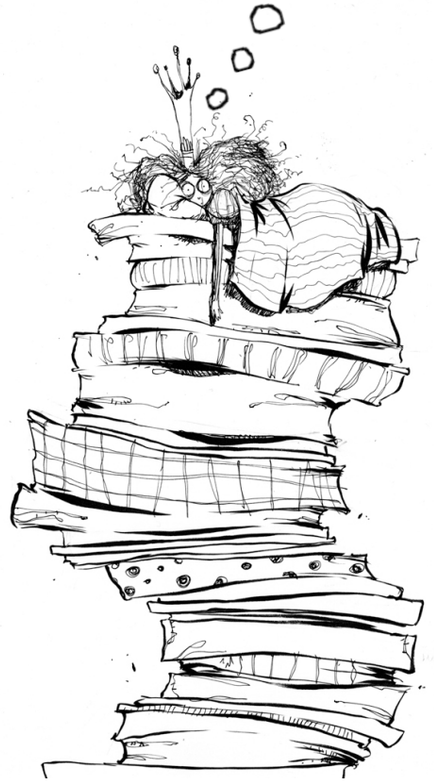
But - **which** NP model?

Realised at which **scale** Λ_{NP}? How to unveil it?

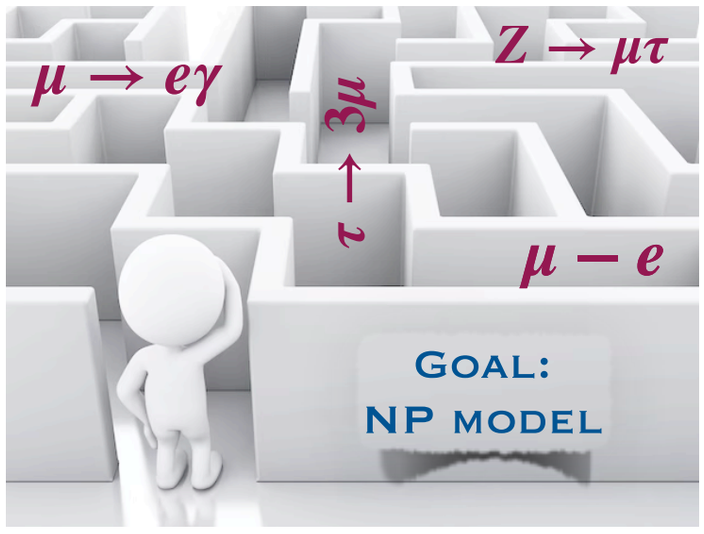
⇒ **Numerous hints from lepton physics, fantastic prospects!**

Well-motivated **NP models** for ν **mass generation!**

- **cLFV observables - paths to New Physics**
- Extending the SM: **sterile fermions** and ν **mass generation**
- **cLFV from Heavy Neutral Leptons: the role of CPV phases (and new observables)**

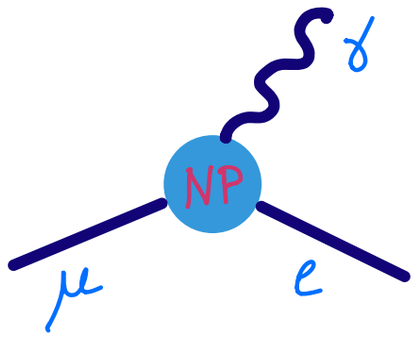


Probing power of cLFV - from experimental reach to models of NP



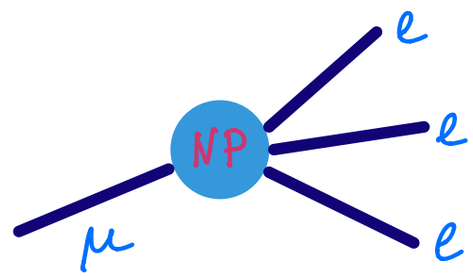
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cLFV muon decays



- cLFV decay: $\mu^+ \to e^+\gamma$
  - **Event signature:** $E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)
    Back-to-back $e^+ - \gamma$ ($\theta \sim 180°$); Time coincidence
  - **Status:** $\mathbf{BR}(\mu^+ \to e^+\gamma) \leq 4.2 \times 10^{-13}$ (90% CL) [MEG Coll., 1605.05081]
    MEG II (@ PSI): $\mathbf{BR}(\mu^+ \to e^+\gamma) \leq 6 \times 10^{-14}$ [MEG II Coll., 2201.008200]
    very hard to go beyond 10^{-15} without conceptually different approach

- cLFV decay: $\mu^+ \to e^+e^-e^+$
  - **Event signature:** $\Sigma E_e = m_\mu$; $\Sigma \vec{P}_e = \vec{0}$
    common vertex; Time coincidence
  - **Status:** $\mathbf{BR}(\mu^+ \to e^+e^-e^+) \leq 1.0 \times 10^{-12}$ (90% CL) [SINDRUM Coll., '88]
    Mu3e (@ PSI): expected sensitivity $\mathcal{O}(10^{-15})$ for Phase I [Mu3e Coll., 2009.11690]
    with HIMB $\mathcal{O}(10^{-16})$ for Phase II [Aiba et al, 2111.05788]



cLFV in muonic atoms: $\mu - e$ conversion

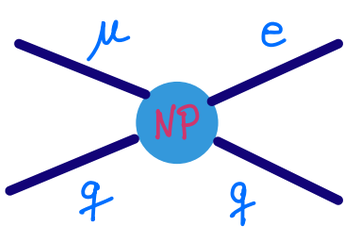
- **Muonic atoms:** 1s bound state formed when μ^- stopped in target

  SM allowed processes: decay in orbit (DIO) $\mu^- \to e^- \nu_\mu \bar{\nu}_e$

  nuclear capture $\mu^- + (A,Z) \to \nu_\mu + (A, Z-1)$

- In the presence of **New Physics** - **cLFV neutrinoless $\mu^- - e^-$ conversion**

$$\mu^- + (A,Z) \to e^- + (A,Z)$$



- **Event signature:** single mono-energetic electron

$$E_{\mu e} = m_\mu - E_B(A,Z) - E_R(A,Z) \quad \rightsquigarrow \quad E_{\mu e} \approx \mathcal{O}(100\ \text{MeV})\ \text{[Aluminium]}$$

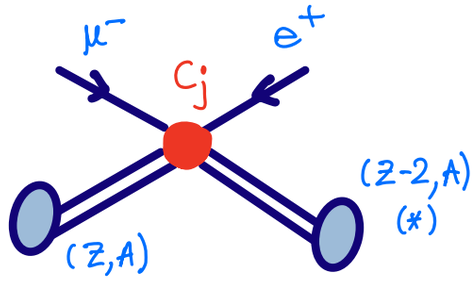
- **Status:** $\text{CR}(\mu^- - e^-, \text{Au}) \leq 7.1 \times 10^{-13}$ (90% CL) [SINDRUM II Coll., '06]

  Mu2e (@ FNAL) - $\mathcal{O}(10^{-17})$; COMET (@ JPARC) - $\mathcal{O}(10^{-15} - 10^{-17})$, ...

  [Bartoszek et al, 1501.05241] [Abramishvili et al, '20]

- **cLFV & LNV New Physics:** neutrinoless $\mu^- - e^+$ conversion

$$\mu^- + (A,Z) \to e^+ + (A, Z-2)^*$$



- **Event signature:** single positron - but **complex** energy spectrum

$$E^{N^*}_{\mu e} = m_\mu - E_B(A,Z) - E_R(A,Z) - \Delta_{Z-2^{(*)}}$$

cLFV tau decays: leptonic and more

Tau leptons - **heaviest of all charged leptons!** *Cannot have "intense tau beams"*

Copious production at B-factories (BaBar, Belle, LHCb, Belle II, ...)

Production and decay: $e^+ e^- \to \tau^+ \tau^-$ signal "hemisphere"

tagging "hemisphere" (e.g. $\tau^+ \to \bar{\nu}_\tau \nu_e e^+$)

- **Radiative decay:** $\tau^\pm \to \ell^\pm \gamma$
  - **Event signature:** $E_{\text{final}} - \sqrt{s}/2 = \Delta E \sim 0$; $M_{\text{final}} = M_{\ell\gamma} \sim m_\tau$

- **3-body leptonic decay:** $\tau^\pm \to \ell_i^\pm \ell_j^\mp \ell_k^\pm$
  - **Event signature:** $E_{3\ell} - \sqrt{s}/2 \sim 0$; $M_{3\ell} \sim m_\tau$

- **Semi-leptonic cLFV tau decays**

  2-body final state: $\tau \to \ell h^0$ & **3-body** final state: $\tau \to \ell h_i h_j$ $(h \leftrightsquigarrow \pi^\pm, K^\pm, K_s^0)$

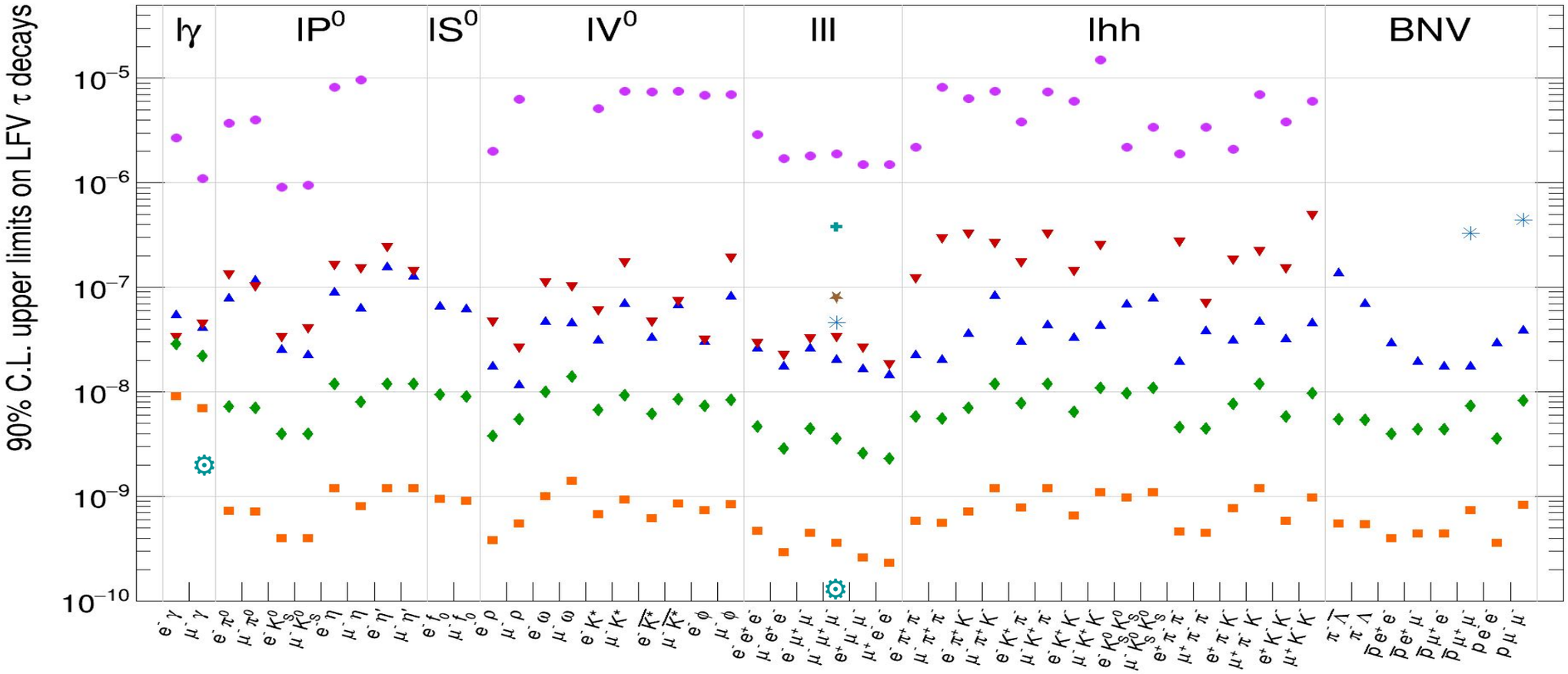
- **cLFV exotic modes** (also lepton & baryon number violating)

  $\tau^- \to \ell^+ h_i^\pm h_j^\pm$ $(h \leftrightsquigarrow \pi^\pm, K^\pm)$; $\tau^- \to \Lambda h^-$ $(h \leftrightsquigarrow \pi^\pm, K^\pm)$; $\tau \to p \ell_i \ell_j$

cLFV tau decays: experimental status

Tau cLFV - extensive array of modes!

$\tau \to \ell\gamma$ $\quad \tau \to \ell M(P,S,V)$ $\quad \tau \to \ell\ell\ell$ $\quad \tau \to \ell MM$



⇒ **Tau cLFV:** increasingly good prospects!

At **B-factories** (LHCb, **Belle II**)

and also at **FCC-ee** ⚙

Decay	Present bound	FCC-ee sensitivity ⚙
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}

cLFV collider searches

- **SM "heavy" states - Higgs, Z-bosons, top** quarks ... and **(semi)leptonic meson** decays!

Top-quark decays @ LHC: BR($t \to u\,e\,\mu$) $\lesssim 10^{-7}$; BR($t \to c\,e\,\mu$) $\lesssim 10^{-6}$

Z^0 decays ⇒ searched for at **LEP & LHC;** excellent prospects for **FCC-ee (@Z-pole)!**

Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau \mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}

Higgs decays ⇒ profit from a **Higgs factory (LHC)!**

BR($H \to \tau\mu$) $\lesssim 2.8 \times 10^{-3}$, BR($H \to \tau e$) $\lesssim 4.7 \times 10^{-3}$ (ATLAS)

BR($H \to \tau\mu$) $\lesssim 1.5 \times 10^{-3}$, BR($H \to \tau e$) $\lesssim 2.2 \times 10^{-3}$ (CMS)

In the future, **e^+e^- colliders** (circular or linear) offer **striking advances** (even $e\mu$):

BR($H \to e\mu$) $\lesssim 1.2 \times 10^{-5}$ @ FCC-ee/CEPC, BR($H \to e\mu$) $\lesssim 2.1 \times 10^{-5}$ @ ILC

BR($H \to \tau\ell$) $\lesssim 1.5 \times 10^{-4}$ @ FCC-ee/CEPC, BR($H \to \tau\ell$) $\lesssim 2.4 \times 10^{-4}$ @ ILC

- Further **future** colliders: **Muon collider, ..., asymmetric muon collider ($e\mu$) - μTRISTAN!**

The EFT approach to flavour

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

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

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

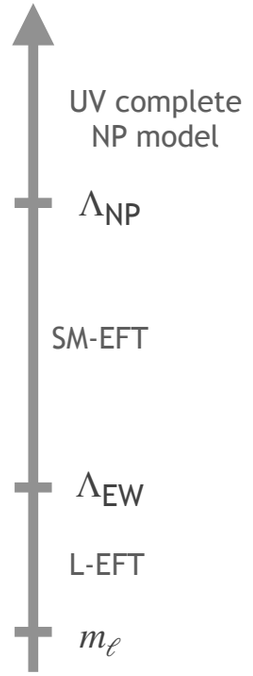
(unknown) NP **scale**

effective coefficients

effective **operators**

$\mathcal{O}^5 \rightsquigarrow$ Weinberg operator (m_ν)

$\mathcal{O}^6 \rightsquigarrow$ flavoured contributions (among many others!)



