# Charged lepton flavour violation: theory overview


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# Flavour and CP violation: SM

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

$Y^u_{ij}, Y^d_{ij}$ and $Y^\ell_{ij}$ $\rightsquigarrow$ encode **flavour** dynamics (masses, mixings & CP violation)
flavour-universal gauge interactions

**SM quark sector:** 6 massive states
flavour violated in charged current interactions $V^{ij}_{\text{CKM}}\, W^\pm \bar{q}_i q'_j$
conservation of total baryon number in SM interactions
CP violation sources: $\delta_{\text{CKM}}$ and $\theta_{\text{QCD}}$
(strongly constrained by **tiny** neutron **EDM**)
not enough to explain observed **BAU from baryogenesis**

Extensive probes of the **"CKM paradigm"**: meson oscillation and decays, CP violation...
... *and a roller-coaster ride for hints of New Physics in recent years!*

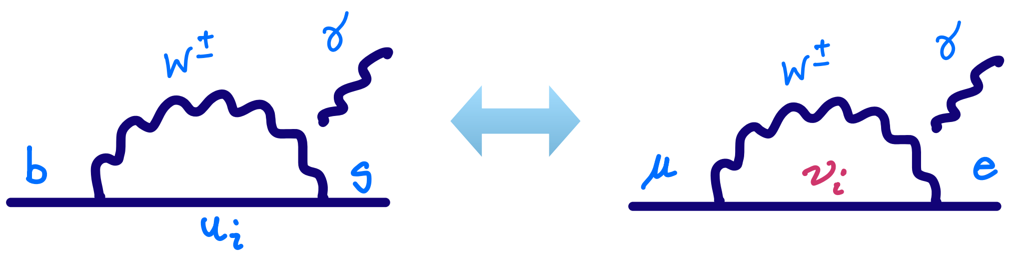
**SM lepton sector:** (strictly) **massless neutrinos**
**conservation** of total lepton number and lepton flavours
**tiny** leptonic **EDMs** (4-loop... $d_e^{\text{CKM}} \leq 10^{-38} e$ cm)

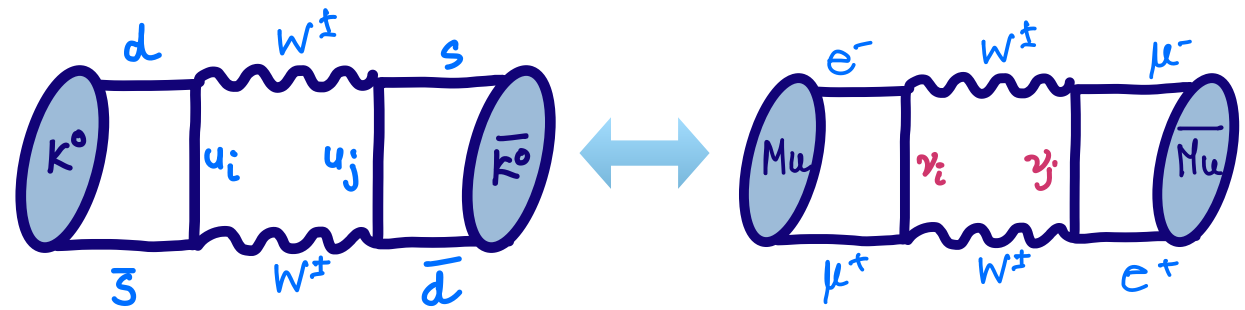
**Neutrino oscillations:** SM description **insufficient! First** laboratory **discovery of New Physics!**

# Lepton flavours: from $\nu$ oscillations...

**Neutrino oscillations:** SM description **insufficient!** Added complexity to the flavour problem...

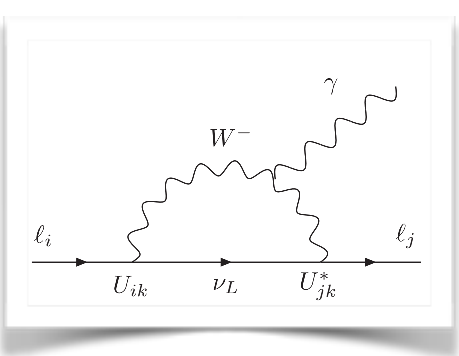
Violation of lepton flavour in neutral lepton sector opens a wide door
to flavour violation in the charged lepton sector!




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

In the most **minimal extension** $\text{SM}_{m_\nu}$ [$\text{SM}_{m_\nu}$ = "ad-hoc" $m_\nu$ (Dirac), $U_{\text{PMNS}}$]




$$\Gamma(\mu \to e\gamma) = \frac{m_\mu^5}{16\pi}\left(|A_L|^2 + |A_R|^2\right)$$

$$\sum_i \frac{U_{ei}^* U_{\mu i}}{(k^2 - m_i^2)} = \sum_i \frac{U_{ei}^* U_{\mu i}}{k^2} + \sum_i \frac{U_{ei}^* U_{\mu i}}{k^2}\left(\frac{m_i^2}{k^2}\right) + \mathcal{O}\left(\frac{m_i^4}{k^4}\right) \quad \& \quad \sum_i U_{ei}^* U_{\mu i} \frac{m_i^2}{M_W^2} = U_{e2}^* U^{e2} \frac{\Delta m_{21}^2}{M_W^2} + U_{e3}^* U^{e3} \frac{\Delta m_{31}^2}{M_W^2}$$

$$\text{BR}(\mu \to e\gamma) = \frac{3\alpha_e}{32\pi}\left|\sum_i U_{ei}^* U_{\mu i} \frac{m_i^2}{M_W^2}\right|^2 \qquad \Rightarrow \text{BR}(\mu \to e\gamma) \approx 10^{-54 \div -55}$$

# Lepton flavours: from $\nu$ oscillations...

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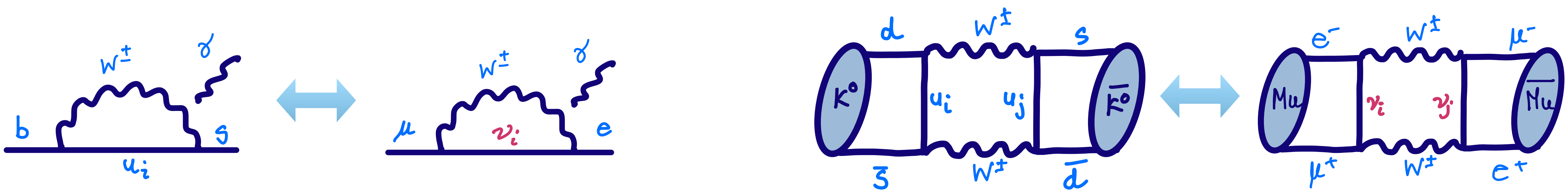


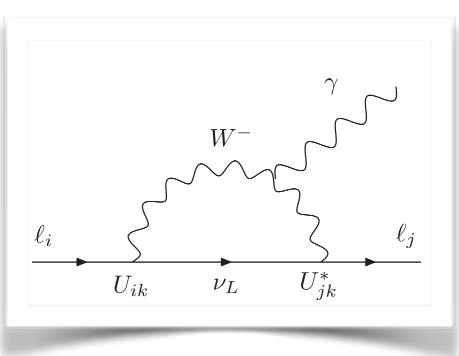

*How general is this once we extend the SM to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$?*

In the most **minimal extension** SM$_{m_\nu}$ [SM$_{m_\nu}$ = "ad-hoc" $m_\nu$ (Dirac), $U_{\text{PMNS}}$]

total **lepton number** still **conserved** (LNC)

lepton EDMs still beyond observation (2-loop contributions from $\delta_{\text{CP}}$)

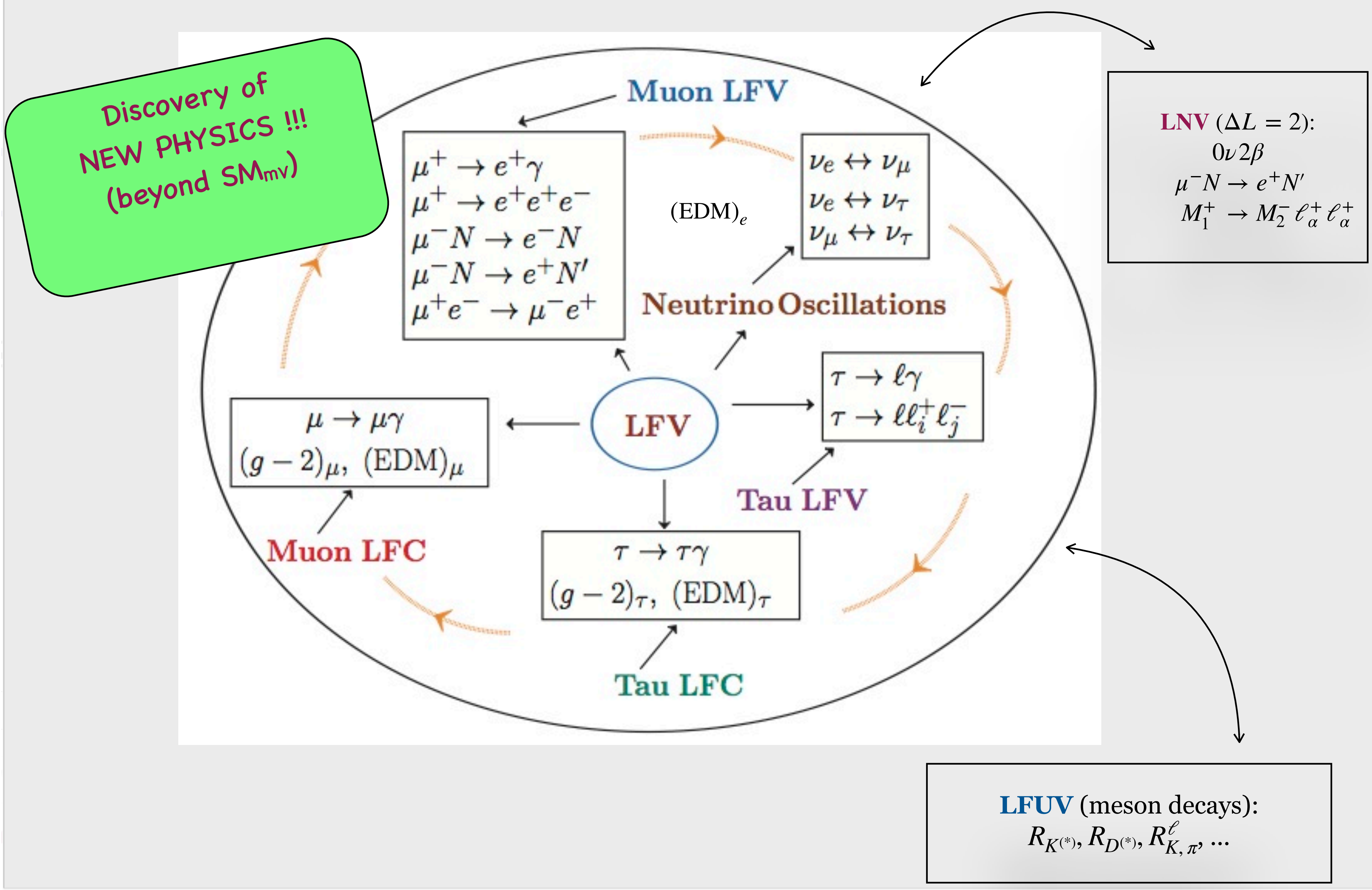
cLFV possible... but not observable!! **BR($\mu \to e\gamma$)** $\sim 10^{-54}$



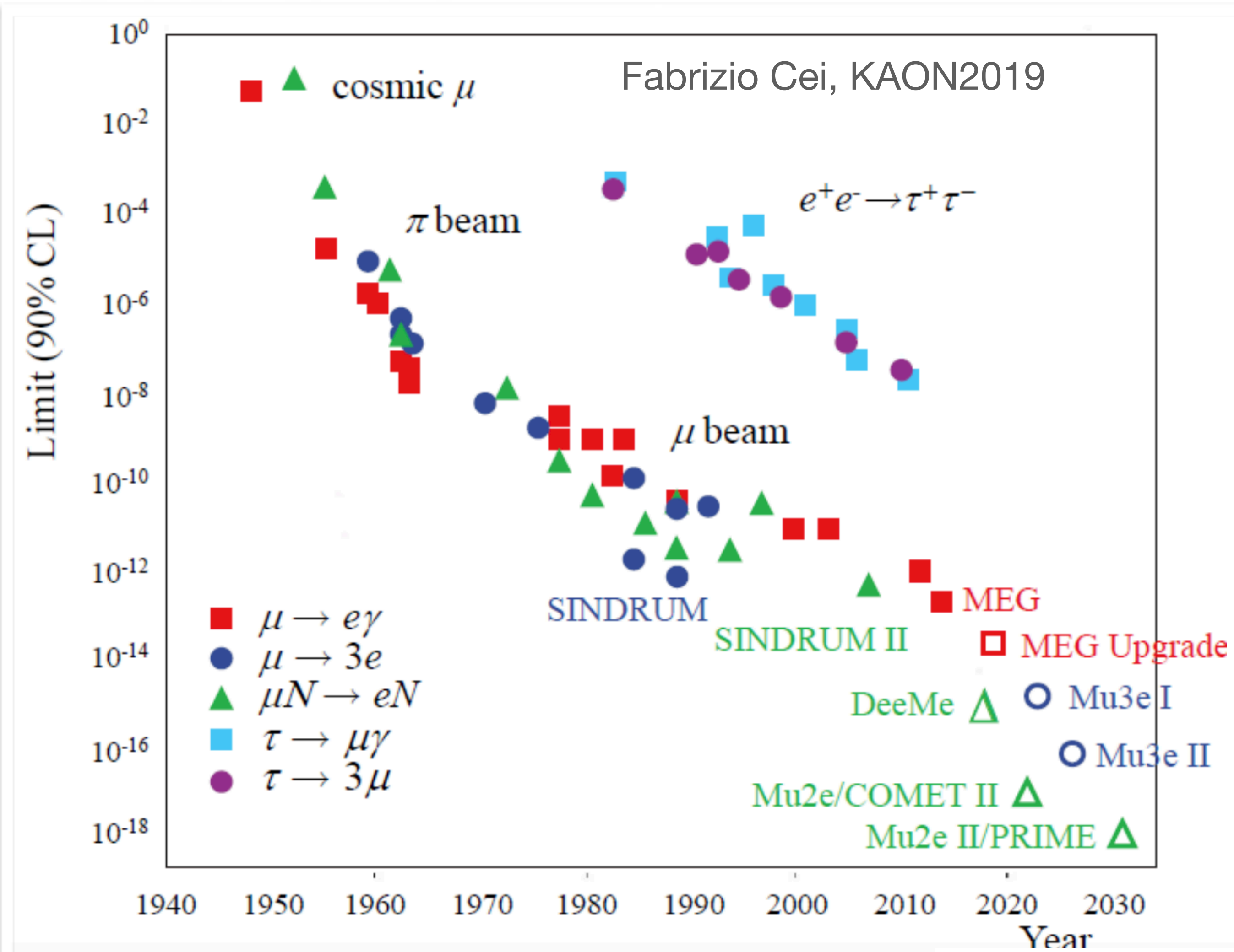

cLFV, LNV, lepton EDMs, ...: observation of SM-forbidden leptonic modes
$\Rightarrow$ Discovery of New Physics! (possibly before direct signal @ LHC)