For lepton flavours, many potential contributions:

$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \frac{\mathscr{C}_5 \mathcal{O}^5}{\Lambda_{\text{LNV}}}(m_\nu) + \boxed{\frac{\mathscr{C}_6 \mathcal{O}^6}{\Lambda^2_{\text{cLFV}}}(\ell_\alpha \leftrightarrow \ell_\beta)} + \dots + \frac{\mathscr{C}_7 \mathcal{O}^7}{\Lambda'^3_{\text{LNV}}}(0\nu 2\beta) + \dots$$

⇒ **Experimental data to constrain** $\mathscr{C}_{ij}$ and/or **infer sensitivity** of process to Λ_{NP}

Cast **current cLFV data** in terms of $\mathscr{C}^6_{ij}$ and Λ^2_{NP} ($\Lambda_{\text{NP}} = \Lambda^{\text{NP}}_{\text{FV}}, \Lambda^{\text{NP}}_{\text{cLFV}}, \Lambda^{\text{NP}}_{\text{CPV}}, \Lambda^{\text{NP}}_{\text{LNV}} \dots$)

minimal assumptions: "reachable" $\Lambda_{\text{NP}} \rightarrow$ constrain $\mathscr{C}^6_{ij}$

"natural" $\mathscr{C}^6_{ij} \approx 1 \rightarrow$ hint on Λ_{NP}

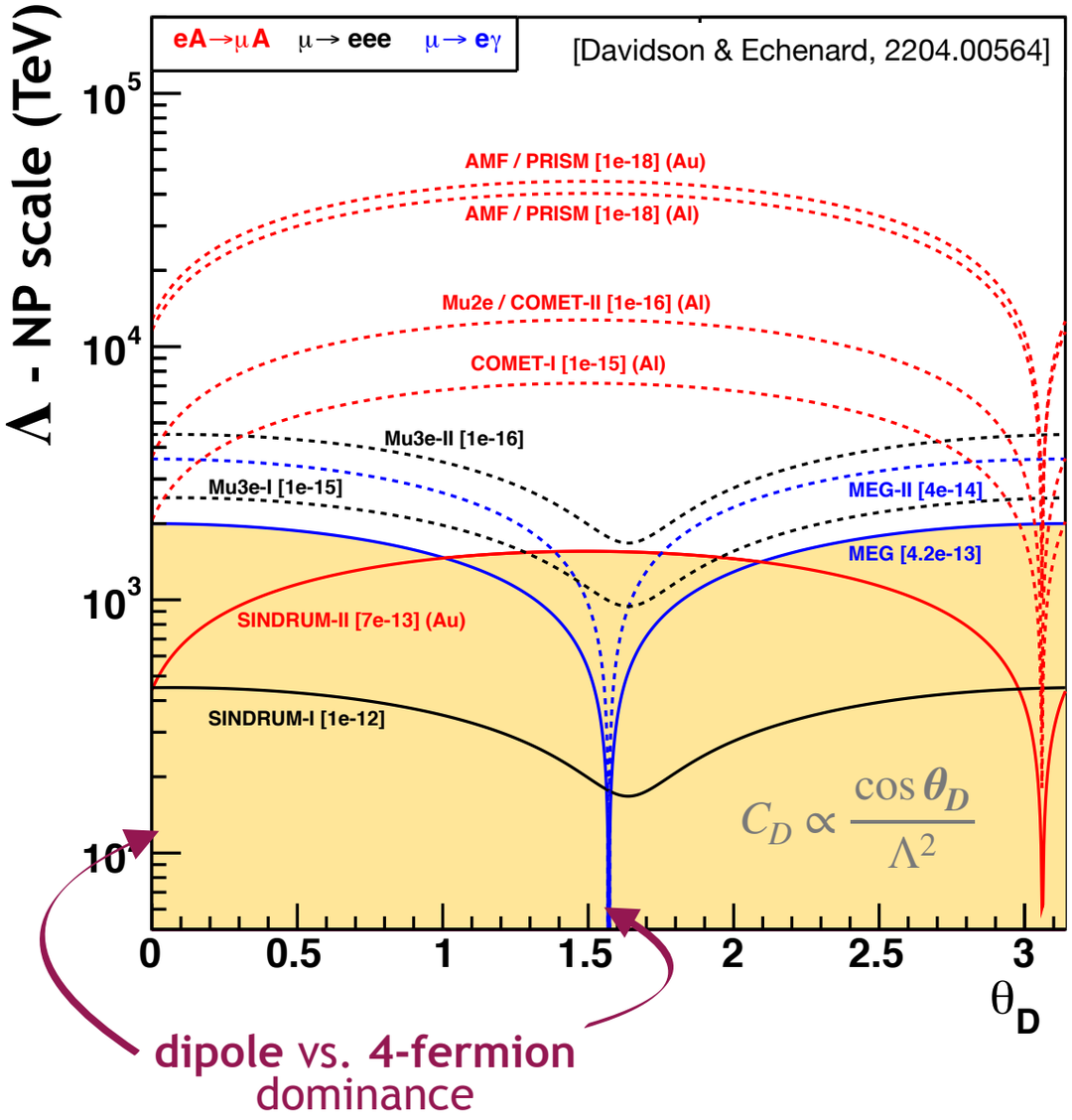
Muon cLFV: EFT approach to New Physics

Results of a recent **EFT** approach to **muon transitions:**

$$\mathscr{L}^{\text{eff}}_{\text{NP, cLFV}} = \frac{1}{\Lambda^2}\Big[C_D(\bar{e}\sigma^{\nu\rho}P_R\mu)F_{\nu\rho} + C_S(\bar{e}P_R\mu)(\bar{e}P_R e) + C_{VR}(\bar{e}\gamma^\nu P_L\mu)(\bar{e}\gamma_\nu P_R e) + C_{VL}(\bar{e}\gamma^\nu P_L\mu)(\bar{e}\gamma_\nu P_L e) + \\ + C_{\text{N-light}}\mathcal{O}_{\text{N-light}} + C_{\text{N-heavy}\perp}\mathcal{O}_{\text{N-heavy}\perp}\Big]$$

$$\vec{C} = \{C_D, C_S, C_{VR}, C_{VR}, C_{VL}, C_{\text{N-l}}, C_{\text{N-h}\perp}\}$$

$$\text{BR}(\mu \to e\gamma) \simeq 384\pi^2\frac{v^4}{\Lambda^4}|\vec{C}\,.\,\hat{e}_{DR}|^2$$



Sensitivity to NP scales (current & future):

nature of NP ⇜⇝ dipole vs. 4-fermion

MEG $(\mu \to e\gamma)$ ⇜⇝ $\Lambda_{\text{cLFV}} \sim \mathcal{O}(10^3\ \text{TeV})$ [dipole]

steadily improved by **Mu3e** $\sim \mathcal{O}(5\times 10^3\ \text{TeV})$

SINDRUM II $(\mu - e, \text{Au})$ ⇜⇝ $\Lambda_{\text{cLFV}} \sim \mathcal{O}(10^3\ \text{TeV})$ [4f]

Mu2e/COMET II $(\mu - e, \text{Al})$ ⇜⇝ $\Lambda_{\text{cLFV}} \gtrsim \mathcal{O}(10^4\ \text{TeV})$

[either dipole or 4f]

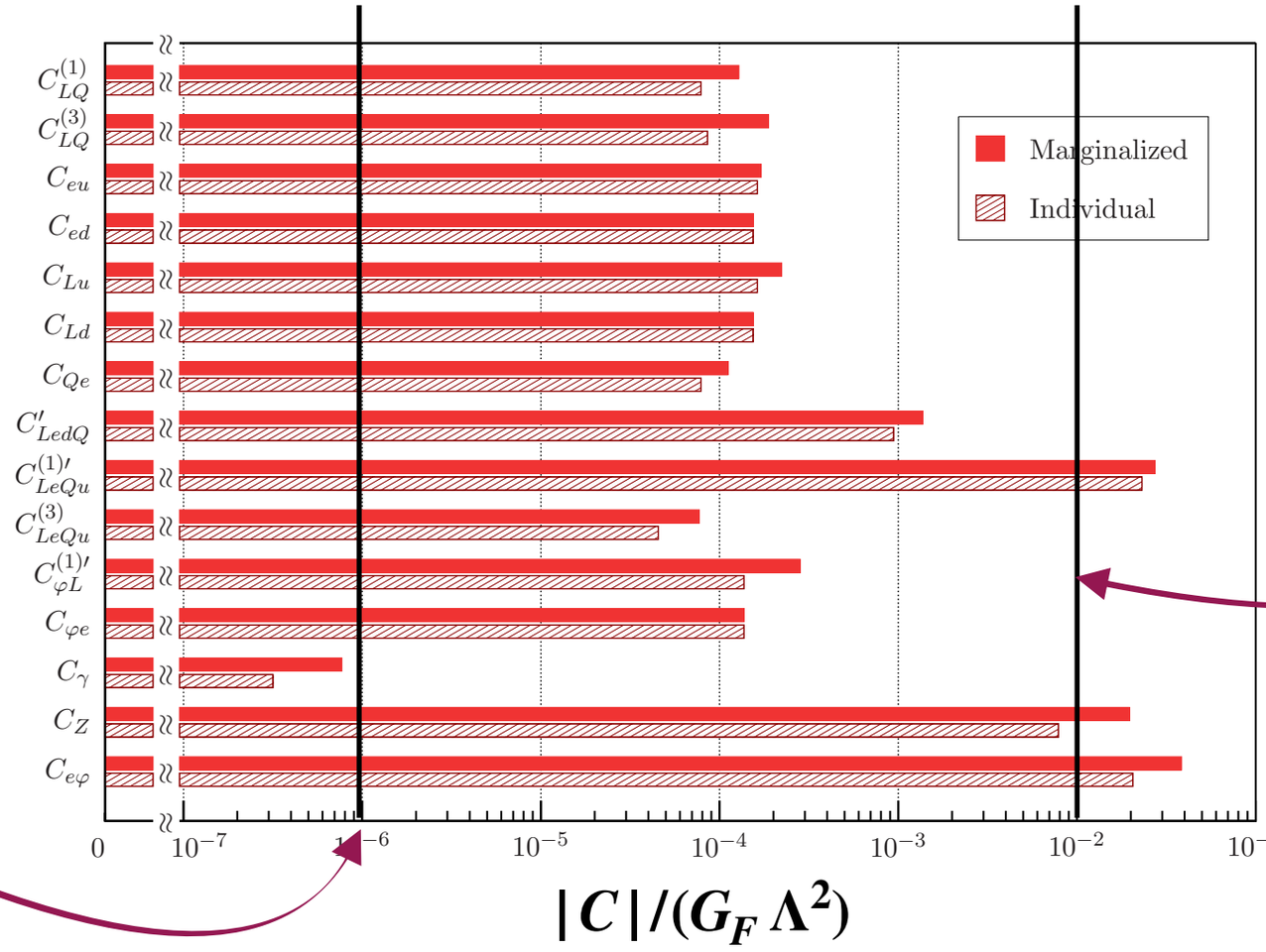
Tau cLFV: (semi-) leptonic modes

Flavour violating tau decays: leptonic & semi-leptonic (light mesons, 2- and 3-body)

⇒ **EFT** approach theoretically much more involved (scales, hadronisation, ...)

⇒ larger set of contributing operators (e.g. numerous $qq\ell\ell$, gluon, ...)

More challenging to **disentangle** operator dominance - even at tree level!



For $C \approx 1$,
$\Lambda_{NP} \sim 300$ TeV

For $C \approx 1$,
$\Lambda_{NP} \sim 3$ TeV

[Banerjee et al, 2203.14919]

Overview of Belle II limits on relevant coefficients (and NP scales) for **cLFV tau decays**

⇒ $\Lambda_{NP} \sim 30 - 300$ TeV (for $C \approx 1$)

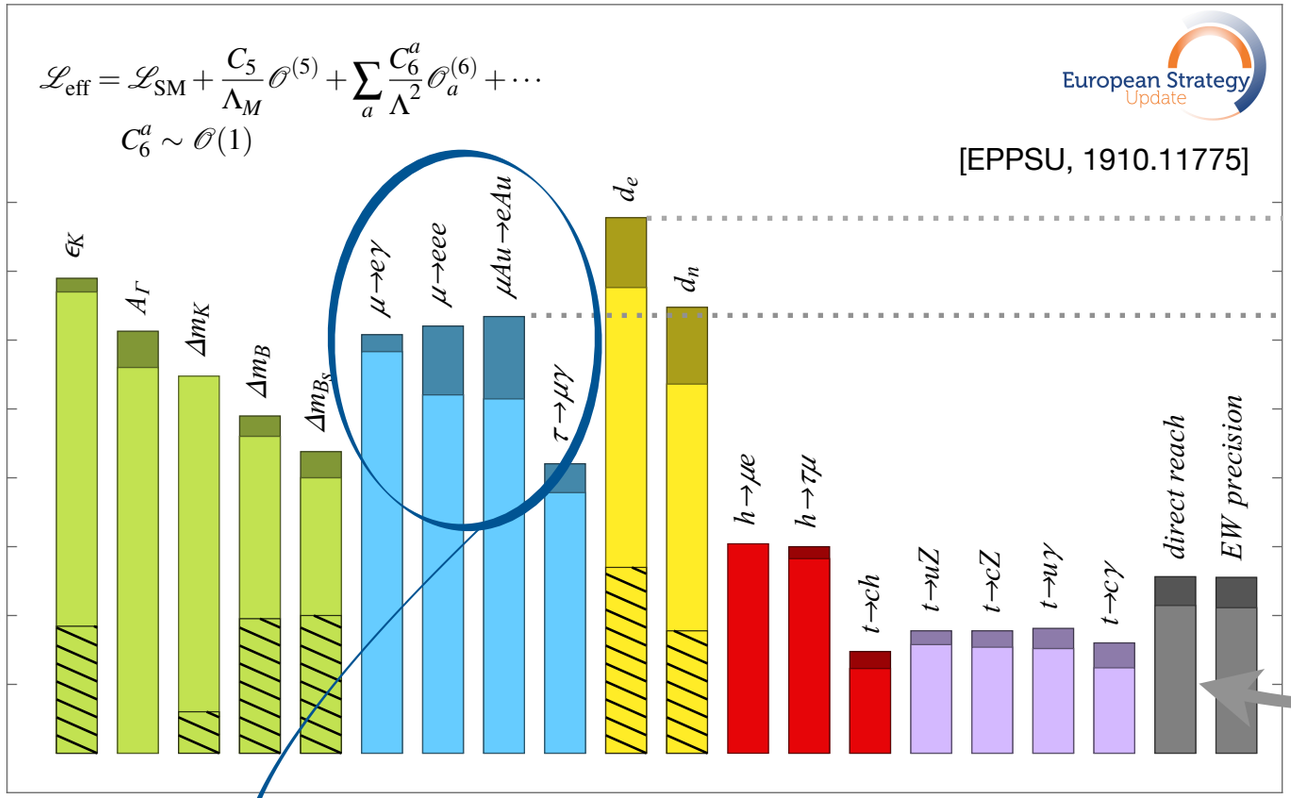
The probing power of flavour & CPV

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



Flavour & CPV observables:
probes sensitive to very high NP **scales**

$$\Lambda_{\text{NP}} \sim \mathscr{O}(10^5 \text{ TeV})$$

well beyond **collider's reach!**

charged lepton flavour violating observables!