# Lepton flavours: from $\nu$ oscillations...

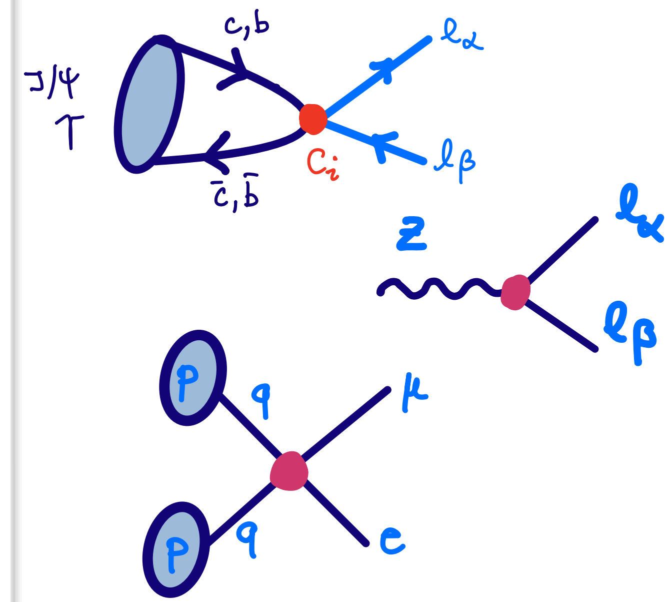
**Neutrino oscillations:** SM description **insufficient!** Added complexity to the flavour problem...



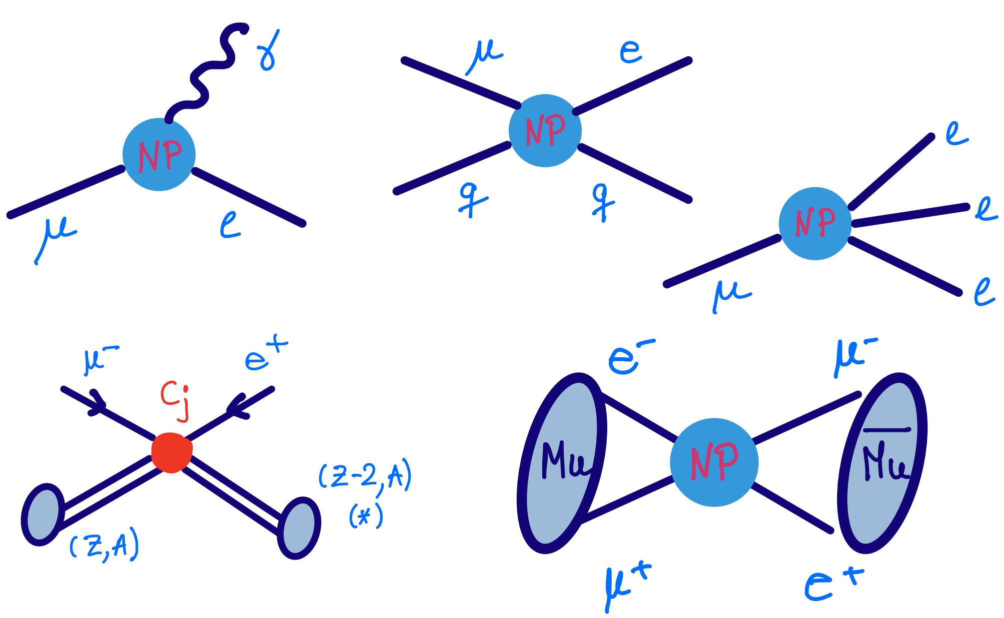
# Amazing prospects for NP searches - cLFV!

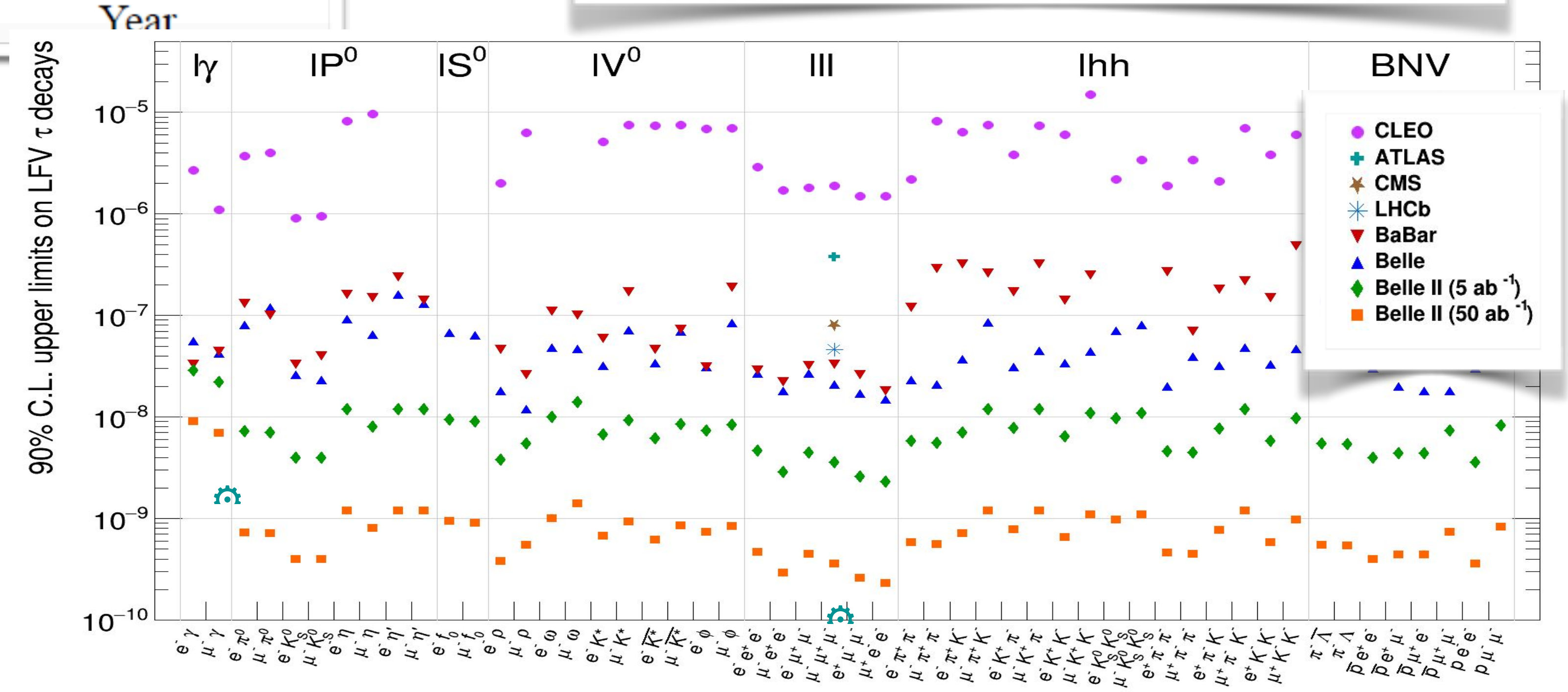



| | |
|---|---|
| $\pi^0 \to \mu e$ | $< 3.6 \times 10^{-10}$ |
| $K_L^0 \to \mu e$ | $< 4.7 \times 10^{-12}$ |
| $K_L^0 \to \pi^0 \mu^+ e^-$ | $< 7.6 \times 10^{-11}$ |
| $K^+ \to \pi^+ \mu^+ e^-$ | $< 1.3 \times 10^{-11}$ |
| $J/\psi \to \mu e$ | $< 1.5 \times 10^{-7}$ |
| $J/\psi \to \tau e$ | $< 8.3 \times 10^{-6}$ |
| $J/\psi \to \tau \mu$ | $< 2.0 \times 10^{-6}$ |
| $B^0 \to \mu e$ | $< 2.8 \times 10^{-9}$ |
| $B^0 \to \tau e$ | $< 2.8 \times 10^{-5}$ |
| $B^0 \to \tau \mu$ | $< 2.2 \times 10^{-5}$ |
| $B \to K \mu e^{(b)}$ | $< 3.8 \times 10^{-8}$ |
| $B \to K^* \mu e^{(b)}$ | $< 5.1 \times 10^{-7}$ |
| $B^+ \to K^+ \tau \mu$ | $< 4.8 \times 10^{-5}$ |
| $B^+ \to K^+ \tau e$ | $< 3.0 \times 10^{-5}$ |
| $B_s^0 \to \mu e$ | $< 1.1 \times 10^{-8}$ |
| $\Upsilon(1s) \to \tau \mu$ | $< 6.0 \times 10^{-6}$ |

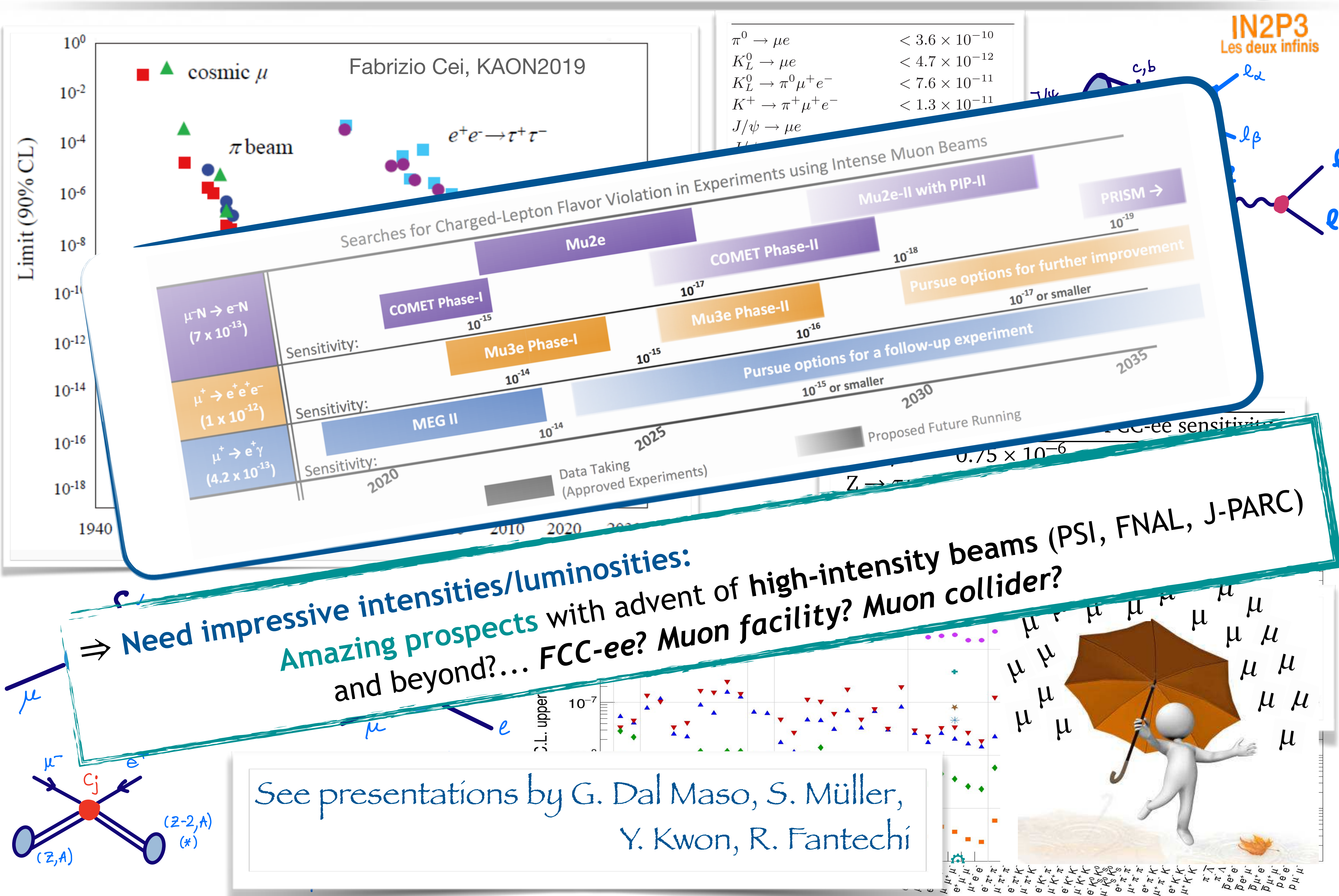



| Decay | Present bound | FCC-ee sensitivity |
|---|---|---|
| $Z \to \mu e$ | $0.75 \times 10^{-6}$ | $10^{-10}$–$10^{-8}$ |
| $Z \to \tau \mu$ | $12 \times 10^{-6}$ | $10^{-9}$ |
| $Z \to \tau e$ | $9.8 \times 10^{-6}$ | $10^{-9}$ |



# Amazing prospects for NP searches - cLFV!




⇒ **Need impressive intensities/luminosities:**
**Amazing prospects** with advent of **high-intensity beams** (PSI, FNAL, J-PARC)
and beyond?... ***FCC-ee? Muon facility? Muon collider?***

See presentations by G. Dal Maso, S. Müller,
Y. Kwon, R. Fantechi

# Flavour'ed paths: SM and beyond...

## Strong arguments in favour of New Physics!

- **Neutrino oscillations**: 1st laboratory ("flavoured") evidence of NP
  - ⇒ massive neutrinos and leptonic mixings $U_{\mathrm{PMNS}}^{\alpha i}$
  - ⇒ New (Majorana) fields? New sources of CP violation?
    $\Delta L \neq 0$ and leptogenesis... (?)
  - ⇒ **Open door for cLFV transitions and decays!**


**Observations unaccounted for in the SM:**
baryon asymmetry of the Universe, viable dark matter candidate,
neutrino oscillations *(and some "tensions"...)*

And a number of **theoretical** caveats...

Many **hints** and a clear **necessity** of **New Physics...**
**Which** NP model? Realised at which **scale** $\Lambda_{\mathrm{NP}}$?

⇒ **Unique opportunities to search for NP in the lepton sector via cLFV**
first characterisation of New Physics (scale, interactions) - **EFT approach**;
exploring connections to $\nu$ mass generation! ***(among many other possible BSM!)***

# New Physics EFT quests with (muon) cLFV

# EFT approach to New Physics

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

$\Rightarrow$ **Model-independent**, **effective field theory approach (EFT)**

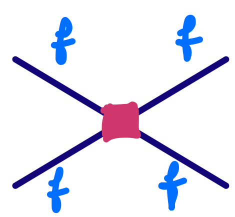
$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathscr{C}^n(g, Y, \ldots)\, \mathscr{O}^n(\ell, q, H, \gamma, \ldots)$$

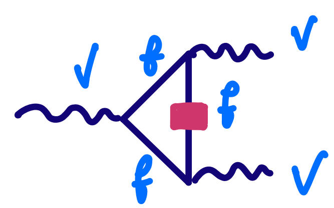
(unknown) NP **scale**

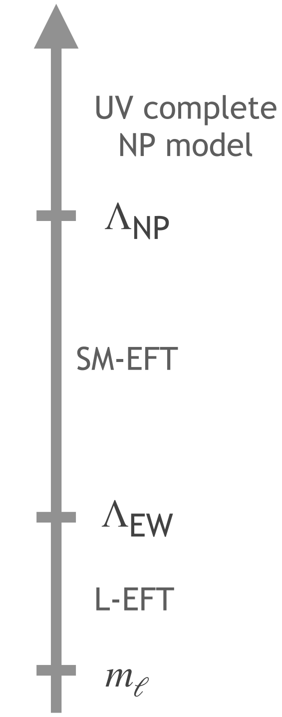
**effective** coefficients

effective **operators**

$\mathscr{O}^5 \rightsquigarrow$ Weinberg operator ($m_\nu$)
$\mathscr{O}^6 \rightsquigarrow$ flavoured contributions
(among many others!)








Derive the new "effective" interactions (vertices, ...), and compute contributions to observables

Agnostic approach, allowing to generically parametrise NP effects

on observables forbidden in SM and/or observables suggesting deviations from SM

$$\mathscr{A} \sim \mathscr{A}\left(\frac{\mathscr{C}^6}{\Lambda^2_{\text{NP}}}\right) + \ldots$$

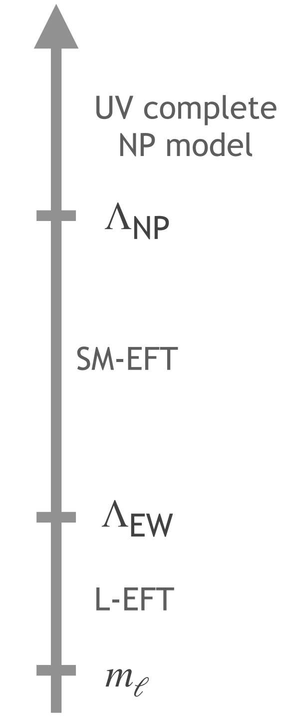
$$\mathscr{A} \sim \mathscr{A}^{\text{SM}} + \mathscr{A}\left(\frac{\mathscr{C}^6}{\Lambda^2_{\text{NP}}}\right) + \ldots$$

$\Rightarrow$ master SM prediction!

# EFT approach to New Physics

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

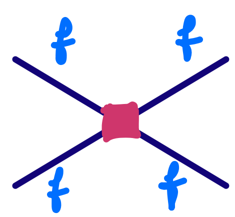
$\Rightarrow$ **Model-independent**, **effective field theory approach (EFT)**

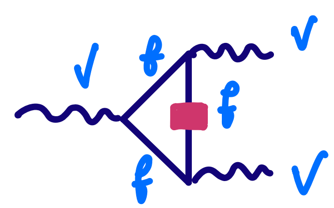



$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathscr{C}^n(g, Y, \ldots)\, \mathscr{O}^n(\ell, q, H, \gamma, \ldots)$$

(unknown) **NP scale** — effective coefficients — effective **operators**

$\mathscr{O}^5 \rightsquigarrow$ Weinberg operator ($m_\nu$)
$\mathscr{O}^6 \rightsquigarrow$ flavoured contributions (among many others!)





Cast current data (limits, ...) in terms of $\mathscr{C}^6_{ij}$ and $\Lambda^2_{\text{NP}}$

and attempt at **inferring info** on the dominant operator, and scale of NP

$\Rightarrow$ Beyond $(V-A)$ structure? New vector/axial, (pseudo)scalar or tensor currents?
Flavour violation beyond SM flavour paradigm?

$\Rightarrow$ But **many unknowns:** minimal assumptions must be made, e.g.

"natural" $\Lambda_{\text{NP}} \rightarrow$ constrain $\mathscr{C}^6_{ij}$

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

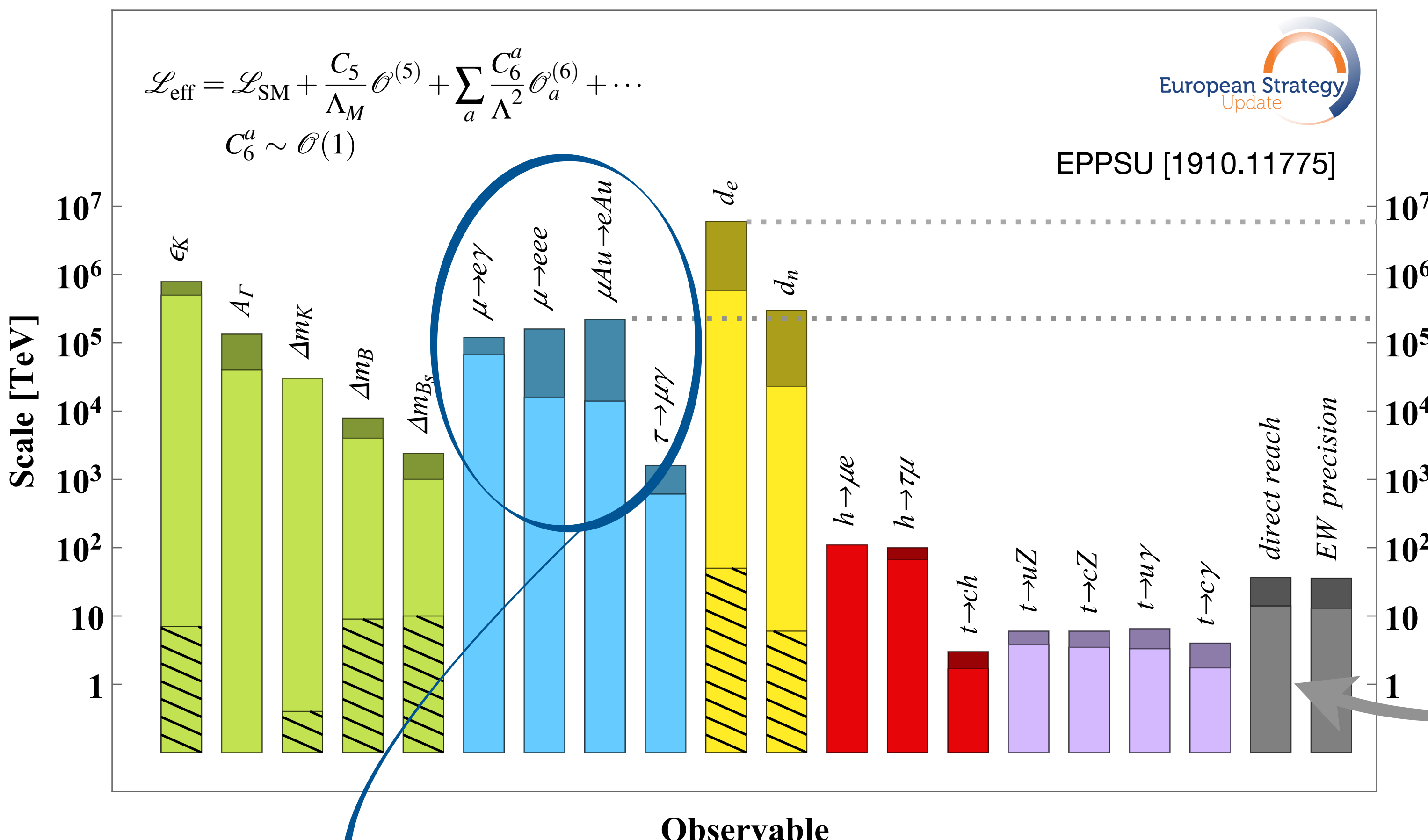
# The probing power of flavour & CPV

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

$\Rightarrow$ **Model-independent, effective approach (EFT)**

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

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




**Flavour 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!**

# EFT approach to New Physics: lepton flavours

- **Generic New Physics observables** in the lepton sector:
  - Lepton number violation (e.g. neutrino masses, $0\nu2\beta$ decays, ...)
  - Electric and (anomalous) magnetic moments - $d_\ell$, $(g-2)_\ell$
  - charged lepton flavour violation

Cast observables in terms of $\mathscr{C}_{ij}$ and $\Lambda_{\text{NP}}$; Apply current data (limits, ...)

$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \frac{\mathscr{C}_5\mathscr{O}^5}{\Lambda_{\text{LNV}}}(m_\nu) + \frac{\mathscr{C}_6\mathscr{O}^6}{\Lambda^2_{\text{cLFV}}}(\ell_\alpha \leftrightarrow \ell_\beta) + \ldots + \frac{\mathscr{C}_7\mathscr{O}^7}{\Lambda^3_{\text{LNV}}}(0\nu2\beta) + \ldots$$

Majorana $\nu$ masses

Kinetic corrections, ...
EW precision, top physics, ...
Electric dipole & anomalous magnetic moments, ...
cLFV (dipole, 3 body, matter assisted, ...)

Lepton number violation,
cLFV & LNV,
...

⇒ **cLFV data to constrain** $\mathscr{C}_{ij}$ and/or **infer sensitivity** of process to large sets of $\mathscr{C}_{ij}$

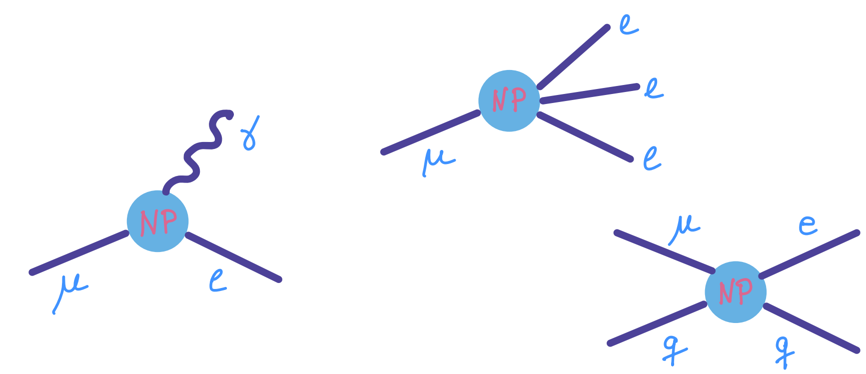
⇒ **Hints on** $\Lambda_{\text{NP}}$ (and on **properties** of new states & **nature** of couplings)

*Deceptively simple task...* different new physics scales, numerous operators!
Technically very involved, *even if no "SM background"...*

# Muon cLFV: EFT approach to New Physics

Cast current data (limits, …) in terms of $\mathscr{C}_{ij}$ and $\Lambda_{\rm NP}$: cLFV operators ($\mathscr{O}^6$)

$$\mathscr{L}^{\rm eff} = \mathscr{L}^{\rm SM} + \frac{\mathscr{C}_5 \mathscr{O}^5}{\Lambda_{\rm LNV}}(m_\nu) + \frac{\mathscr{C}_6 \mathscr{O}^6}{\Lambda^2_{\rm cLFV}}(\ell_\alpha \leftrightarrow \ell_\beta) + \ldots$$