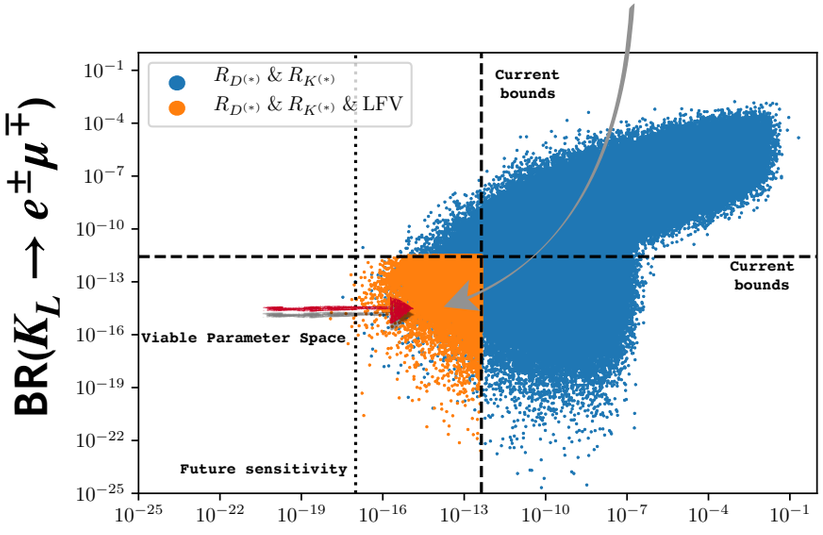
After EFT - New Physics models of cLFV

- **Effective approach:** *first characterisation* (mostly constraints & hints) on
  scale of NP and nature of new interactions (couplings and currents)

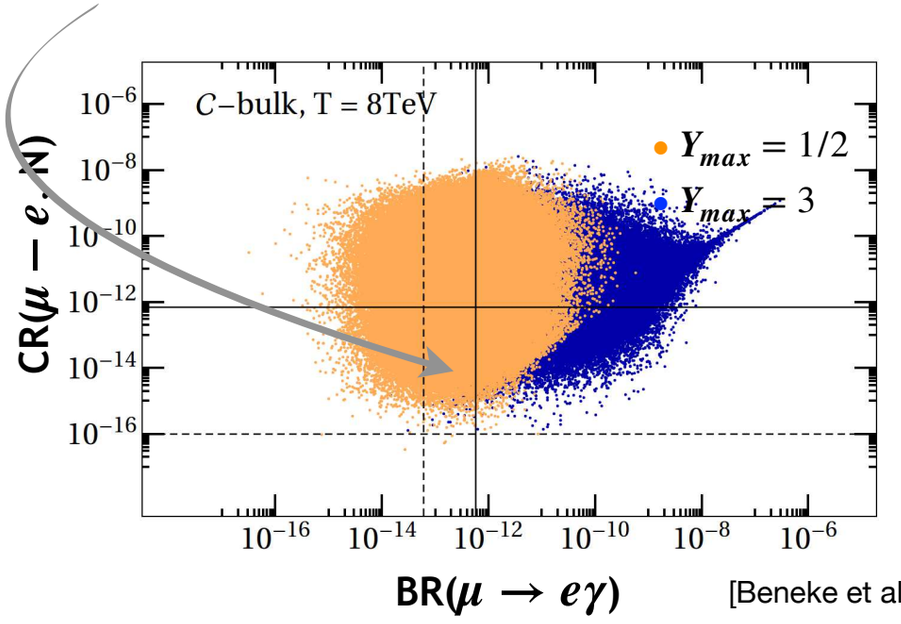
  ⇒ Ultimately we do *need to unveil the model of NP at work!*

- Although **oscillation data** (massive neutrinos) does **imply cLFV** *(not necessarily observable)*,
  (observable) **cLFV** can be **independent** of mechanism of neutrino mass generation

  Supersymmetry, **Leptoquark** models, **Extra-dimensions,** extended Higgs sectors, ...



[Hati, Kriewald, Orloff, AMT, 1907.05511]

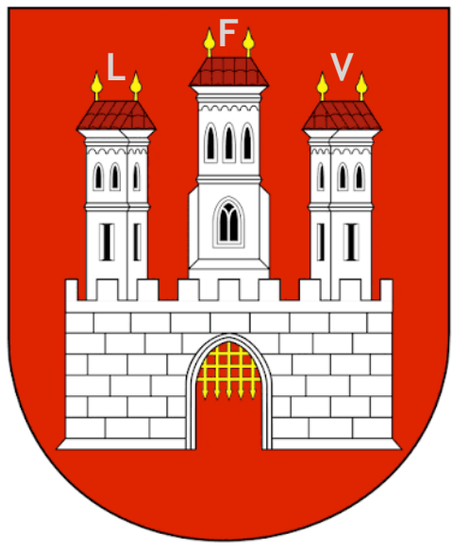


[Beneke et al, 1508.01705]

- **Here:** focus on **SM extensions** aiming at addressing **neutrino mass generation via HNLs!**

Heavy neutral leptons - appealing (minimal) extensions of the SM





A.M. Teixeira, LPCA Clermont

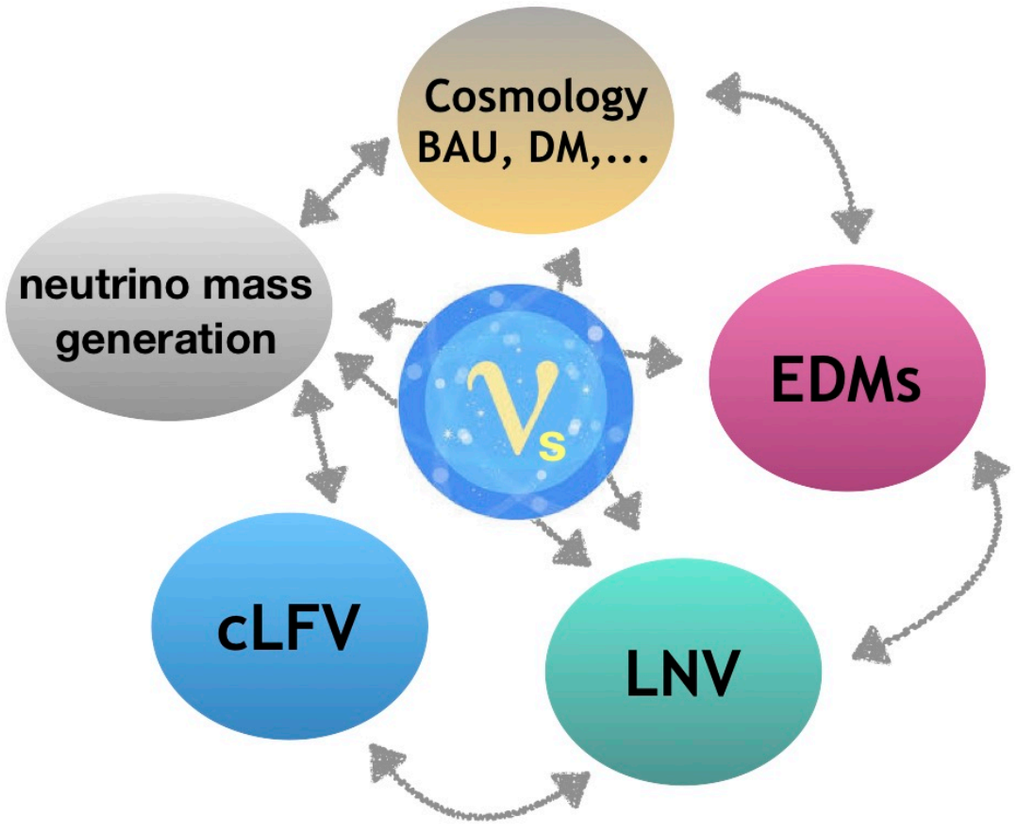
New physics in the lepton sector

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

Extended lepton sectors
and/or
New states coupling to **leptons**
(exotic fermions, scalars, vectors...)

⇒ **Neutrino** oscillations,
Baryon asymmetry of the Universe,
Viable **dark matter** candidate (?)

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



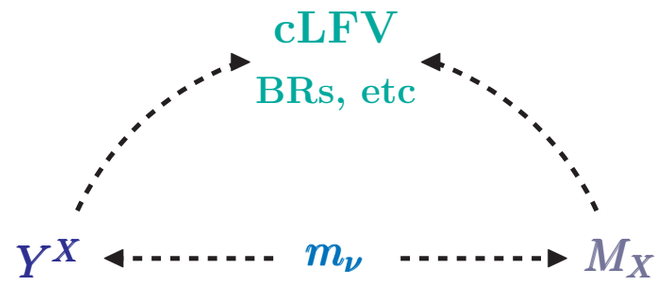
SM-singlets, present in appealing NP constructions (seesaws, Left-Right models, GUTs)

Potentially very **"visible NP portal":** extensive imprints from ***colliders*** to ***low-energy*** experiments, ...

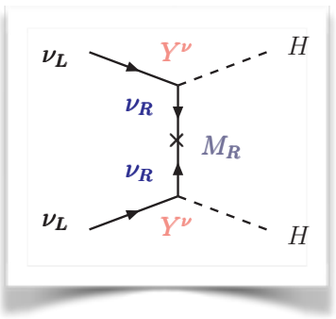
⇒ **Focus** on HNL's impact regarding charged lepton flavour violation and CP violation

Starting point: fermion singlet seesaws and cLFV

- **Mechanisms for neutrino mass generation:** delicate "balance" between
  sources of flavour violation and masses of new propagators
  ⇒ account for oscillation data (**observation!**)



- **Type I Seesaw:** extend the SM via **(Majorana) sterile fermions**
  ⇝ an enlarged spectrum
  ⇝ extended mixings

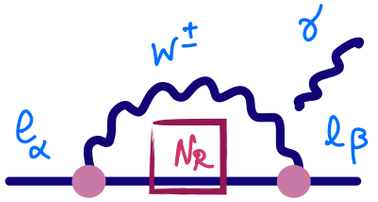


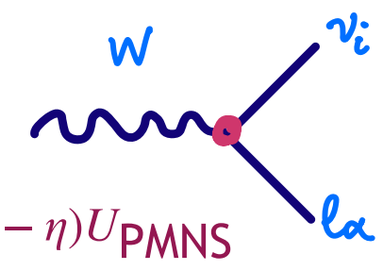
$$m_\nu \sim (Y^\nu v)^T \frac{1}{M_R} (Y^\nu v)$$

leptonic mixing $\approx U_{\text{PMNS}}$ *(non-unitary)*

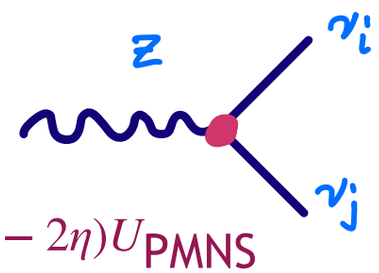
$U^T \mathscr{M}_\nu^{6\times 6} U = \text{diag}(m_{\nu_i})$ $\quad U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix}$

active-sterile mixings $(\theta \propto m_D^\dagger M_R^{-1})$





$\propto (1-\eta) U_{\text{PMNS}}$



$\propto (1-2\eta) U_{\text{PMNS}}$

$\tilde{U}_{\text{PMNS}} = (1-\eta) U_{\text{PMNS}}$; $\eta = \frac{1}{2}\theta\theta^\dagger$

$$\mathscr{L}_6^{\prime\text{eff}} \propto \eta_{\alpha\beta} [(\bar{L}_\alpha \gamma^\mu L_\beta)(\phi^\dagger \overleftrightarrow{D}_\mu \phi) - (\bar{L}_\alpha \gamma^\mu \tau^i L_\beta)(\phi^\dagger \overleftrightarrow{D}^i_\mu \phi)]$$

Source of **cLFV!**

[see also Blennow et al, 2306.01040]

Ad-hoc models of massive Majorana neutrinos

Simplified approach for phenomenological analyses: SM + ν_s (& non-unitary PMNS)

- **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 $\quad |n_L> = \mathcal{U}_{5\times5}\,|\nu_i>$

Left-handed lepton mixing $\tilde{U}_{\rm PMNS}$
3×3 sub-block, **non-unitary!**

Active-sterile mixing $U_{\alpha i}$
3×5 rectangular matrix

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

$n_s = 2$

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

- **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)

cLFV prospects of HNL extensions: CPV phases do matter!



A.M. Teixeira, LPCA Clermont

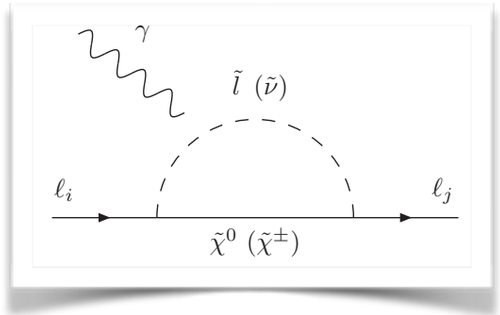
Dominant topologies & NP cLFV patterns

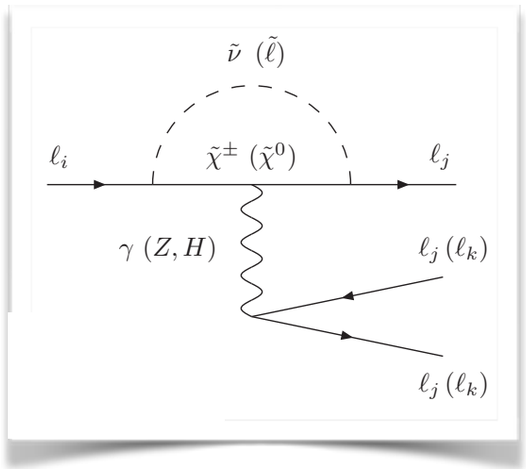
- **Nature** of **new propagators** and **interactions** ⇒ contributions to **cLFV observables**

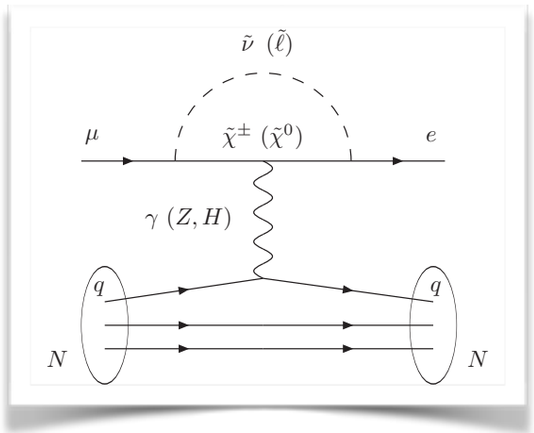
cLFV patterns reflect the **topology** of contributions associated with the **new mediators**
(dipole or Z-dominated, tree vs. loop, ...)

Dominant topologies & NP cLFV patterns

- **Nature** of new propagators and interactions ⇒ contributions to cLFV observables





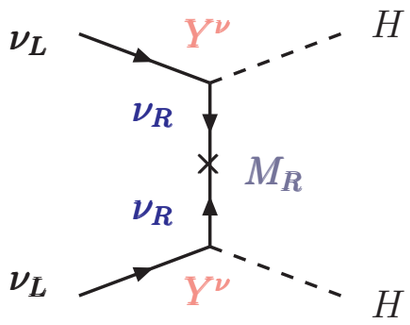


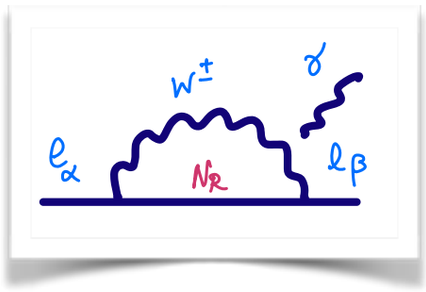
Supersymmetry (SUSY):

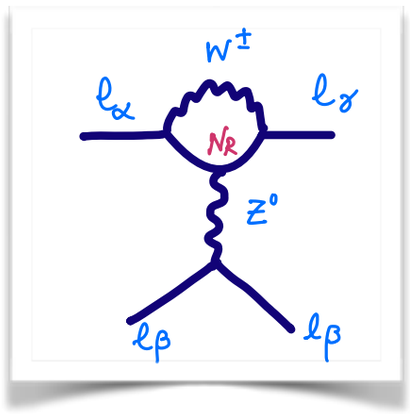
fermions + scalar fermions $[(\ell, \nu) \leftrightsquigarrow (\tilde{\ell}, \tilde{\nu})]$

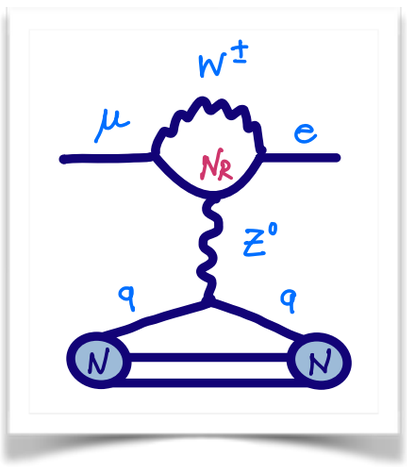
gauge/Higgs + fermionic "inos" $[(Z, W, H) \leftrightsquigarrow (\tilde{\chi}^0, \tilde{\chi}^\pm)]$

"**Dipole** domination" in 3-body decays & $\mu - e$ conversion









Type I seesaw & variants

"**Z-penguin** domination" in 3-body decays & $\mu - e$ conversion

Dominant topologies & NP cLFV patterns

IN2P3 Les deux infinis

- **Nature** of **new propagators** and **interactions** ⇒ contributions to **cLFV observables**

cLFV patterns reflect the **topology** of contributions associated with the **new mediators**
(dipole or Z-dominated, tree vs. loop, ...)

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*	$0.05-0.5$	$2-20$

[adapted from Calibbi et al, 1709.00294]

Upon **experimental determination** of rates for **cLFV transitions:**

comparison of $\left.\frac{\mathrm{BR}(\mu\to 3e)}{\mathrm{BR}(\mu\to e\gamma)}\right|_{\mathrm{exp}}$ **with** $\left.\frac{\mathrm{BR}(\mu\to 3e)}{\mathrm{BR}(\mu\to e\gamma)}\right|_{\text{NP-th}}$

and of $\left.\frac{\mathrm{CR}(\mu-e,\mathrm{N})}{\mathrm{BR}(\mu\to e\gamma)}\right|_{\mathrm{exp}}$ **with** $\left.\frac{\mathrm{CR}(\mu-e,\mathrm{N})}{\mathrm{BR}(\mu\to e\gamma)}\right|_{\text{NP-th}}$

⇒ **Probe NP model** at the **source** of **cLFV**

cLFV contributions from HNL: ad-hoc model

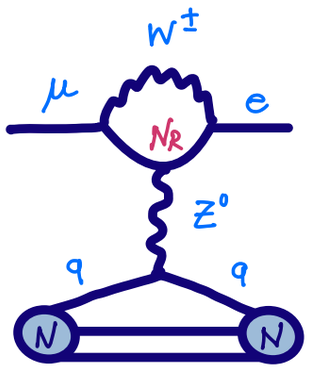
- Consider "**3+2 ν_s**" **ad-hoc model** (addition of **2 heavy sterile** states)

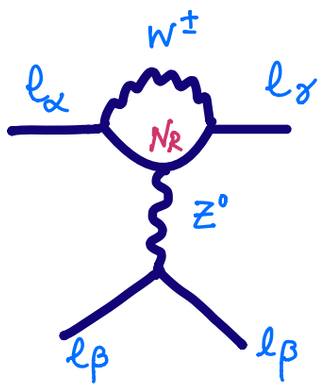
cLFV observables dominated by common topology

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

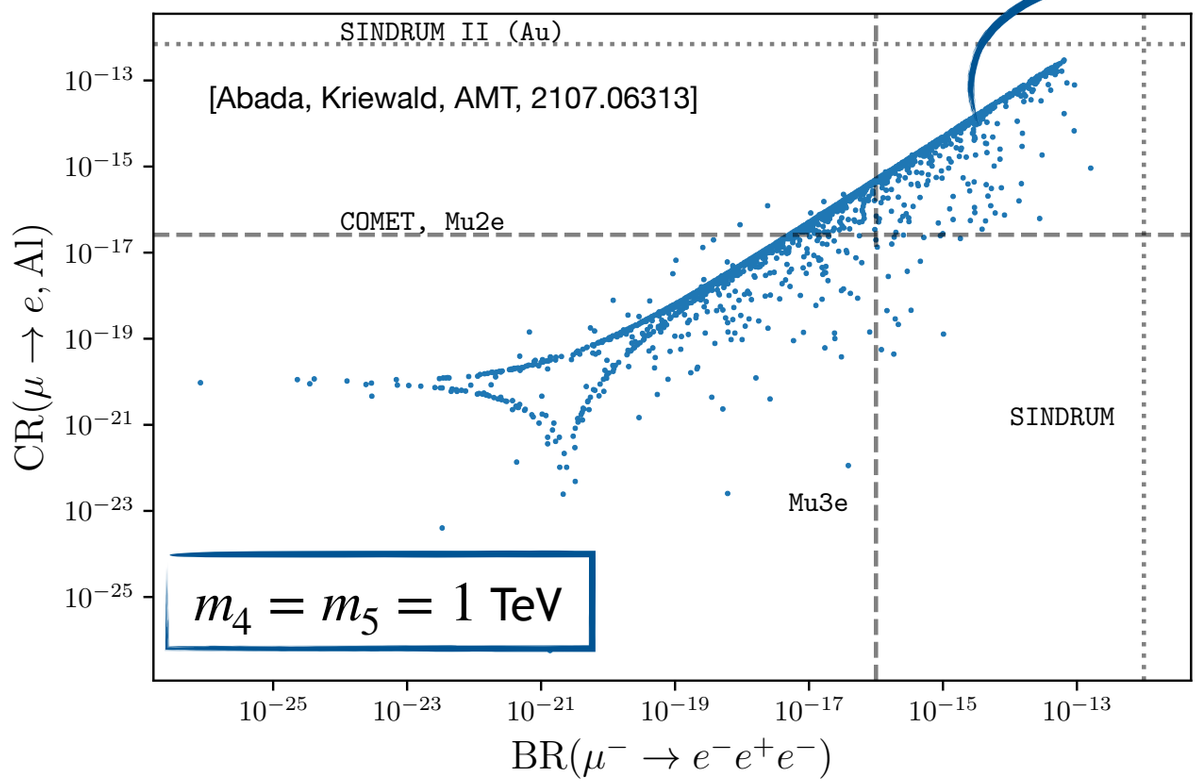
3-body muon decays ($\mu \to 3e$)

} *Z-penguin dominance*





- CP conserving



Strong correlation
(CP conserving)

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

cLFV observables & HNLs: the role of CPV phases

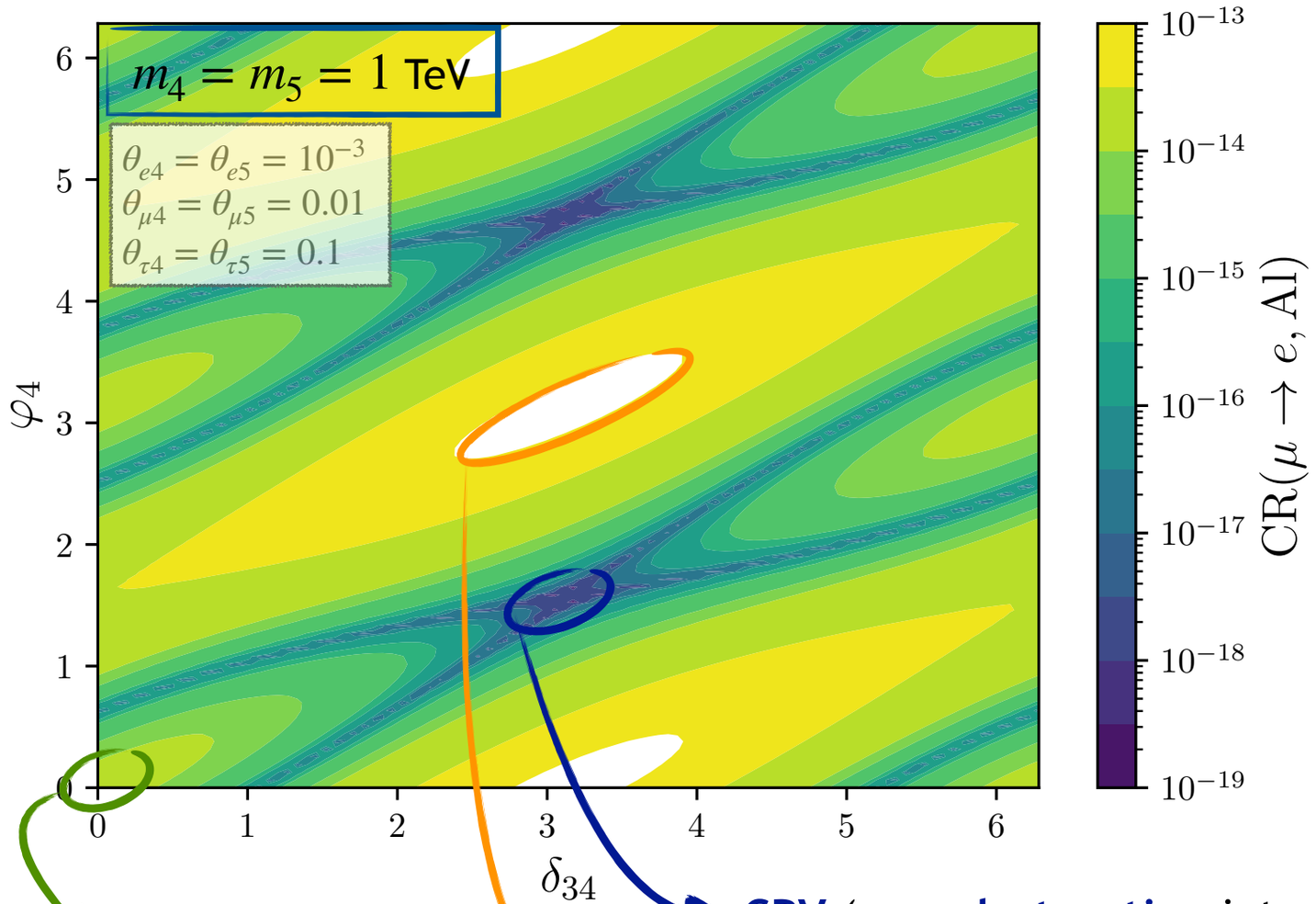
- Consider "**3+2 ν_s" ad-hoc model** (addition of **2 heavy sterile** states)

Phases do matter in **cLFV** transitions...