**Simple *"one-at-a-time"* limits:**

| | $\mathrm{Br}(\mu^+ \to e^+\gamma)$ $4.2\cdot10^{-13}$ | $4.0\cdot10^{-14}$ | $\mathrm{Br}(\mu^+ \to e^+e^-e^+)$ $1.0\cdot10^{-12}$ | $5.0\cdot10^{-15}$ | $\mathrm{Br}^{\rm Au/Al}_{\mu\to e}$ $7.0\cdot10^{-13}$ | $1.0\cdot10^{-16}$ |
|---|---|---|---|---|---|---|
| $C^D_L$ | $1.0\cdot10^{-8}$ | $3.1\cdot10^{-9}$ | $2.0\cdot10^{-7}$ | $1.4\cdot10^{-8}$ | $2.0\cdot10^{-7}$ | $2.9\cdot10^{-9}$ |
| $C^{S\,LL}_{ee}$ | $4.8\cdot10^{-5}$ | $1.5\cdot10^{-5}$ | $8.1\cdot10^{-7}$ | $5.8\cdot10^{-8}$ | $1.4\cdot10^{-3}$ | $2.1\cdot10^{-5}$ |
| $C^{S\,LL}_{\mu\mu}$ | $2.3\cdot10^{-7}$ | $7.2\cdot10^{-8}$ | $4.6\cdot10^{-6}$ | $3.3\cdot10^{-7}$ | $7.1\cdot10^{-6}$ | $1.0\cdot10^{-7}$ |
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| $C^{T\,LL}_{\tau\tau}$ | $2.9\cdot10^{-9}$ | $9.0\cdot10^{-10}$ | $5.7\cdot10^{-8}$ | $4.1\cdot10^{-9}$ | $5.9\cdot10^{-8}$ | $8.5\cdot10^{-10}$ |
| $C^{S\,LL}_{bb}$ | $2.8\cdot10^{-6}$ | $8.6\cdot10^{-7}$ | $5.4\cdot10^{-5}$ | $3.8\cdot10^{-6}$ | $9.0\cdot10^{-7}$ | $1.2\cdot10^{-8}$ |
| $C^{T}_{bb}$ | $2.1\cdot10^{-9}$ | $6.4\cdot10^{-10}$ | $4.1\cdot10^{-8}$ | $2.9\cdot10^{-9}$ | $4.2\cdot10^{-8}$ | $6.0\cdot10^{-10}$ |
| $C^{V\,RR}_{ee}$ | $3.0\cdot10^{-5}$ | $9.4\cdot10^{-6}$ | $2.1\cdot10^{-7}$ | $1.5\cdot10^{-8}$ | $2.1\cdot10^{-6}$ | $3.5\cdot10^{-8}$ |
| $C^{V\,RR}_{\mu\mu}$ | $3.0\cdot10^{-5}$ | $9.4\cdot10^{-6}$ | $1.6\cdot10^{-5}$ | $1.1\cdot10^{-6}$ | $2.1\cdot10^{-6}$ | $3.5\cdot10^{-8}$ |
| $C^{V\,RR}_{\tau\tau}$ | $1.0\cdot10^{-4}$ | $3.2\cdot10^{-5}$ | $5.3\cdot10^{-5}$ | $3.8\cdot10^{-6}$ | $4.8\cdot10^{-6}$ | $7.9\cdot10^{-8}$ |
| $C^{V\,RR}_{bb}$ | $3.5\cdot10^{-4}$ | $1.1\cdot10^{-4}$ | $6.7\cdot10^{-5}$ | $4.8\cdot10^{-6}$ | $6.0\cdot10^{-6}$ | $1.0\cdot10^{-7}$ |
| $C^{RA}_{bb}$ | $4.2\cdot10^{-4}$ | $1.3\cdot10^{-4}$ | $6.5\cdot10^{-3}$ | $4.6\cdot10^{-4}$ | $1.3\cdot10^{-3}$ | $2.2\cdot10^{-5}$ |
| $C^{RV}_{bb}$ | $2.1\cdot10^{-3}$ | $6.4\cdot10^{-4}$ | $6.7\cdot10^{-5}$ | $4.7\cdot10^{-6}$ | $6.0\cdot10^{-6}$ | $1.0\cdot10^{-7}$ |

[Crivellin et al, 2017 (courtesy of M. Pruna)]

$\Rightarrow$ BR($\mu \to e\gamma$) depends on dipole $C_D$

(but mixing effects from RGE running and loop contributions render it **also sensitive** to scalar/tensor/vector contributions, even for $q\bar{q}$ operators)

*Unexpected findings!*

- Include as many observables & operators **as possible!**
  (e.g. $\mu e\gamma\gamma$ contact interactions, angular observables in polarised $\mu \to 3e$ decays, …)

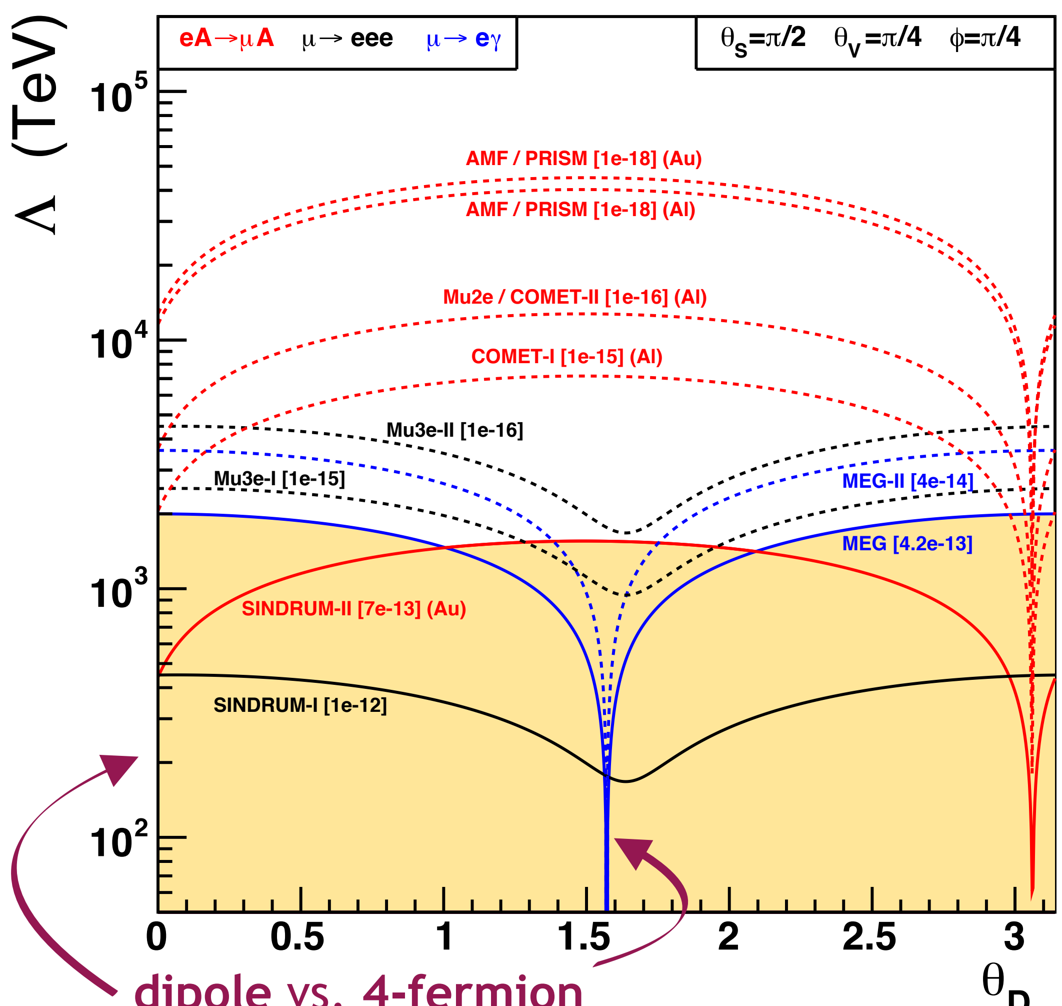
[Davidson et al, 2007.09612] [Bolton, Petcov, 2204.03468]

# Muon cLFV: EFT approach to New Physics

Recent (novel) **EFT** approach to **muon transitions:**

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

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




$$2\sqrt{2}\,C_D \approx \frac{\cos\theta_D}{\Lambda^2}$$

[Davidson & Echenard, 2204.00564]

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

*and likewise for other observables*

*BR($\mu \to 3e$), CR($\mu - e$, N), Muonium oscillations…*

**Sensitivity to NP scales (current & future):**

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

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

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

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

*[either dipole or 4f]*

# Muon cLFV: EFT approach & conversion in nuclei

⇒ **cLFV data to constrain** $\mathscr{C}^6$ (and **infer sensitivity** of a process **to operator** $\mathscr{O}^6$)

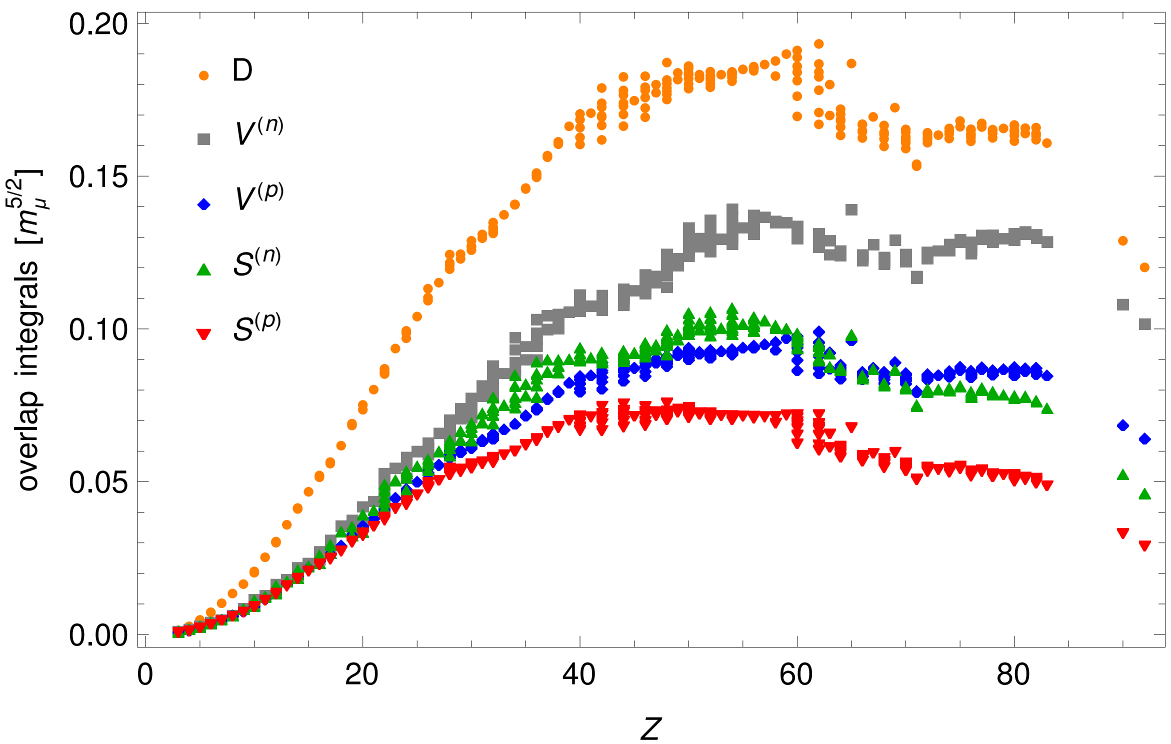
- Fully exploring the potential of atomic (elastic) **muon-electron conversion,** CR($\mu - e$,N):

  *Comparatively more involved theoretical approach!*

  **Explore target-nucleus dependence** to distinguish dominant operator (hint on **NP** model!)

  [extensive contributions since Kitano et al, 0203110! see Davidson et al, 1810.01884; Heeck et al, 2203.00702, ...; Haxton et al, 2406.12818]

$$\mathrm{BR}_{\mathrm{SI}}(\mu A \to eA) = \frac{32 G_F^2}{\Gamma_{\mathrm{capture}}} \left[ \left| C_{V,R}^{pp} V^{(p)} + C_{S,L}^{pp'} S^{(p)} + C_{V,R}^{nn} V^{(n)} + C_{S,L}^{nn'} S^{(n)} + C_{D,L} \frac{D}{4} \right|^2 + \{L \leftrightarrow R\} \right].$$




[Heeck et al, 2203.00702]

**Overlap integrals:**
**more distinguishable** at **large $Z$** !

*Better disentangle dominant NP contributions... but not "experimentally" feasible...*

# Muon cLFV: EFT approach & conversion in nuclei

CNRS IN2P3 Les deux infinis

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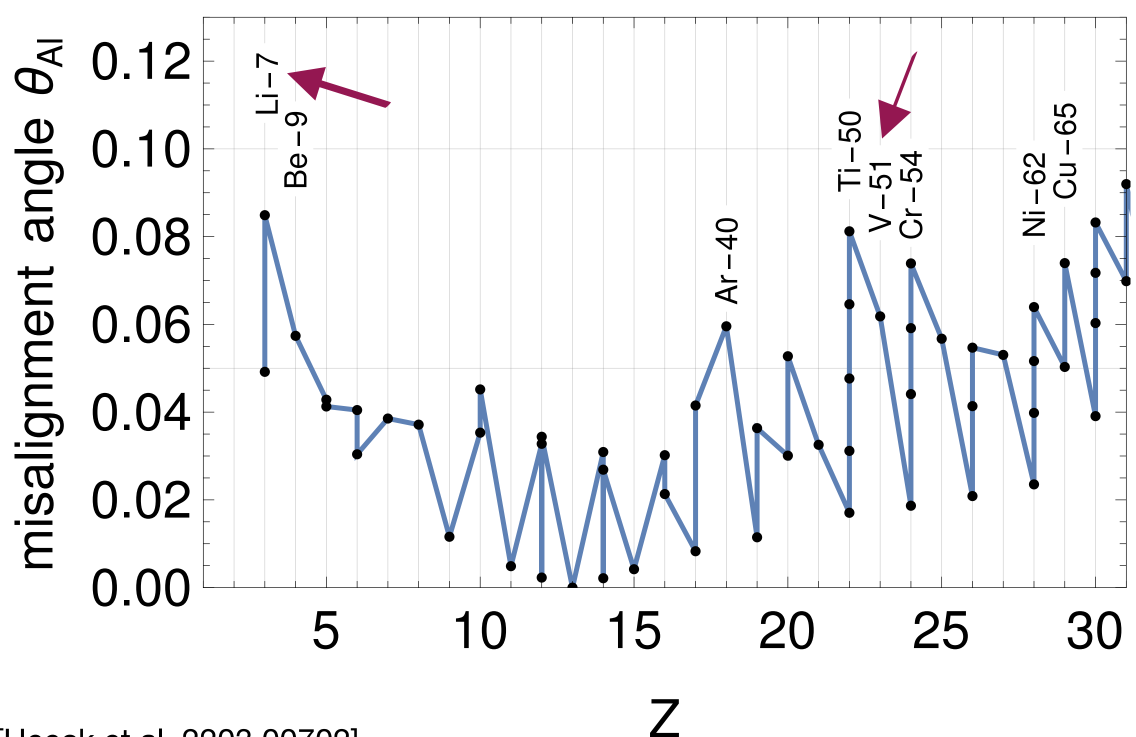
- Fully exploring the potential of atomic (elastic) **muon-electron conversion,** CR($\mu - e$,N):

  *Comparatively more involved theoretical approach!*

  **Explore target-nucleus dependence** to distinguish dominant operator (hint on **NP** model!)

  [extensive contributions since Kitano et al, 0203110! see Davidson et al, 1810.01884; Heeck et al, 2203.00702, ...; Haxton et al, 2406.12818]

In the advent of an observation (@ Mu2e, COMET ⇝ using Aluminium targets)
prepare **choice of future targets! Largest complementarity** with respect to Al? $\theta_{\mathrm{Al}}$




[Heeck et al, 2203.00702]

- **Heavier nuclei** (Au, Pb)! ... not feasible...
  (pulsed beams)
- Among experimental-friendly $Z \leq 25$ targets

  several (theoretically good) candidates
  Li-7, Ti-50, Ti-49, Cr-54, .., V-51

⇒ **Li-7 and/or V-51 :** preferable **"second" targets**
**post CR($\mu - e$,Al) observation**

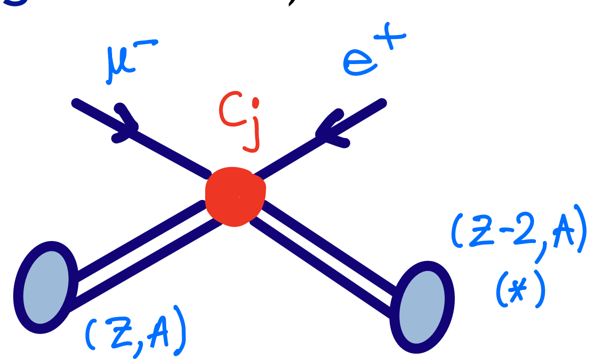
# Muon cLFV: EFT approach & conversion in nuclei

⇒ **cLFV data to constrain** $\mathscr{C}^6$ (and **infer sensitivity** of a process **to operator** $\mathscr{O}^6$)

- Fully exploring the potential of atomic (elastic) **muon-electron conversion,** CR($\mu - e$,N):

  *And of its lepton number violating counterpart,* $\boldsymbol{\mu^- + (A,Z) \to e^+ + (A, Z-2)^{(*)}}$

  A **unique connection** between **LNV** (in association with Majorana nature and possibly, neutrino mass generation) and **cLFV**




$\mu^- - e^-$ conversion: coherent process, single nucleon, nuclear ground states
$\mu^- - e^+$ conversion: 2 nucleons ($\Delta Q = 2$), possibly excited final state

From a theoretical point of view, not straightforward!

- Higher-dimension operators in $\mathscr{L}^{\text{eff}}$ (dim 6, 10, 14…)
- Nuclear matrix elements extremely hard to compute!

$$\Gamma^{\text{LNV}}_{\mu e} \approx \frac{G_F^4\, g_A^4}{32\pi^2}\,|\epsilon^2_{C_j}|\,\frac{m_e^2 m_\mu^2}{R^2}\,|F(Z-2, E_e)|\ <\phi_\mu>^2\ |\mathscr{M}^{(\mu^-,e^+)}|^2$$

(only two $\mathscr{M}^{(\mu^-,e^+)}$ known, for Ti-48…)

[Domin et al, 0409033; Simkovic et al, 0103029]

⇒ Very hard to draw implications… **Must tackle NME!**

# Tau cLFV: (semi-) leptonic modes

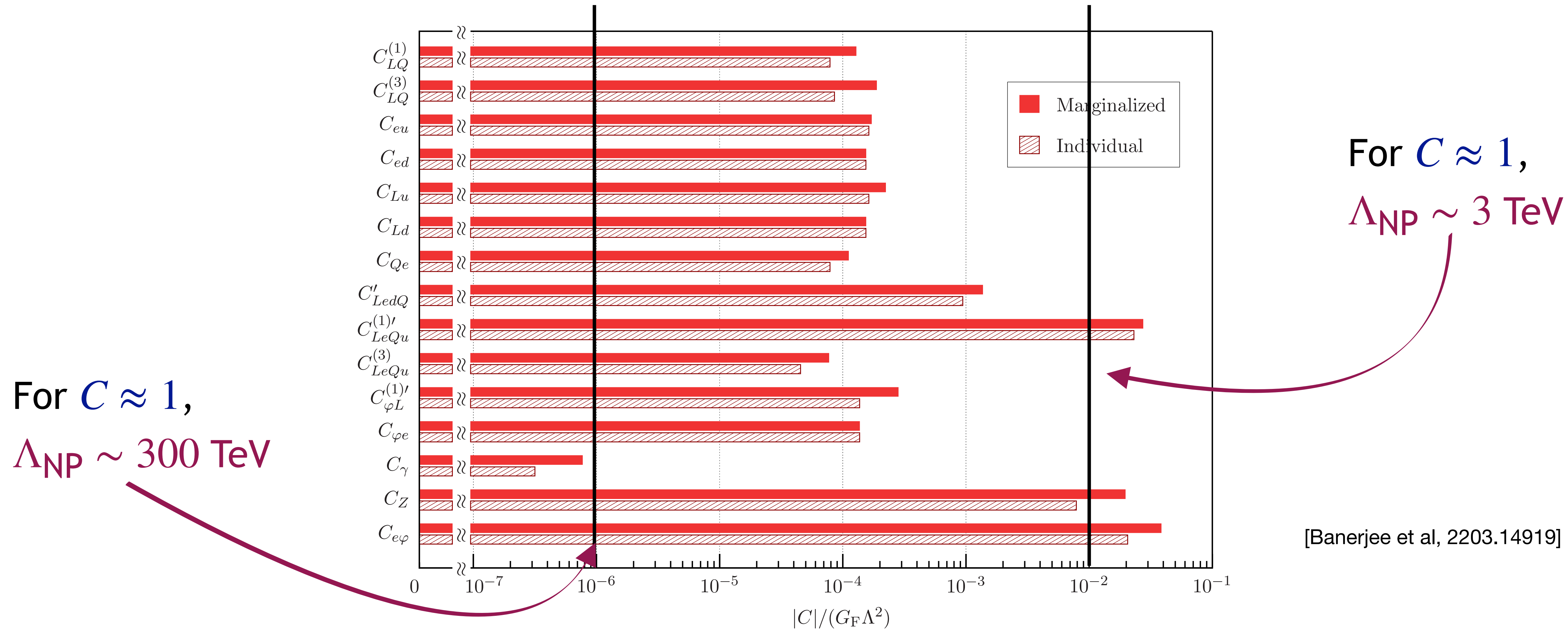
**Flavour violating tau decays:** comparatively **large number** of modes

Leptonic (radiative, three-body) as well as semi-leptonic (light mesons, 2- and 3-body)

⇒ theoretically much more involved (scales, hadronisation, ...)

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

⇒ more challenging to **disentangle** operator dominance... *(even @ tree level!)*




[Banerjee et al, 2203.14919]

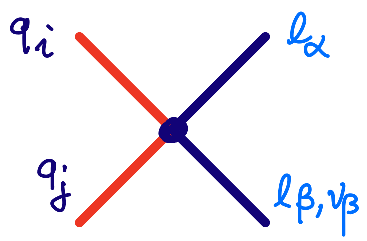
**Overview of Belle II limits** on relevant coefficients (and NP scales) for **cLFV tau decays**

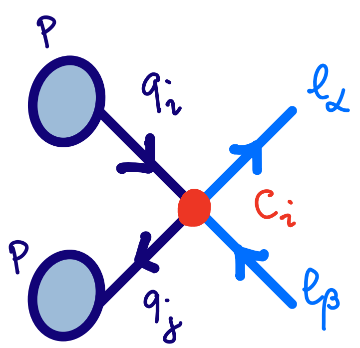
# cLFV at higher-energies: spinning operators

- Albeit leading to **formally different transitions**, the same leptonic and semi-leptonic operators can be at the origin of flavour violating transitions in very distinct contexts

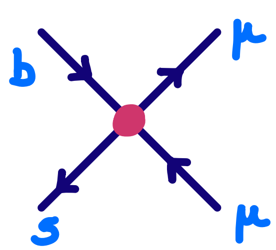
Consider a 4-fermion quark-lepton operator ($q_i\, q_j\, \ell_\alpha\, \ell_\beta$), with $i = j, \alpha \neq \beta$

One operator can source **rare LHC cLFV decays** (rich "flavour" content!),




$pp \to \ell_\alpha \ell_\beta$



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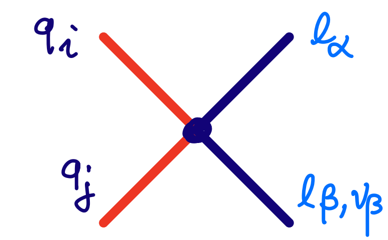
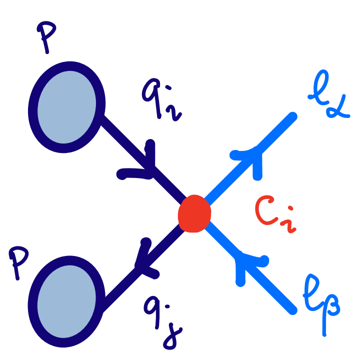



One operator can source rare LHC cLFV decays (rich "flavour" content!), cLFV semileptonic decays, muon-electron conversion, ...

[recent review, see Fernandez-Martinez et al, 2403.09772 ]

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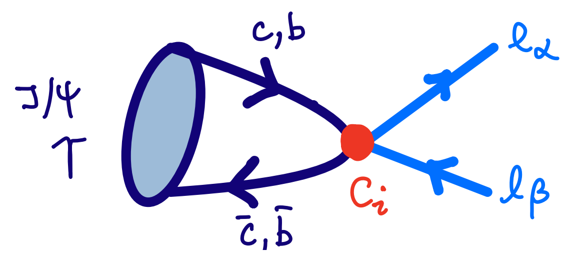
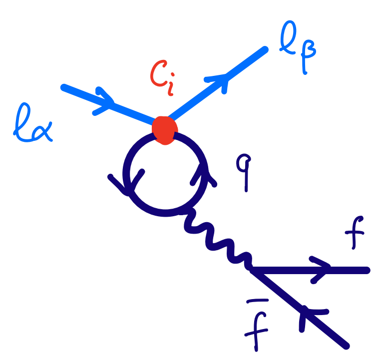
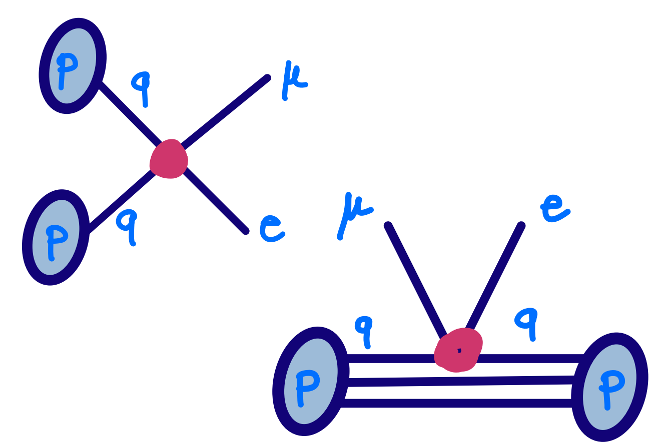
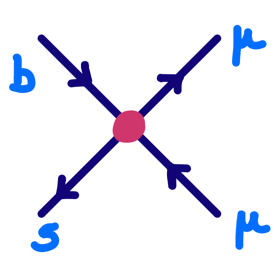