A very simple study: **focus on $\mu - e$ conversion in nuclei**

fix all parameters (masses & mixings) **and *vary only CPV phases***

[Abada, Kriewald, AMT, 2107.06313]



- **Interference effects**

  Both **destructive *AND*** **constructive!**

  Joint effect of **Dirac** (δ_{34}) and **Majorana** (φ_4) **CPV phases**

⇒ **From within near future reach to beyond experimental sensitivity...**

or even **already excluded!**

CP conserving
(within future **reach)**

CPV (**max destructive** interference, **beyond!**)

CPV (**max constructive** interference, **excluded!**)

cLFV observables & HNLs: the role of CPV phases

- Consider "**3+2 ν_s**" **ad-hoc model** (addition of **2 heavy sterile** states)

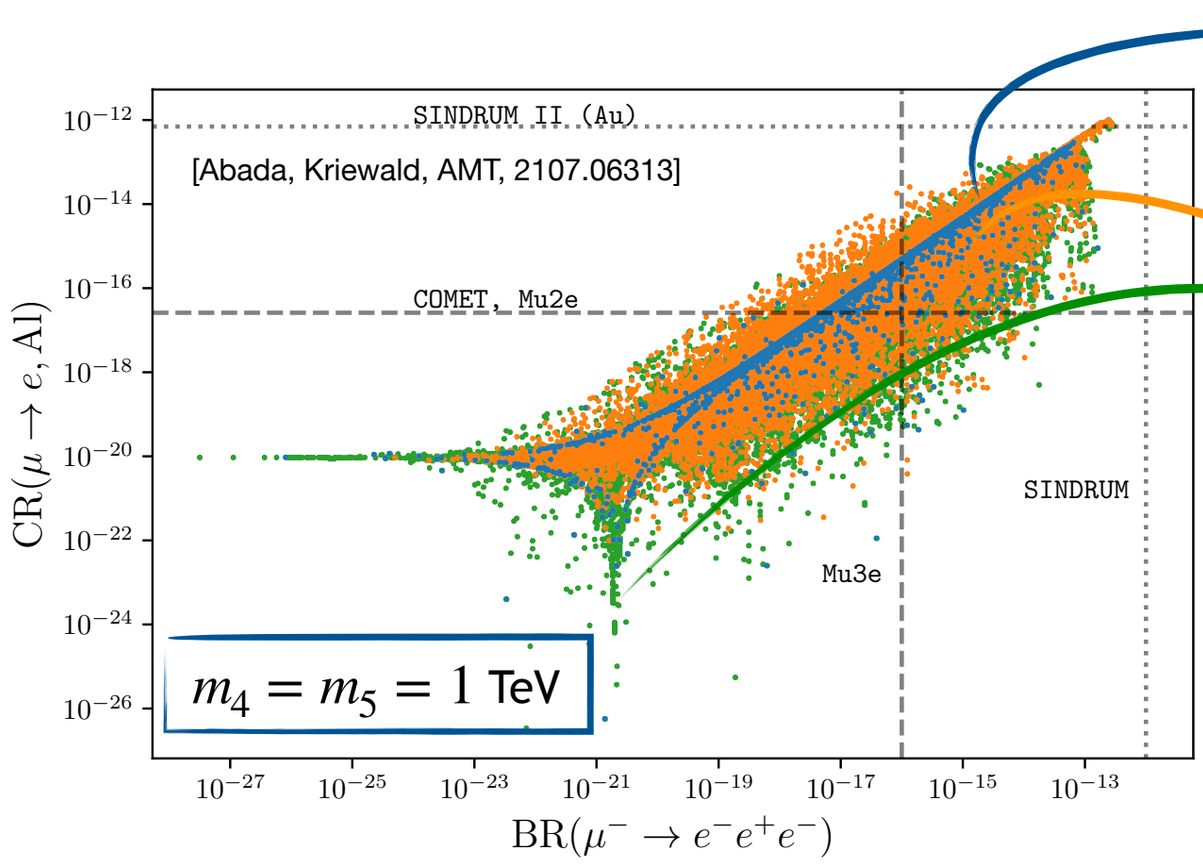
cLFV observables dominated by common topology

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

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

} *Z-penguin dominance*

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



Strong correlation
(CP conserving)

Loss of correlation!
(CP violating)

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

CP violating phases do matter for cLFV!

Impacting naïve expectations (also for experimental searches)

Enlarging the set of cLFV observables

- **cLFV patterns:** extensively used to **falsify/discriminate** potential **NP constructions**
- In most NP models, **CPV phases** are naturally **present** - and essential to **address the BAU!**

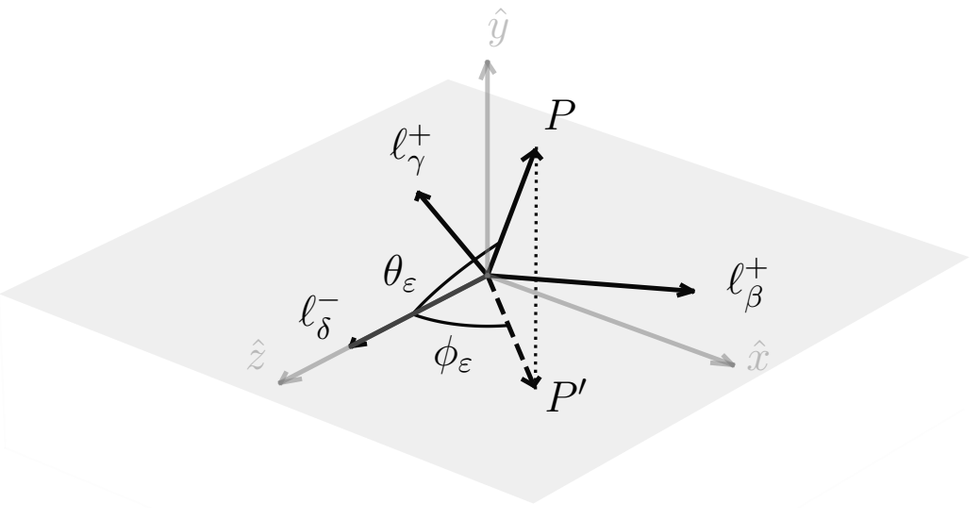
  In HNL extensions of the SM, CPV phases strongly disrupt cLFV patterns...

- **cLFV experiments** - including Mu3e, Belle II and SCTF - aim at producing **polarised μ and τ**

  ⇒ Can we explore a **new class of cLFV (& CPV) observables?**

[Kuno and Okada, 9909265; Kitano and Okada, 0012040; ... ; Bolton and Petcov, 2204.03468; Redigolo, Tammaro, Tesi, 2408.00847]

Asymmetries in 3-body cLFV decays !



Several **cLFV decays** to explore:

a) $\ell_\alpha \to 3\,\ell_\beta$; b) $\ell^+_\alpha \to \ell^+_\beta\,\ell^+_\gamma\,\ell^-_\gamma$; c) $\ell^+_\alpha \to \ell^+_\beta\,\ell^+_\beta\,\ell^-_\delta$

New observables sensitive to CPV phases (δ, φ)

$$\mathcal{A}_T^{\mu 3e} = \frac{\Gamma(\mu \to 3e; s_\phi > 0) - \Gamma(\mu \to 3e; s_\phi < 0)}{\Gamma(\mu \to 3e)}$$

[Darricau, Kriewald, AMT, 2512.05032]

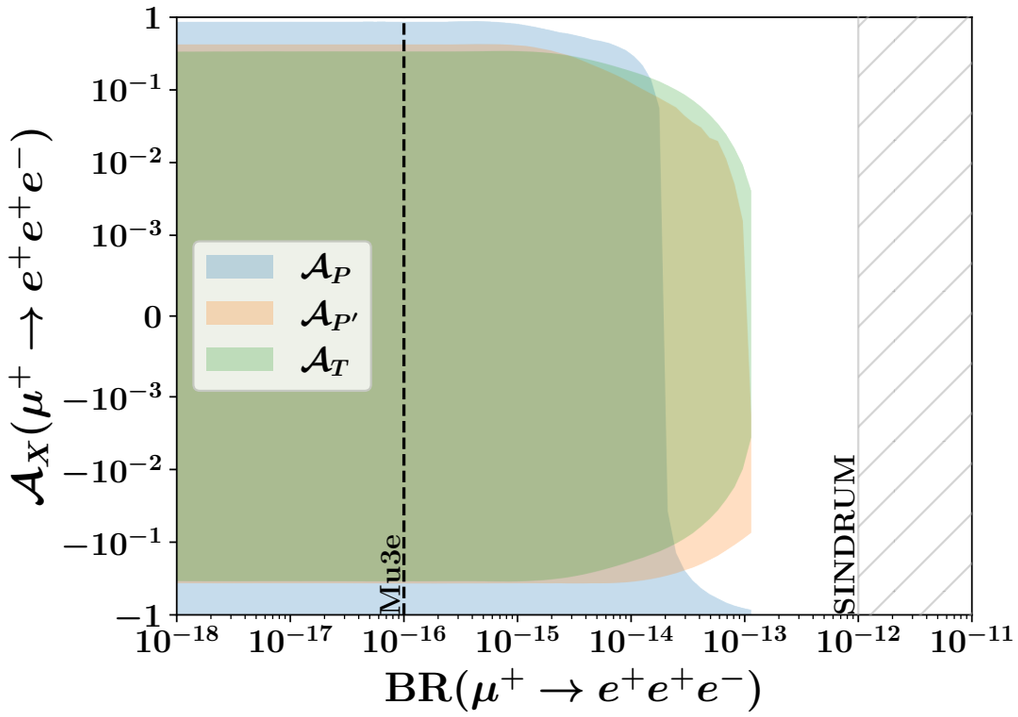
$$\{\ \mathcal{A}_P\ ,\ \mathcal{A}_{P'}\ ,\ \mathcal{A}_T\ \}$$

& $\{\ \mathcal{A}^{FB}\ ,\ \mathcal{A}^{FB}_P\ ,\ \mathcal{A}^{FB}_{P'}\ ,\ \mathcal{A}^{FB}_T\ \}$ (for case "b")

Asymmetries in cLFV μ 3-body decays

- Consider "**3+2 ν_s" ad-hoc model** (addition of **2 heavy sterile** states)

  Carry out a comprehensive survey of prospects for the distinct **asymmetries**



[Darricau, Kriewald, AMT, 2512.05032]

- **Asymmetries in $\mu \to 3e$ decays (at Mu3e)**

  Excellent prospects for the relevant observables within clear **reach of Mu3e** (even @ 10^{-15})

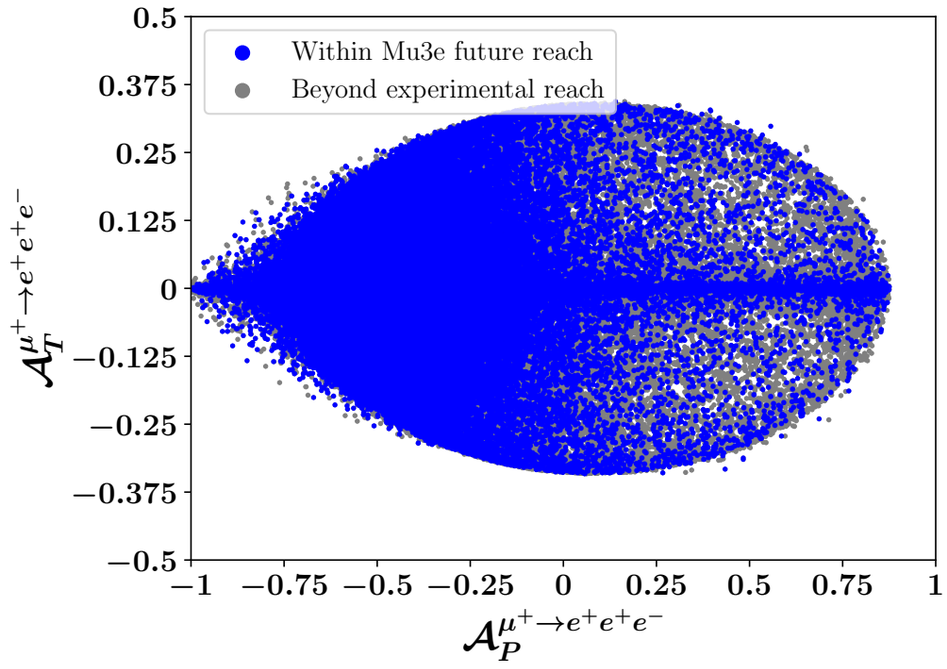
Strong case for **exploitation of asymmetries** (and angular observables) from the **onset of cLFV measurements !**

T-asymmetries in $\mu \to 3e$ decays:

Possible **first discovery of leptonic CPV!**

(other than δ^{D}_{13} in U_{PMNS})

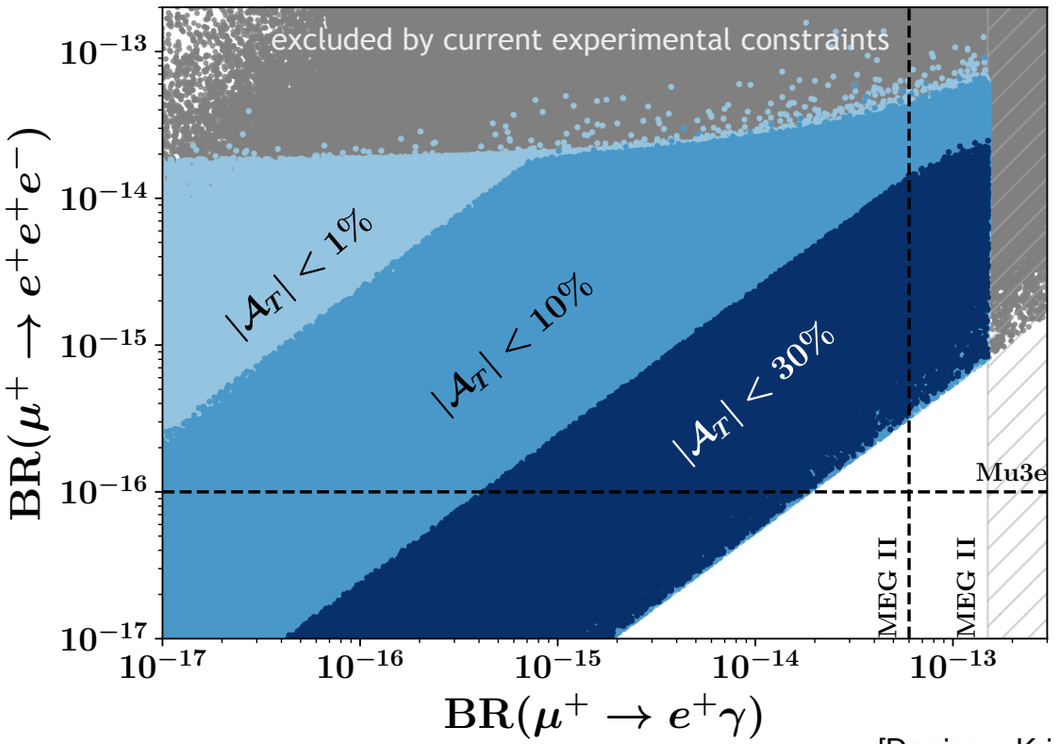
[see also Redigolo, Tammaro, Tesi, 2408.00847]

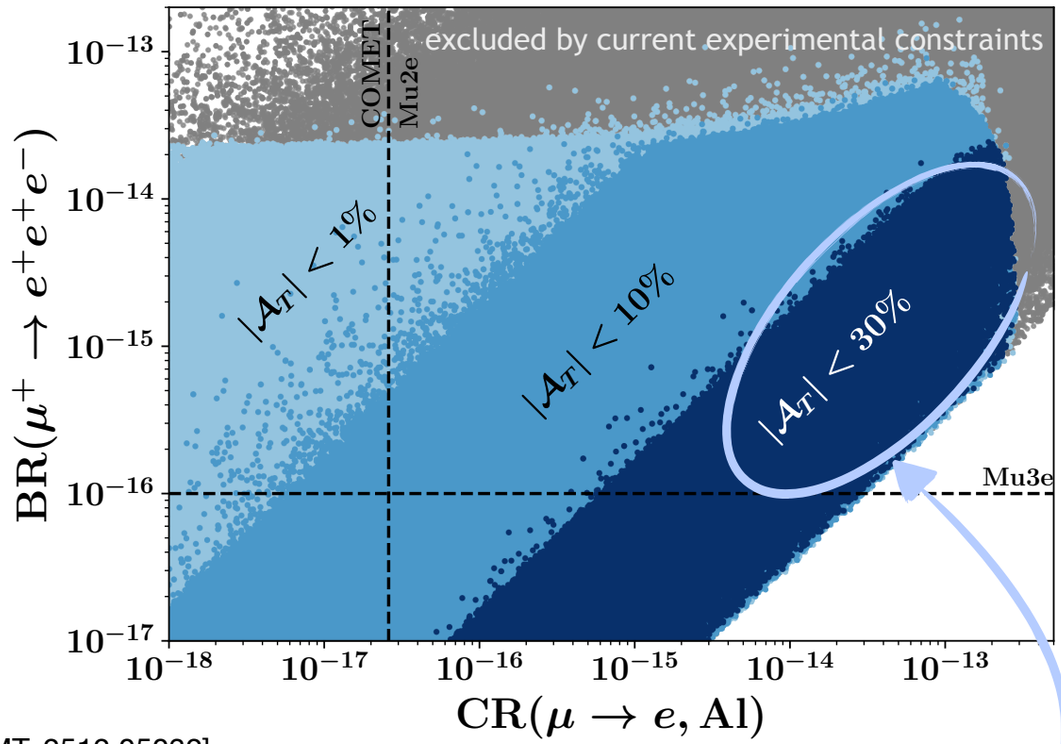


Asymmetries in cLFV μ 3-body decays

- Consider "**3+2 ν_s" ad-hoc model** (addition of **2 heavy sterile** states)

  Can **asymmetries complement (lost) synergies in cLFV observables** due to CPV phases?