$J/\Psi \to \ell_\alpha \ell_\beta$

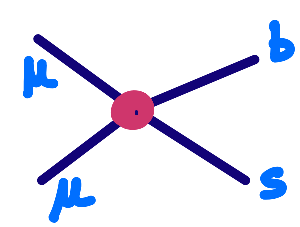



$\mu \to e, \mathrm{N}$

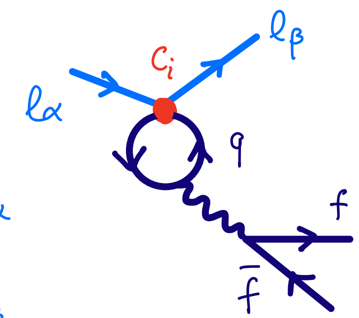



$\Rightarrow b \to s\ell\ell$ at a $\mu^+\mu^-$ collider

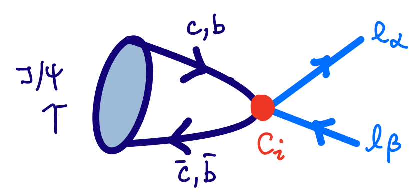


# Meson decays: cLFV and more

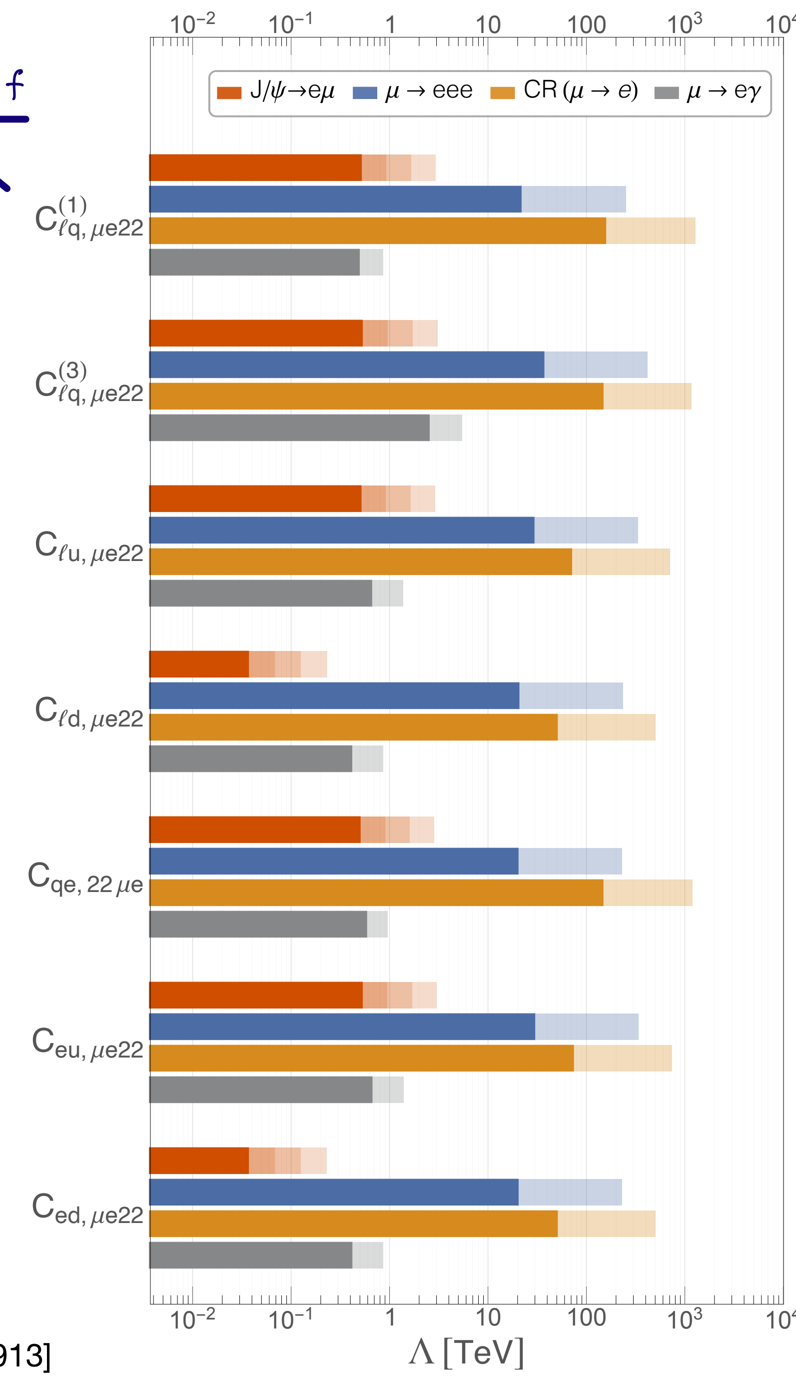
- **Meson decays:** excellent hunting grounds for **"leptophilic"** New Physics
  - ⇒ **deviations from SM** (lepton flavour universality violation, angular distributions, ...)
  - ⇒ **new phenomena** (**cLFV**, LNV, ...)




- **cLFV semileptonic meson decays!**




| 2q2ℓ operators | | | |
|---|---|---|---|
| $\mathcal{O}^{(1)}_{\ell q,prst}$ | $(\bar L_p \gamma_\mu L_r)(\bar Q_s \gamma^\mu Q_t)$ | $\mathcal{O}^{(3)}_{\ell q,prst}$ | $(\bar L_p \gamma_\mu \tau^I L_r)(\bar Q_s \gamma^\mu \tau^I Q_t)$ |
| $\mathcal{O}_{\ell u,prst}$ | $(\bar L_p \gamma_\mu L_r)(\bar u_s \gamma^\mu u_t)$ | $\mathcal{O}_{\ell d,prst}$ | $(\bar L_p \gamma_\mu L_r)(\bar d_s \gamma^\mu d_t)$ |
| $\mathcal{O}_{eu,prst}$ | $(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$ | $\mathcal{O}_{ed,prst}$ | $(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$ |
| $\mathcal{O}_{qe,prst}$ | $(\bar Q_p \gamma^\mu Q_r)(\bar e_s \gamma_\mu e_t)$ | $\mathcal{O}_{\ell edq,prst}$ | $(\bar L_p e_r)(\bar d_s Q_t)$ |
| $\mathcal{O}^{(1)}_{\ell equ,prst}$ | $(\bar L^a_p e_r)\epsilon_{ab}(\bar Q^b_s u_t)$ | $\mathcal{O}^{(3)}_{\ell equ,prst}$ | $(\bar L^a_p \sigma_{\mu\nu} e_r)\epsilon_{ab}(\bar Q^b_s \sigma^{\mu\nu} u_t)$ |
| **4ℓ operators** | | **Dipole operators** | |
| $\mathcal{O}_{\ell\ell,prst}$ | $(\bar L_p \gamma_\mu L_r)(\bar L_s \gamma^\mu L_t)$ | $\mathcal{O}_{eW,pr}$ | $(\bar L_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$ |
| $\mathcal{O}_{ee,prst}$ | $(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$ | $\mathcal{O}_{eB,pr}$ | $(\bar L_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ |
| $\mathcal{O}_{\ell e,prst}$ | $(\bar L_p \gamma_\mu L_r)(\bar e_s \gamma^\mu e_t)$ | | |
| **Lepton-Higgs operators** | | | |
| $\mathcal{O}^{(1)}_{\varphi\ell,pr}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar L_p \gamma^\mu L_r)$ | $\mathcal{O}^{(3)}_{\varphi\ell,pr}$ | $(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar L_p \gamma^\mu \tau^I L_r)$ |
| $\mathcal{O}_{\varphi e,pr}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$ | $\mathcal{O}_{e\varphi 3,pr}$ | $(\bar L_p e_r \varphi)(\varphi^\dagger \varphi)$ |




**Comparative study** of the **probing power of quarkonium** (charmonium) $\mu - e$ **cLFV decays** for relevant $\mathscr{C}_{\mu e} = 1$

[recent study - Calibbi et al, 2207.10913]

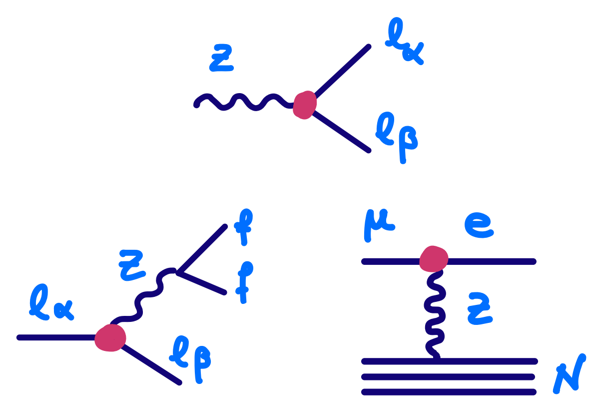
# Lepton flavours @ high Tera-Z

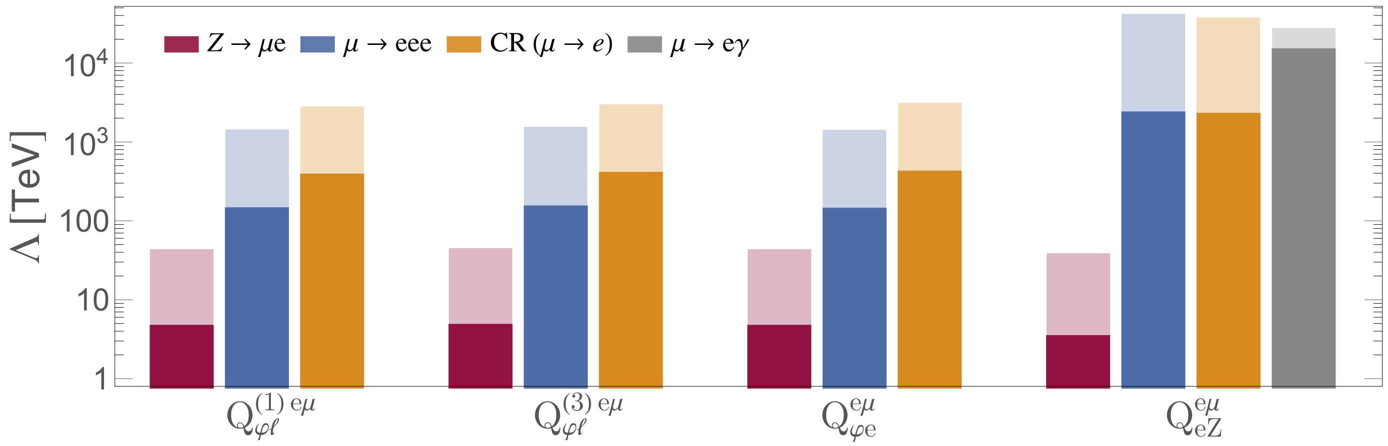
**High-energy colliders:** also **high-intensity frontier** (amazing luminosities!)

**LHC** ⤳ abundant sources of flavour in pp collisions

*(and also a Higgs-factory...)*

**TeraZ factory** (FCC-ee, CEPC) ⤳ **EW precision & flavour violation**




**TeraZ factory** ⤳ **cLFV $Z$ decays**

[Calibbi et al, 2107.10273]

For $Z \to \mu e$ better sensitivity of

**dedicated (low-energy) cLFV searches**

$\mu \to eee$, $\mu - e$ conversion

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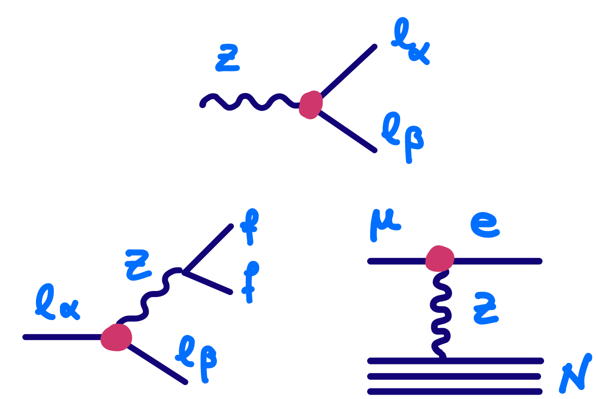


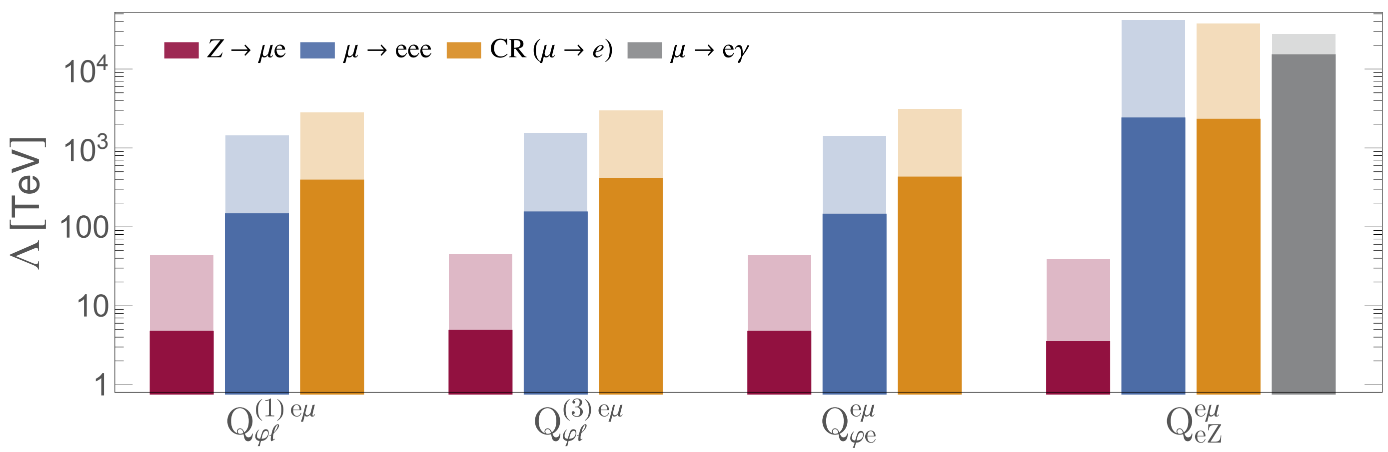


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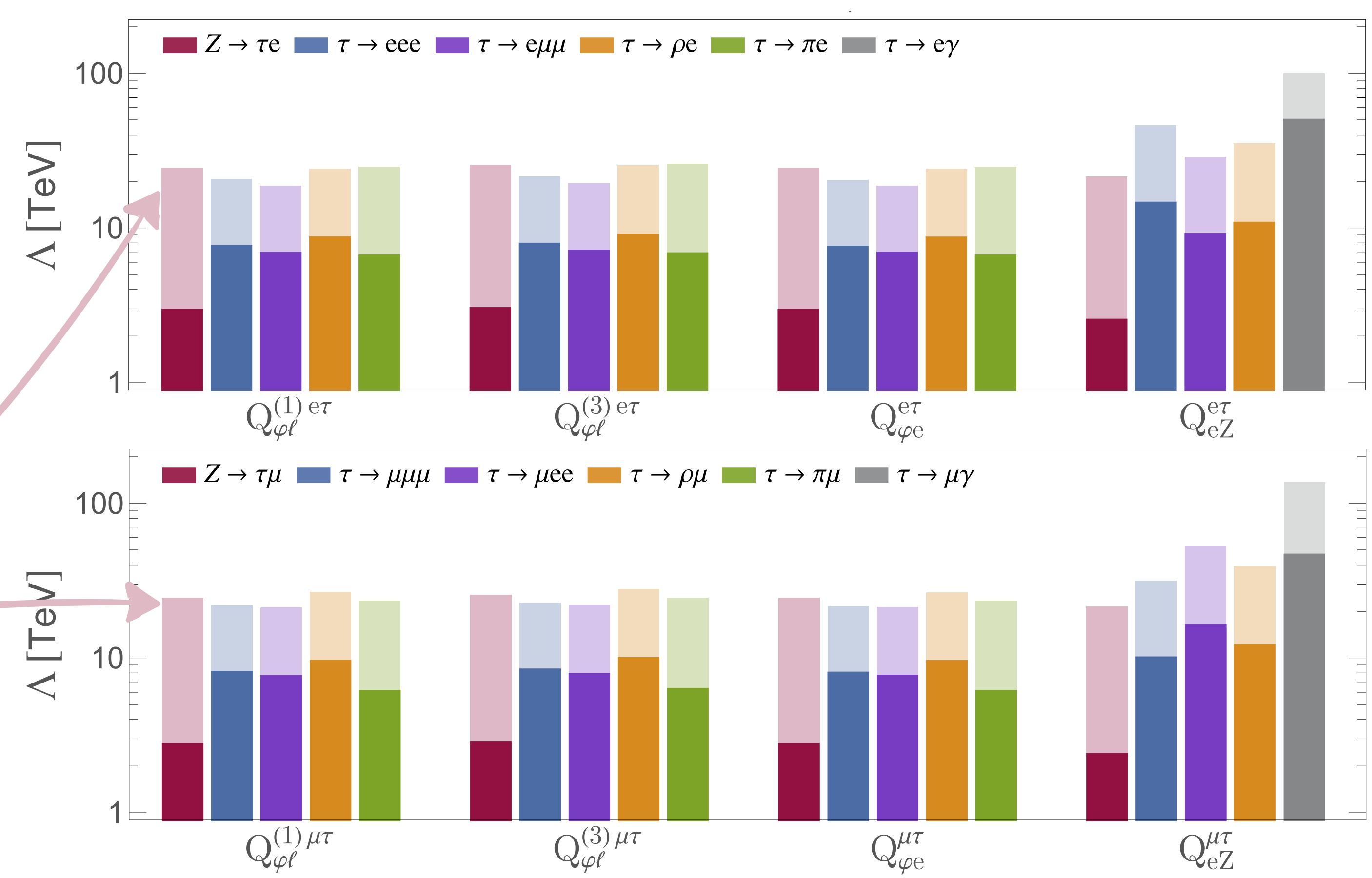



**Promising** potential of **TeraZ factory** to probe **NP** at the origin of $Z \to \tau\ell$ decays

*(competitive with low-energy cLFV)*

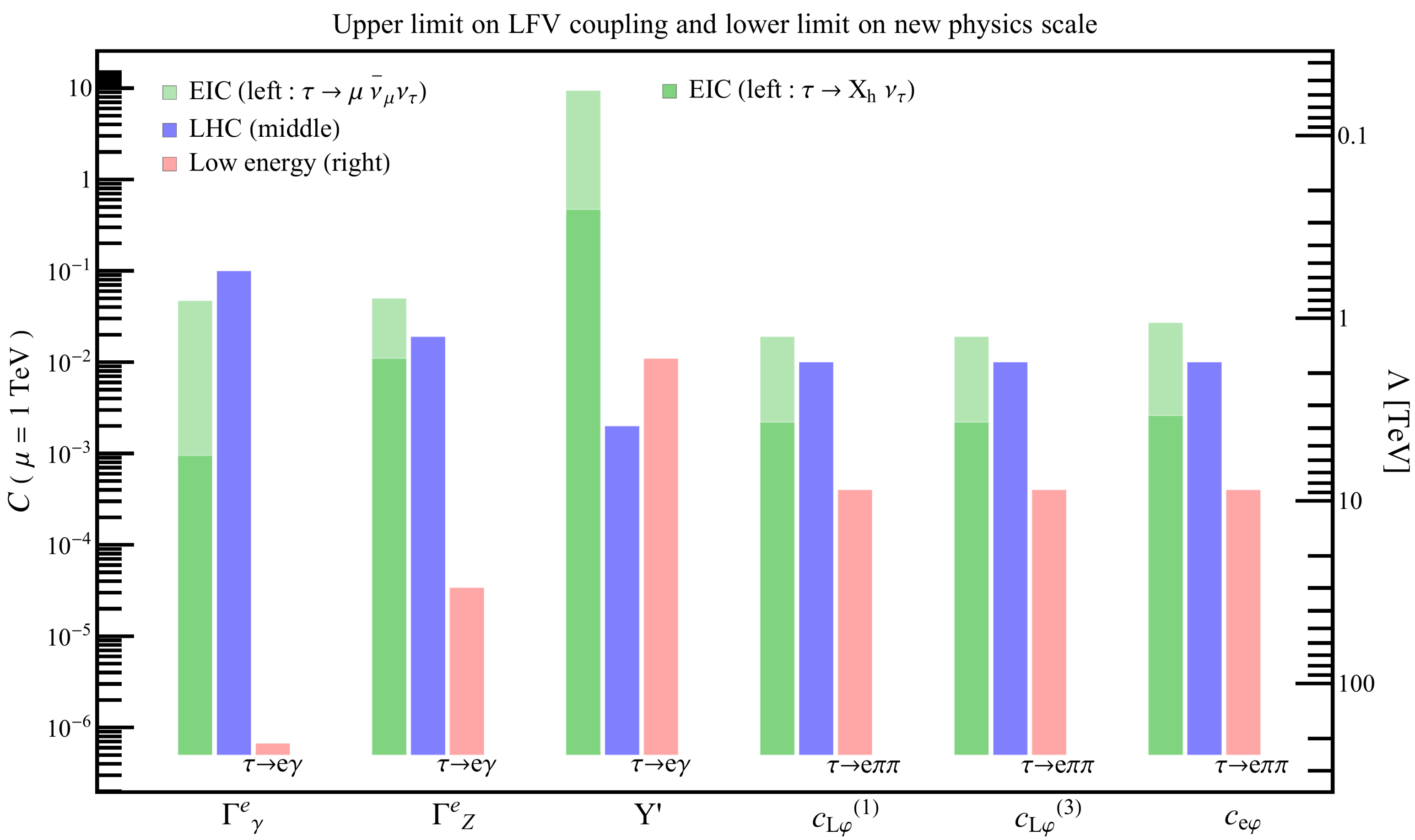
# And at electron-ion colliders (EIC)

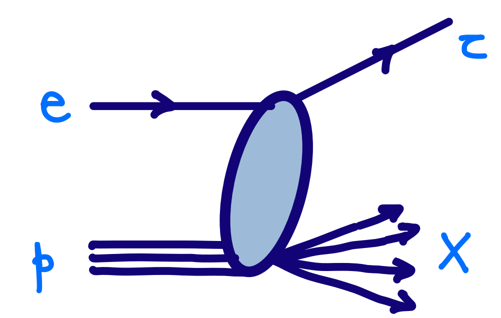
- **Electron-Ion colliders** also offer opportunities to **study cLFV!**

In general, less ambitious probing power (compared to LHC, and especially to dedicated low-energy experiments)

For $C \approx 1$, $\Lambda_{NP} \sim \mathcal{O}$(few TeV)

$$\frac{4\,G_F\,C}{\sqrt{2}} \equiv \frac{1}{\Lambda_{NP}}$$




$$e + p \rightarrow \tau + X$$

[Cirigliano et al, 2102.106176]

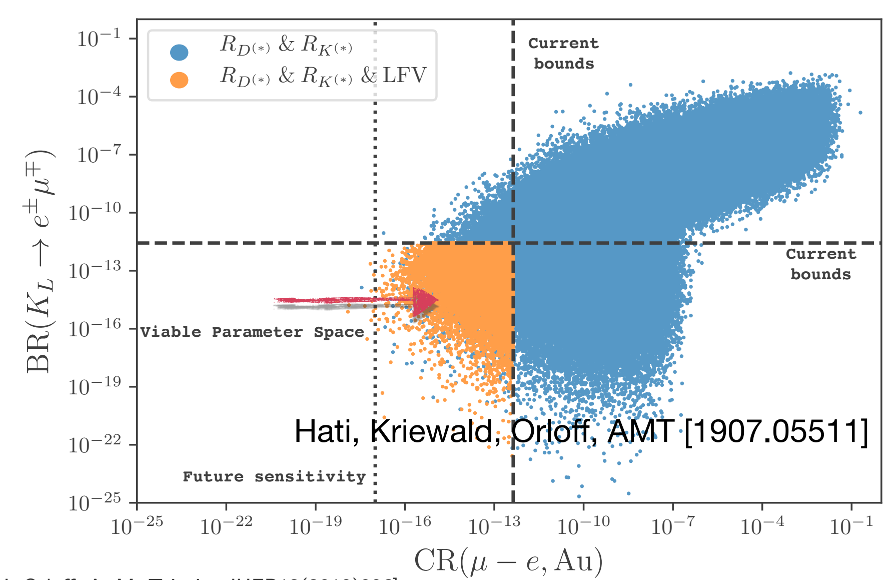
# After EFT - New Physics models of cLFV!

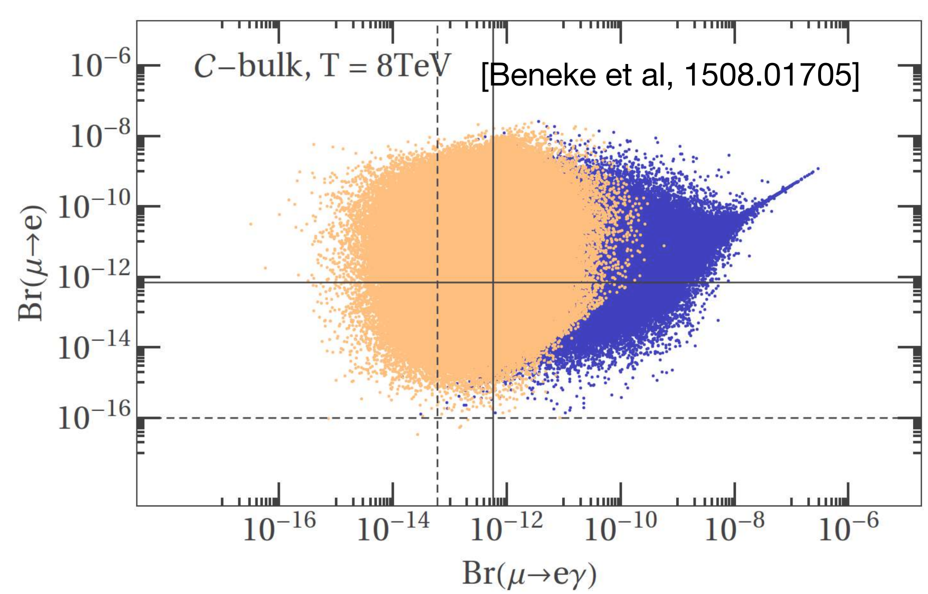
- **Effective approach:** *first characterisation* (mostly constraints & hints) on scale of NP and nature of new interactions (couplings and currents)

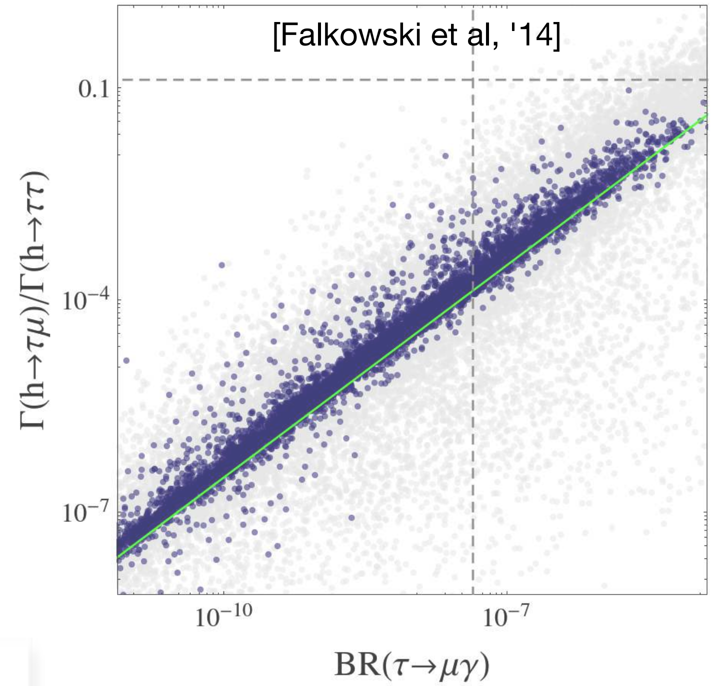
  ⇒ Ultimately we do *need to unveil the model of NP at work!*

- Although **oscillation data** (massive neutrinos) do **imply cLFV** *(direct consequence)*, **cLFV** can be **independent** of mechanism of neutrino mass generation

Supersymmetry: unconstrained models (beyond cMSSM, pMSSM), new sources of LFV
Rp-violating SUSY
Leptoquark models (extended field content); Extra-dimensions; extended Higgs sectors, ...