[Darricau, Kriewald, AMT, 2512.05032]

- **Asymmetries in $\mu \to 3e$ decays & interplay with cLFV muon observables:**

  measurement of **BR($\mu \to 3e$) @ Mu3e** together with $\mathcal{A}_T \geq \mathcal{O}(10\%)$

  $\Rightarrow$ **observation** of $\mu - e$ conversion by **COMET and Mu2e!**

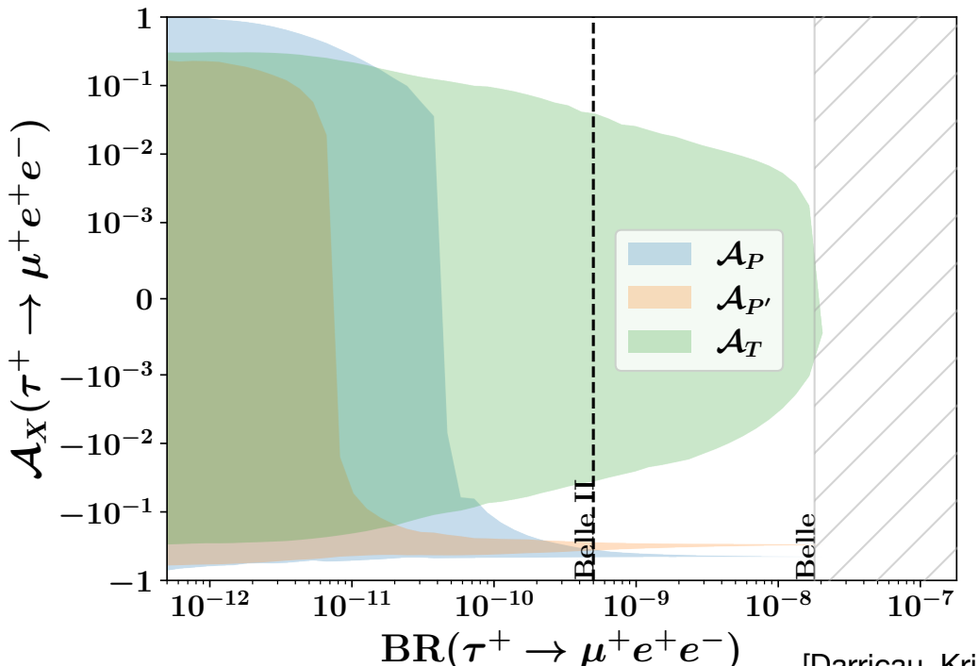
- Potential ***"falsifiability"*** **recovered for large asymmetries**

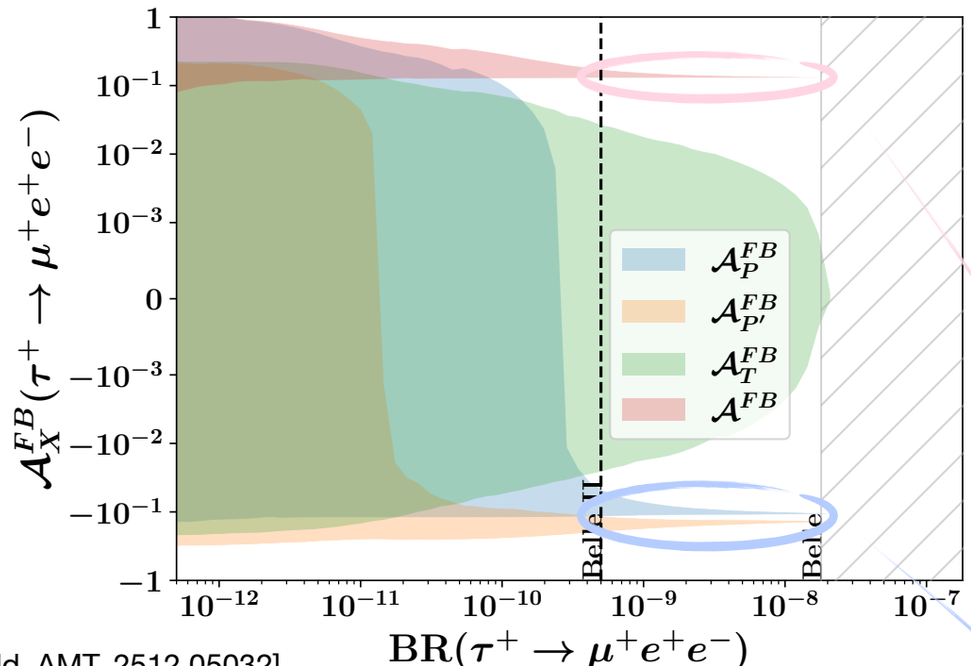
New cLFV & CPV discriminating power !

Asymmetries in cLFV τ 3-body decays

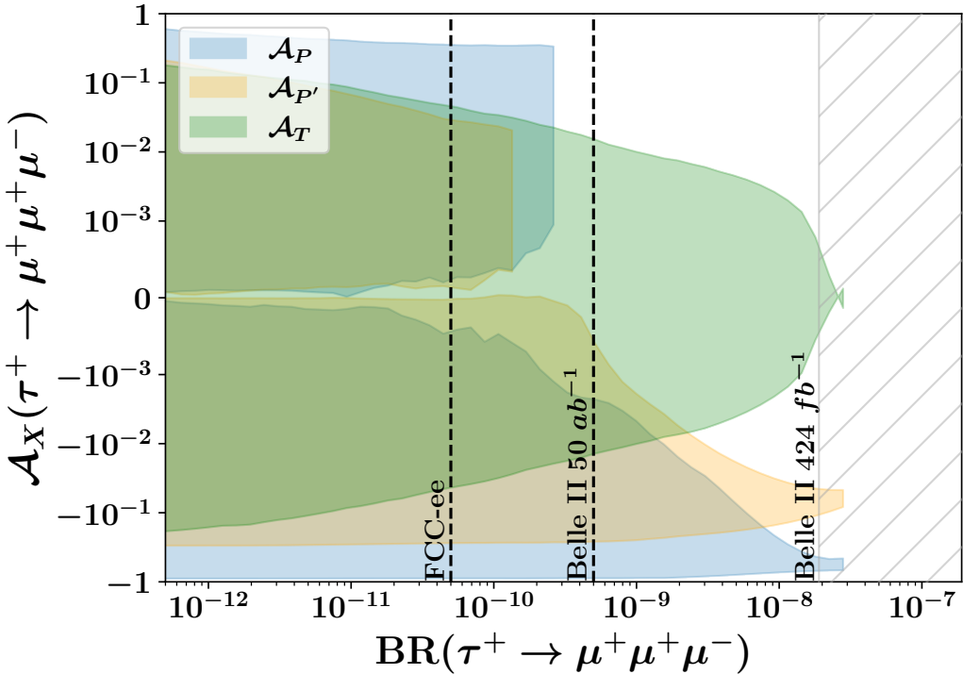
- Consider "**3+2 ν_s**" **ad-hoc model** (addition of **2 heavy sterile** states)

  Carry out a comprehensive survey of prospects for the distinct **asymmetries**





[Darricau, Kriewald, AMT, 2512.05032]



- **Asymmetries** in **tau cLFV decays**

  Potentially **very large** - but associated with **cLFV** rates **beyond** experimental sensitivity

  "Best" prospects for $\mathcal{A}^{FB}$, $\mathcal{A}^{FB}_{P,P'}$, and $\mathcal{A}_{P,P'}$

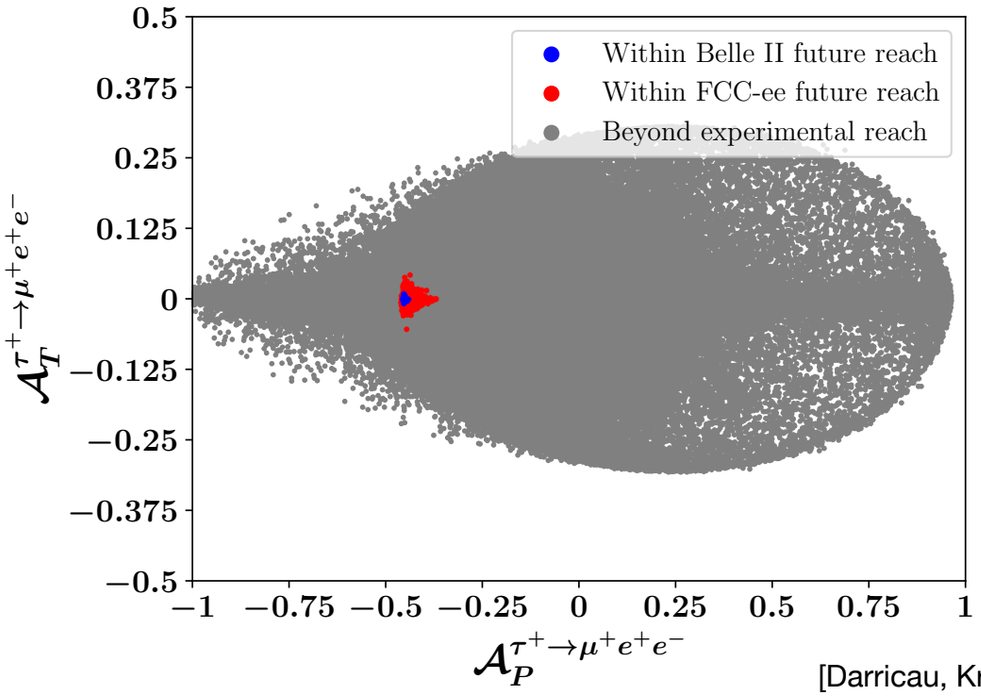
  Narrow bands of allowed values

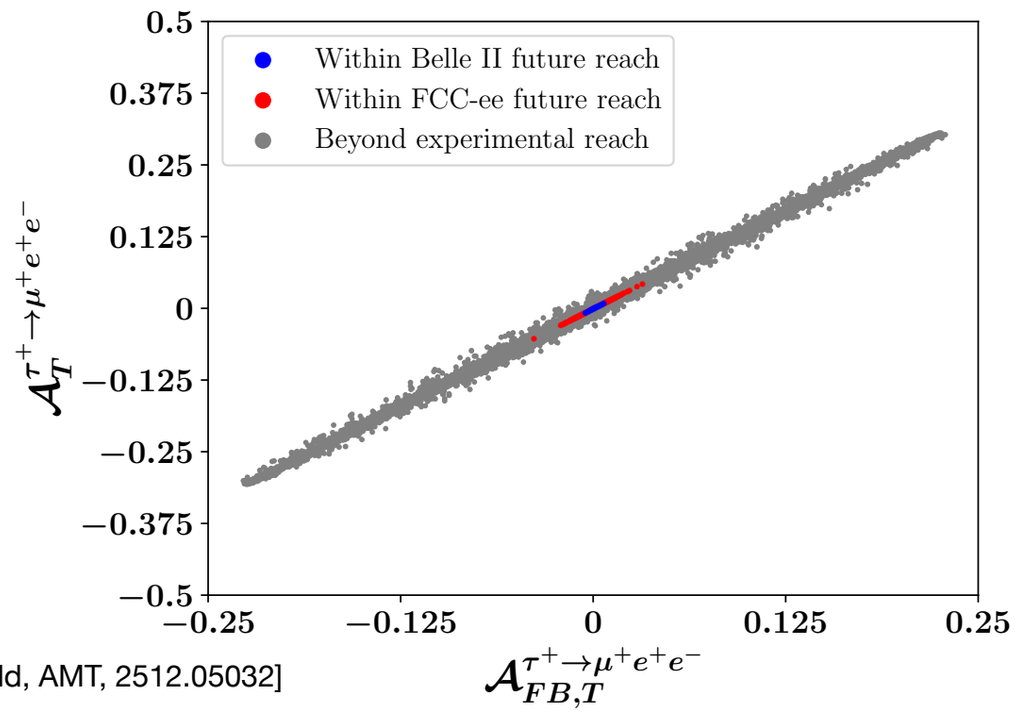
  Leading to (almost) **predictive scenarios**...

Asymmetries in cLFV τ 3-body decays

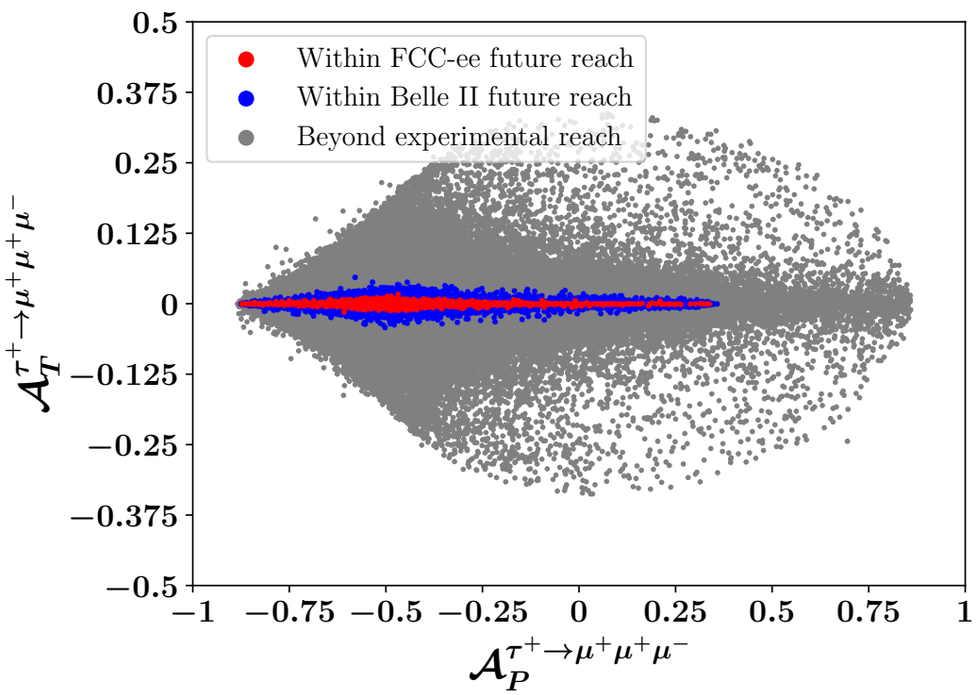
- Consider "**3+2 ν_s**" **ad-hoc model** (addition of **2 heavy sterile** states)

  Carry out a comprehensive survey of prospects for the distinct **asymmetries**





[Darricau, Kriewald, AMT, 2512.05032]



- **Asymmetries** in **tau cLFV decays**

  Potentially **very large** - but associated with **cLFV** rates **beyond** experimental sensitivity

  Narrow bands of allowed values

  Leading to (almost) **predictive scenarios**

  in view of **Belle II** and **FCC-ee** sensitivities

From an ad-hoc model to an appealing mechanism for m_ν ...

Low-scale models for m_ν: Inverse Seesaw

- **Variants** of type I seesaw aiming at **natural** realisations of a **low-scale** m_ν mechanism
- Addition of **two new species** of **fermionic gauge singlets**

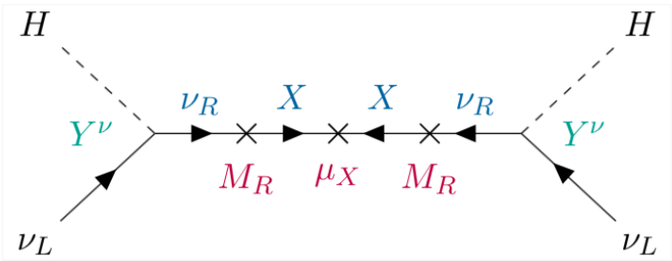
C. Hagedorn's talk

n_R right-handed neutrinos ν_R ($L_{\nu_R} = 1$) and n_X extra sterile states X ($L_X = -1$)

$$\mathscr{L}_{\text{ISS}} = -\,\boldsymbol{Y^\nu}\bar{L}\,\tilde{H}\,\nu_R - \boldsymbol{M_R}\,\bar{\nu}_R^c\,X - \frac{1}{2}\,\boldsymbol{\mu_X}\,\bar{X}^c X$$

lepton number violating!

[Mohapatra and Valle, '86]



$$\mathcal{M}_{\text{ISS}}^{9\times 9} = \begin{pmatrix} 0 & \boldsymbol{Y_\nu v} & 0 \\ \boldsymbol{Y_\nu^T v} & 0 & \boldsymbol{M_R} \\ 0 & \boldsymbol{M_R} & \boldsymbol{\mu_X} \end{pmatrix} \Rightarrow \begin{cases} \textbf{3 light } \boldsymbol{\nu}: m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2}\,\boldsymbol{\mu_X} \\ \textbf{3 pseudo-Dirac pairs}: m_{N\pm} \approx \boldsymbol{M_R \pm \mu_X} \end{cases}$$

ISS(3,3)

$$m_\nu \sim (Y^\nu v)^T \frac{\boldsymbol{\mu_X}}{\boldsymbol{M_R^2}} (Y^\nu v)$$

Interplay of **two scales** driving smallness of m_ν: M_R and μ_X

For **natural values** of $Y^\nu \sim \mathcal{O}(1)$

accommodate comparatively "light" heavy spectrum ($\Lambda_{\text{EW}} \leftrightarrow$ TeV)

for small values of μ_X (around eV - keV)

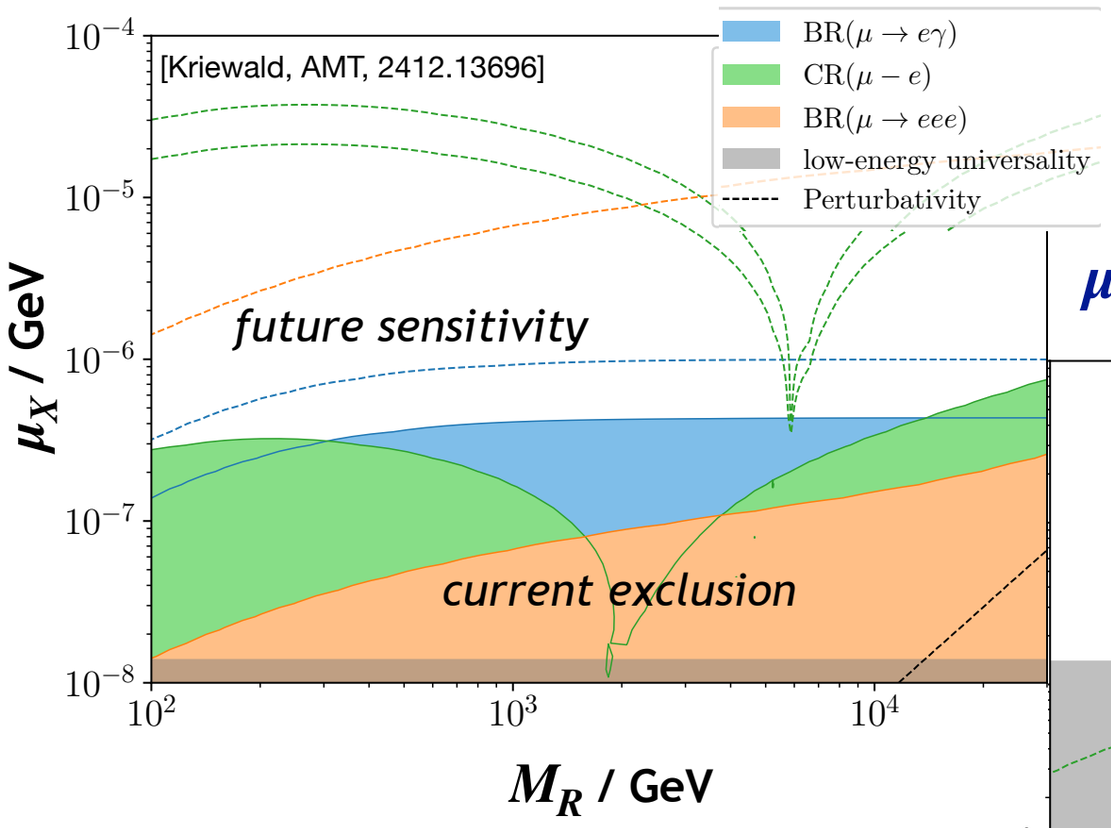
Natural ('t Hooft criterium) since **B-L conservation restored** when $\mu_X \to 0$!

Symmetry protected "smallness" of m_ν - approximate LNC

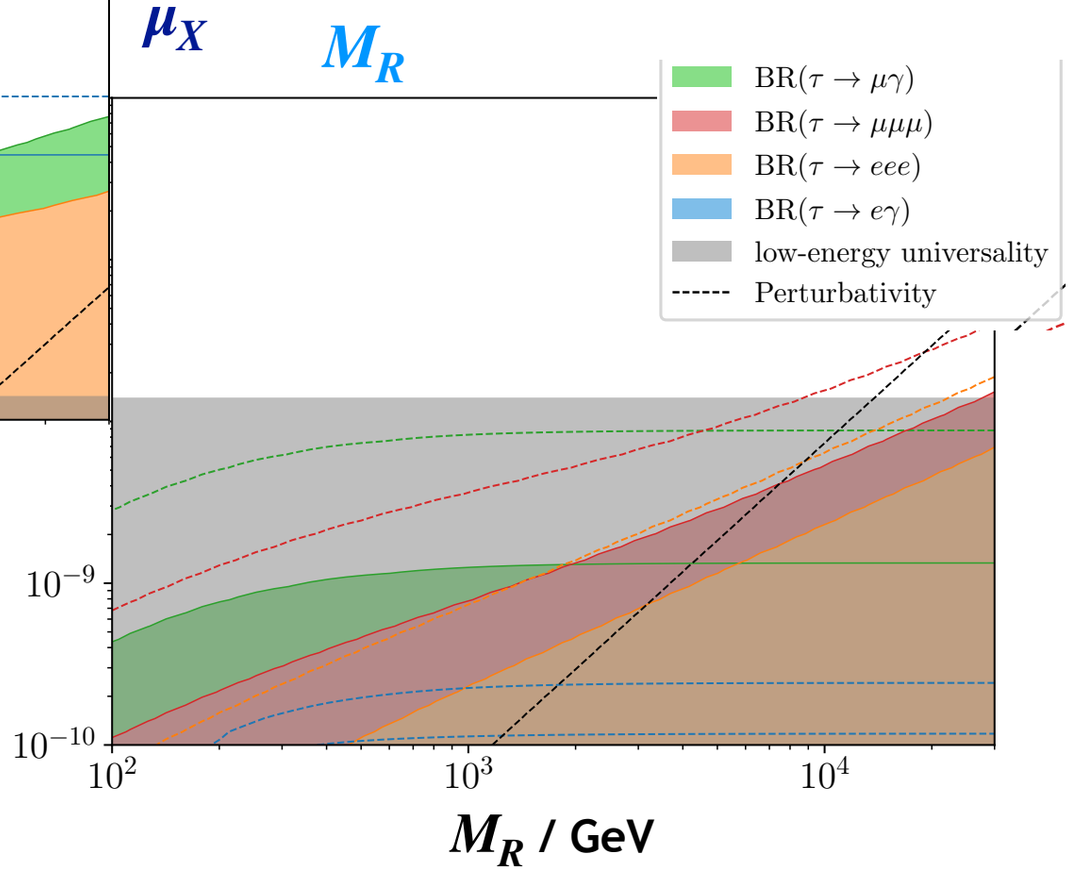
The Inverse Seesaw (3,3): cLFV overview

- **cLFV in the ISS(3,3)** ⇒ thorough exploration of a **non-trivial parameter space**

(no further symmetries imposed)



$$\mathcal{M}_{\text{ISS}}^{9\times 9} = \begin{pmatrix} 0 & Y_\nu v & 0 \\ Y_\nu^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix}$$



⇒ **Sizeable cLFV** contributions in the ISS!
(& constraints on ISS parameter space)

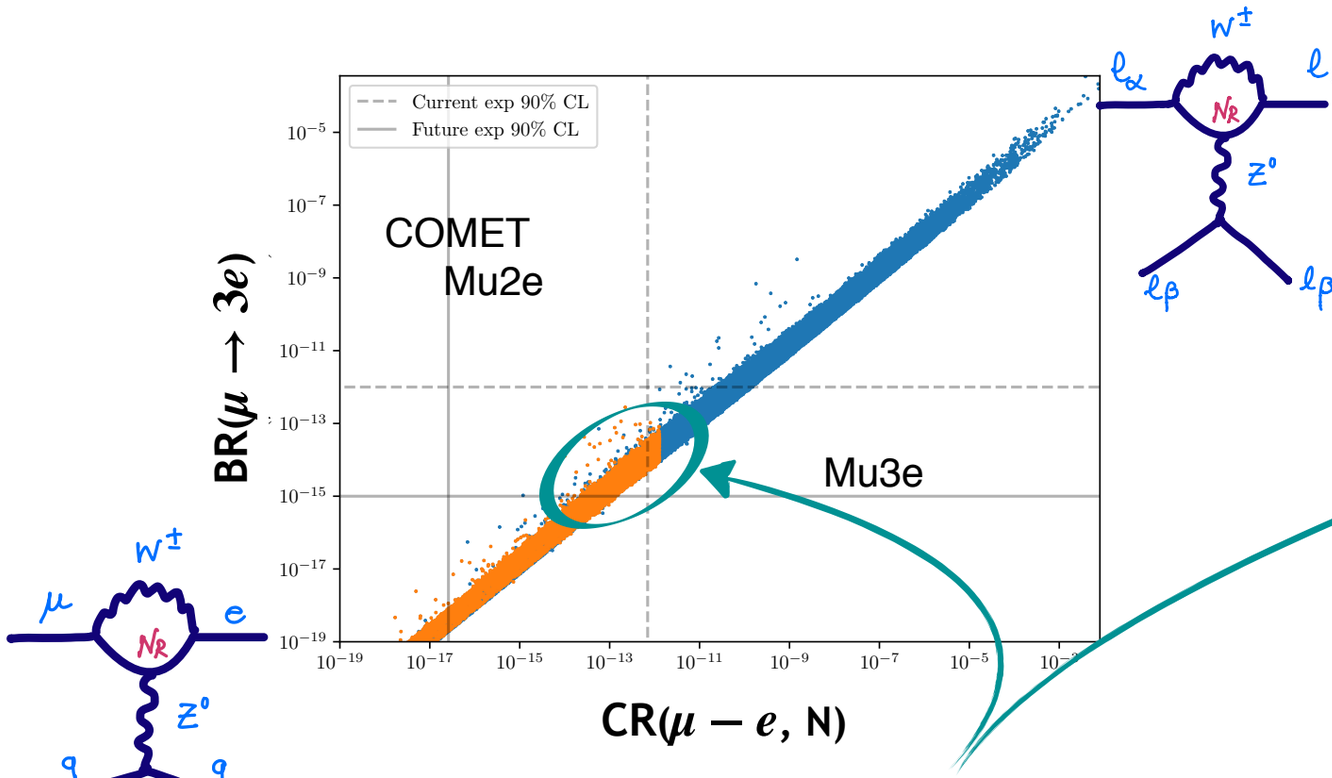
⇒ Highly **entangled observables** (**cLFV, Z-pole observables, ...**)
New approaches to explore **ISS** - *beyond "standard" Casas-Ibarra parametrisation*

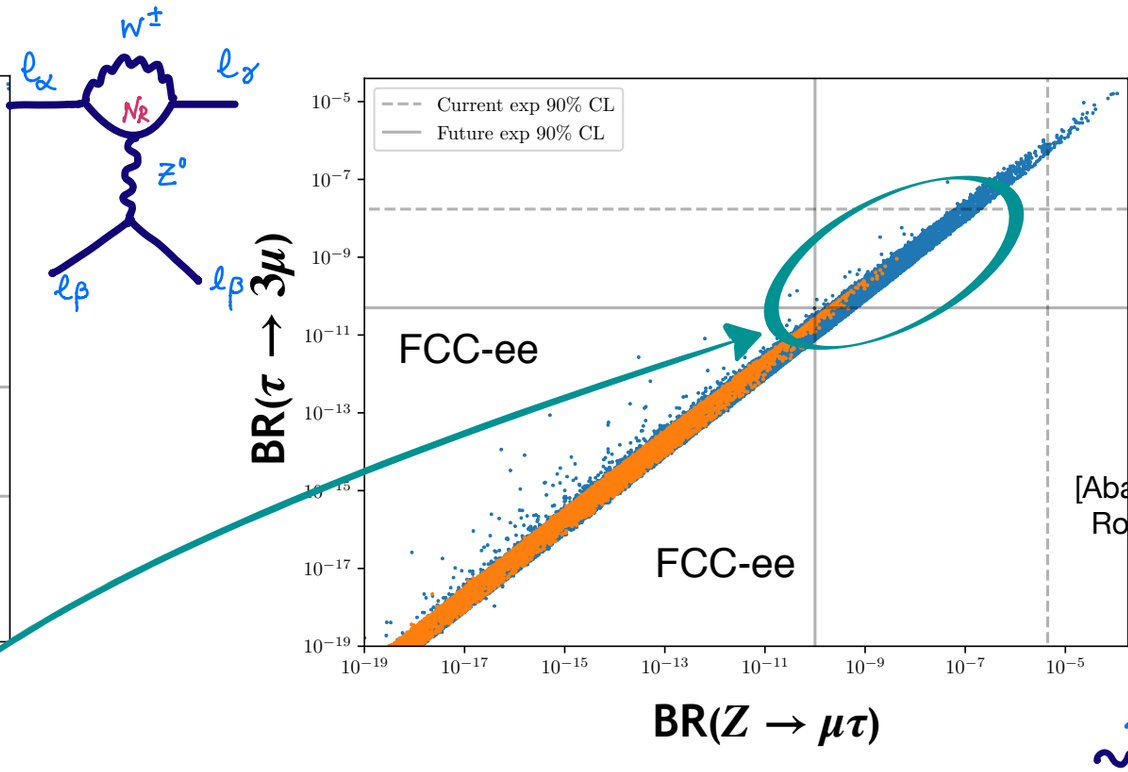
[Kriewald, AMT, 2412.13696]

cLFV in the Inverse Seesaw (3,3)

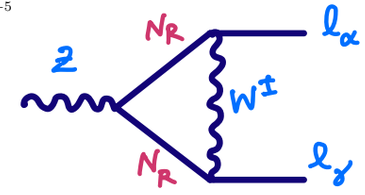
Inverse seesaw: well-motivated **mechanism of neutrino mass generation**

"low" NP scale $\sim M_R$, and sizeable **mixings** $(\theta \propto m_D^\dagger M_R^{-1})$ **!**





[Abada, Kriewald, Pinsard, Rosauro, AMT, '23]



$\Rightarrow$ **Correlated observables** for both $\mu - e$ and $\tau - \mu$ sectors, in the absence of (CPV-driven) interferences

A consequence of the **dominant contribution of Z-penguins** in the 3-body decays and in neutrinoless conversion in nuclei

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

$\tau \to 3\mu$ $\Rightarrow$ *observation* of $Z \to \mu\tau$

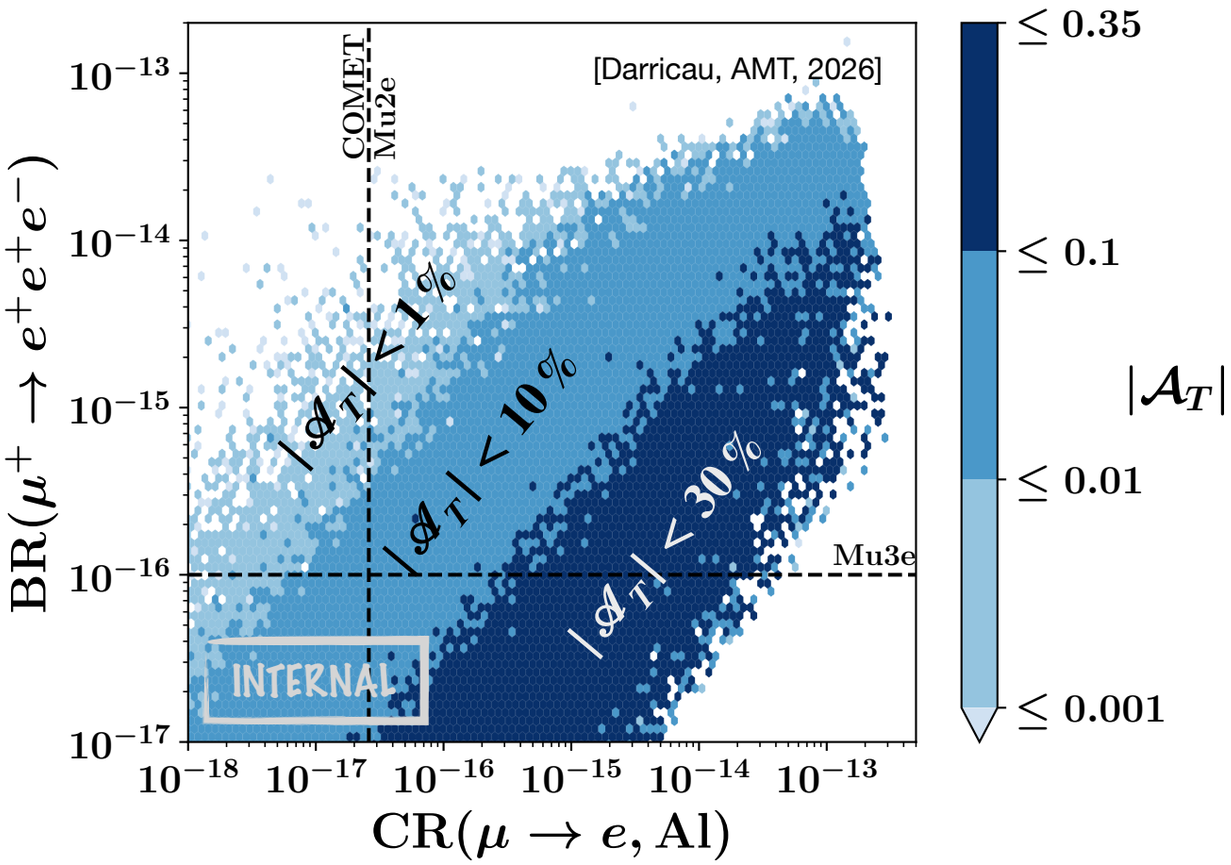
testability !?

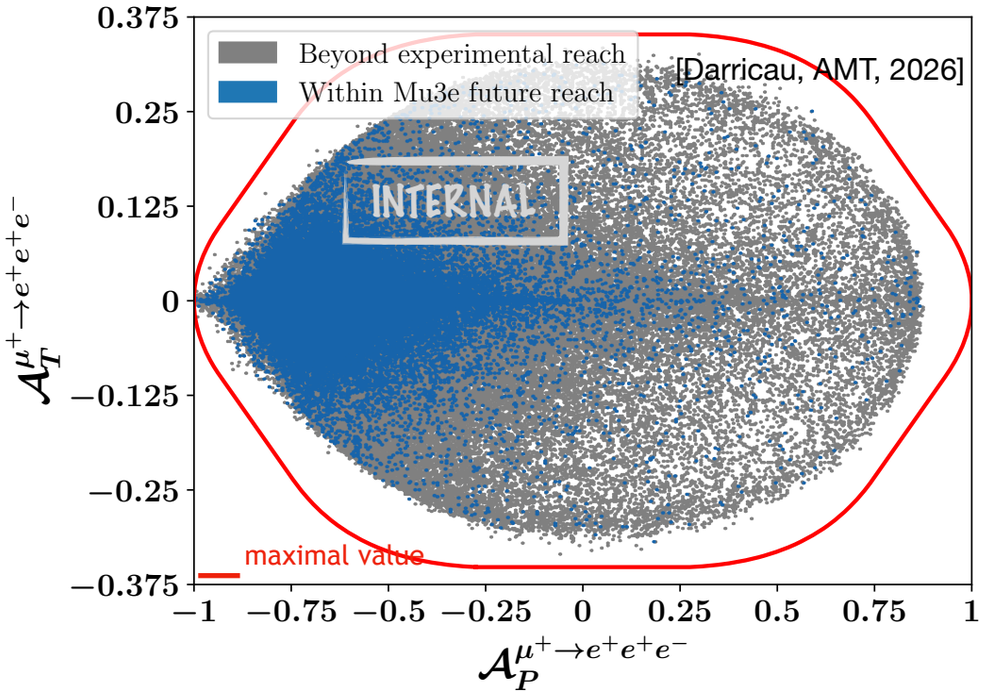
ISS(3,3): asymmetries in cLFV 3-body decays

Inverse seesaw: well-motivated **mechanism of neutrino mass generation**

*Abundant **cLFV contributions**...*

*and significant **interference effects** for generically large **CPV phases!***





- **Asymmetries** in $\mu \to 3e$ **decays & cLFV observables:**

  measurement of BR($\mu \to 3e$) together with $\mathcal{A}_T \geq \mathcal{O}(10\%)$

  $\Rightarrow$ **observation** of $\mu - e$ conversion by **COMET and Mu2e!**

  New **leptonic** sources of **CPV!**

(similar conclusions as for ad-hoc model)

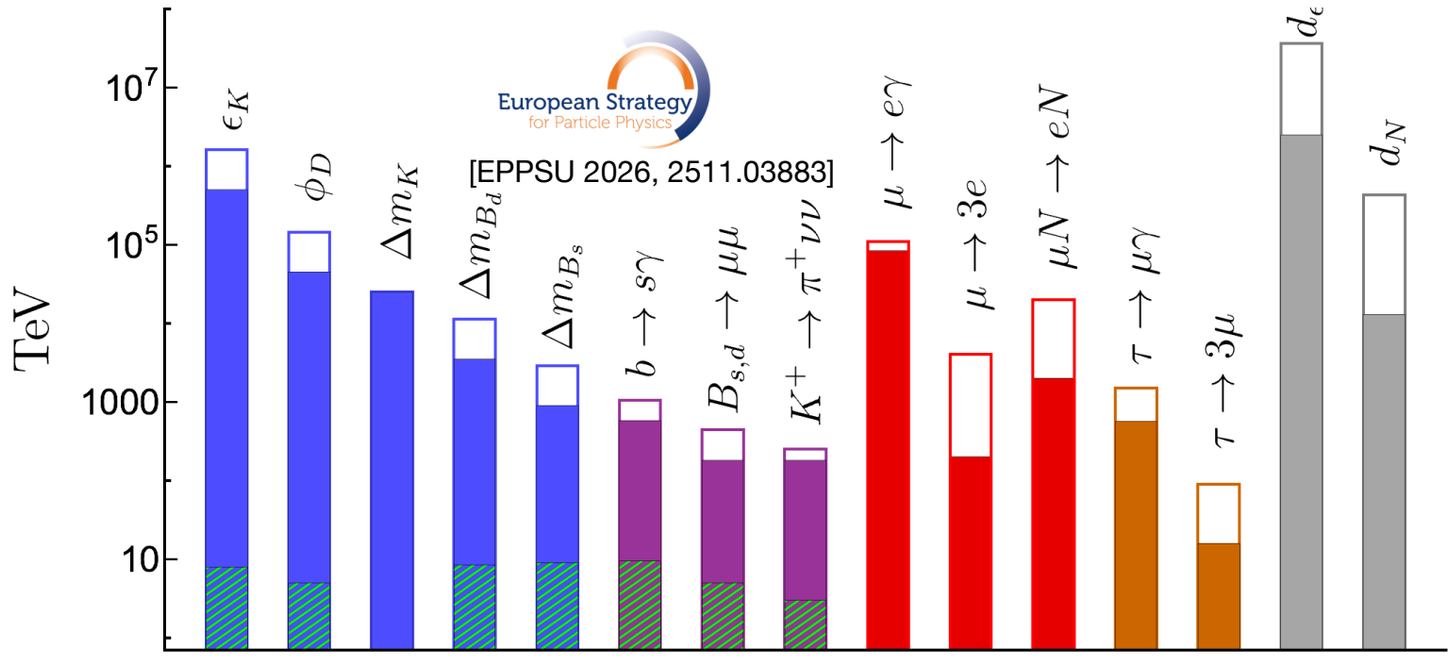
Concluding remarks



Outlook

Confirmed observations and theoretical caveats suggest the need to go **beyond the SM**

In the **lepton sector, ν-masses** provided the 1st laboratory **evidence of NP**



Lepton physics might offer valuable hints in **constructing and probing NP models**

New Physics can be **manifest via cLFV, LNV, ...** even before any **direct discovery!**

Synergies of (cLFV) lepton observables emerge as extremely **powerful probes** to test and falsify **NP in the lepton sector** *(consequence of potential operator dominance)*

Outlook

Heavy neutral leptons feature in very **appealing NP constructions** (ν-mass, BAU, ...) with extensive phenomenological implications (**cLFV**, LNV, colliders, among others)

HNL extensions of SM: *for CP conserving* regimes, operator dominance for various cLFV modes; **correlations** between observables can be used to **probe & falsify constructions...**

CPV phases are generically present (and required to address the BAU!) in HNL constructions and ***impact naïve expectations***, both theory predictions & experimental interpretation



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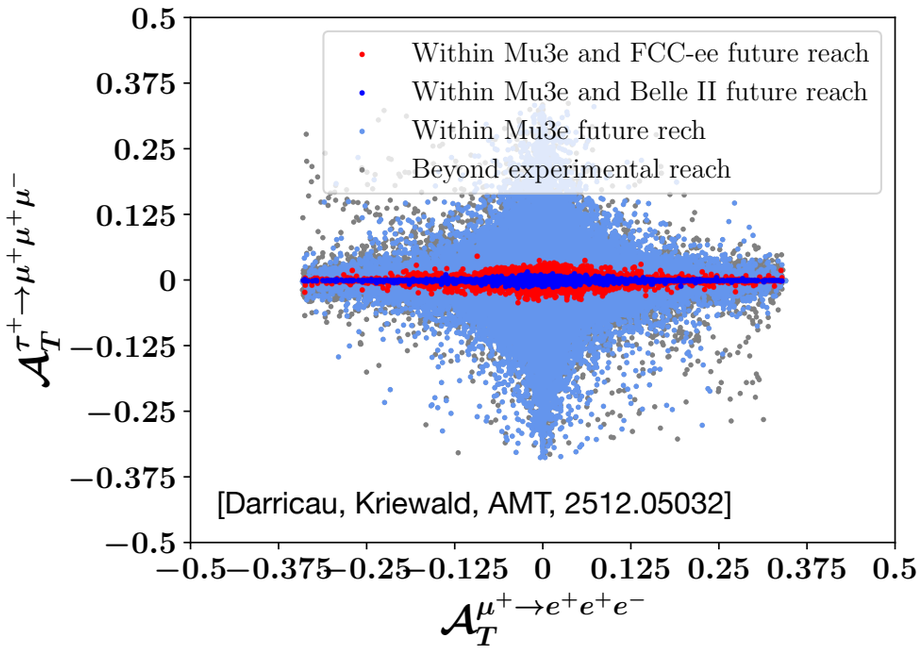
Extend the set of observables, aiming at recovering cLFV discriminating power:
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SM + HNL: large asymmetries expected in μ decays

Potential ***"falsifiability"*** **of HNL cLFV** recovered

⇒ **Exploitation of asymmetries** from the **onset of cLFV measurements !**

And a potential discovery of new leptonic CPV sources...



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Thank you for your attention !