**cLFV : powerful means to test/falsify models of NP**

# After EFT - New Physics models of cLFV!

CNRS IN2P3 Les deux infinis

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

  $\Rightarrow$ Ultimately we do *need to unveil the model of NP at work!*

- Although **oscillation data** (massive neutrinos) do **imply cLFV** (direct consequence), **cLFV contributions** fully **independent** of mechanism of neutrino mass generation

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

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

Majorana $\nu$ masses

cLFV and many others

LNV (& cLFV), ...

*Not always trivial to establish connection between $\mathscr{C}_5$, $\mathscr{C}_6$ (and $\mathscr{C}_7$)*

**cLFV : powerful means to test/falsify models of NP $(m_\nu)$** *(examples ahead!)*

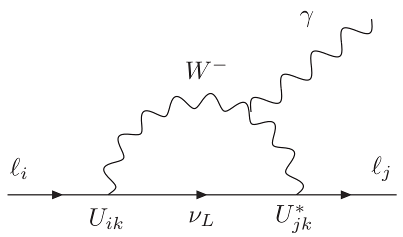
# New Physics paths to cLFV:
# seesaw models of neutrino mass generation

# New Physics and $m_\nu$: cLFV

## Neutrino masses (brief "how to"...)

Most minimal possibility: **SM extended** by Dirac RH neutrinos (impose L conservation)

$\Rightarrow \mathscr{L}_{m_\nu} \sim -Y^\nu L\tilde{H}\nu_R$ but tiny Yukawa couplings, $\mathcal{O}(10^{-13})$




Successfully accounting for oscillation data...

**No impact for** cLFV; GIM-like suppression due to smallness of $m_{\nu_i}$

BR$(\mu \to e\gamma) \sim 10^{-54}$ and similarly for **other observables...**

# New Physics and (Majorana) $m_\nu$: cLFV

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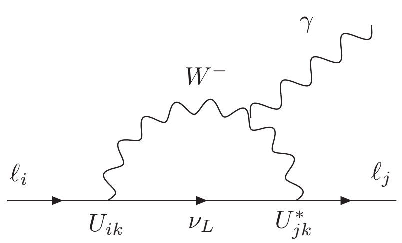
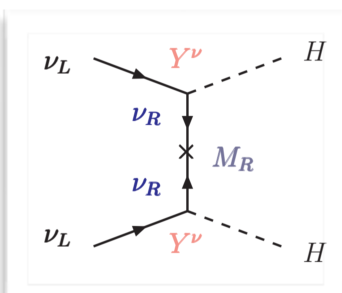



**No impact for cLFV**; GIM-like suppression due to smallness of $m_{\nu_i}$

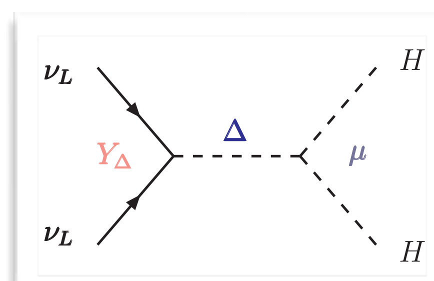
Allow for L violation: realisations of **Weinberg** operator! $\mathscr{L}^5_{m_\nu} \sim \frac{\mathscr{C}^5}{\Lambda_{\rm NP}} (\bar{L}^c H H L)$

### Tree-level seesaw realisations



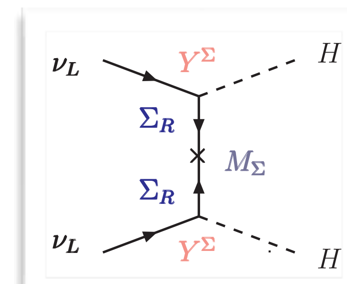

**Type I** (fermion singlet)

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




**Type II** (scalar triplet)

$$m_\nu \sim \frac{Y_\Delta \mu}{2} \frac{v^2}{M^2_\Delta}$$




**Type III** (fermion triplet)

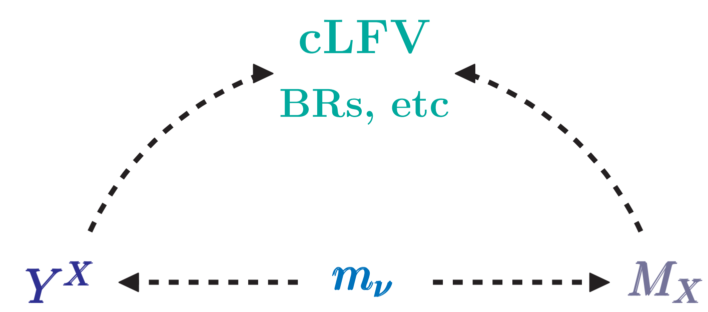
$$m_\nu \sim (Y_\Sigma v)^T \frac{1}{M_\Sigma} (Y_\Sigma v)$$

All successfully accounting for oscillation data... so far, *no hint from experimental searches!*

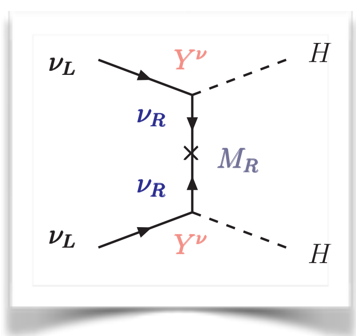
# Type I seesaw and cLFV

- **Mechanisms for neutrino mass generation:** delicate **"balance"** between **sources of flavour violation** and **masses of new propagators**

  $\Rightarrow$ account for **oscillation data** **(observation!)**




- **Type I Seesaw:** extend the SM via **(Majorana) sterile fermions**




$\rightsquigarrow$ an enlarged spectrum

$\rightsquigarrow$ extended mixings

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

$U^T \mathscr{M}_\nu^{6\times6} U = \text{diag}(m_{\nu_i})$ $\quad U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix}$

leptonic mixing $\approx U_{\text{PMNS}}$

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

# Type I seesaw and cLFV

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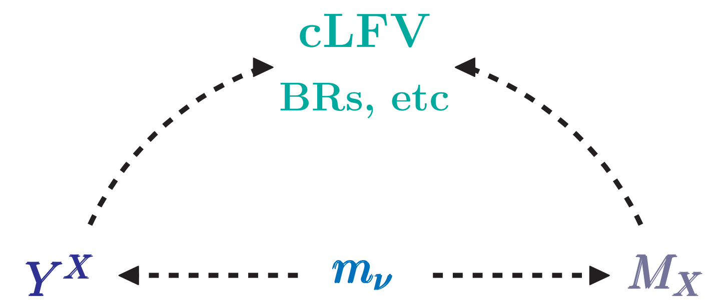


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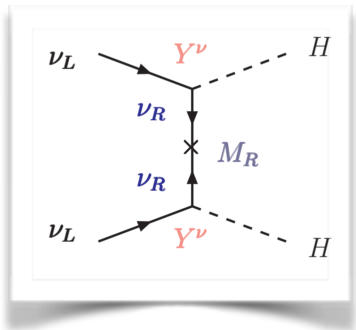
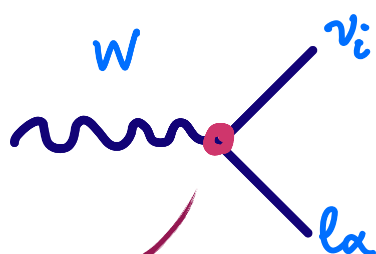



$$\mathcal{L}_{\text{Type I}} \supset v\, Y_\nu \bar{\nu}_L \nu_R + \frac{1}{2} M_R \bar{\nu}_R^c \nu_R$$

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

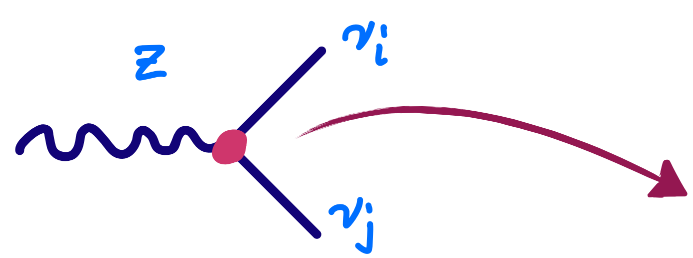
active-sterile mixings: $\nu_L - \nu_R$

$$\Rightarrow \theta \approx \mathcal{O}(m_D^\dagger M_R^{-1})$$




$$\propto \sum_{j=1}^{3+n_s} U_{\alpha j}$$

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




$$\propto \sum_{i,j=1}^{3+n_s} \left( \sum_\rho U^\dagger_{i\rho} U_{\rho j} \right)$$

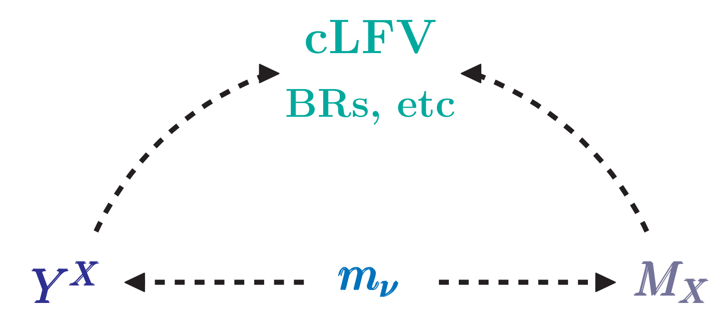
$$\propto (1-2\eta) U_{\text{PMNS}}$$

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

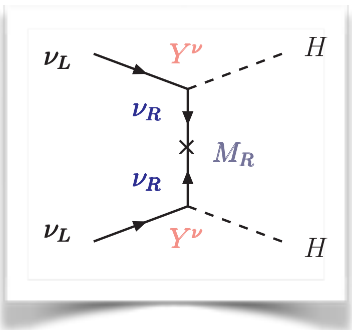
# Type I seesaw and cLFV

- **Mechanisms for neutrino mass generation:** delicate **"balance"** between **sources of flavour violation** and **masses of new propagators**

  $\Rightarrow$ account for **oscillation data** (**observation!**)




- **Type I Seesaw:** extend the SM via **(Majorana) sterile fermions**



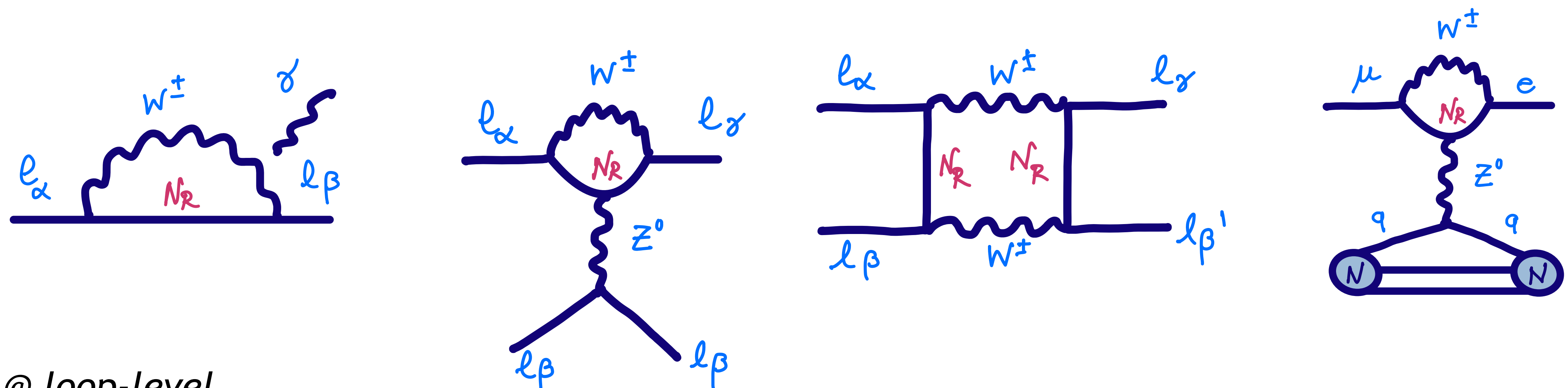

$$m_\nu \sim (Y^\nu v)^T \frac{1}{M_R} (Y^\nu v)$$

$$\mathscr{L}_{\text{Type I}} \supset v\, Y_\nu \bar{\nu}_L \nu_R + \frac{1}{2} M_R \bar{\nu}_R^c \nu_R$$

active-sterile mixings: $\nu_L - \nu_R$

$$\Rightarrow \theta \approx \mathcal{O}(m_D^\dagger M_R^{-1})$$

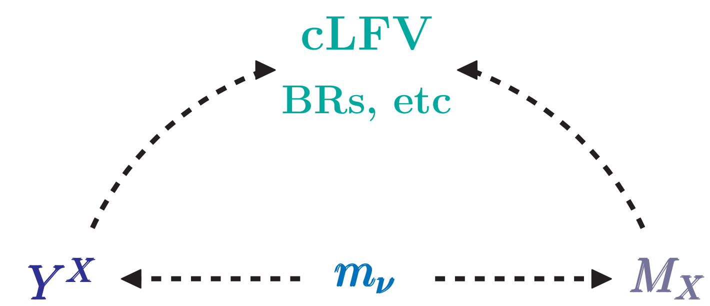
cLFV



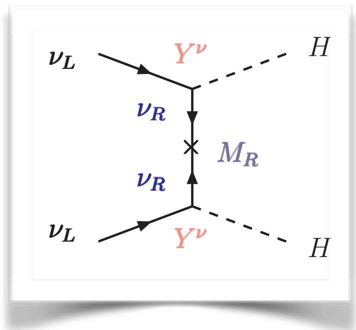

*All @ loop-level...*

# Type I seesaw and cLFV

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




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




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

If **light neutrino masses** generated by **"natural"** new physics $\Rightarrow$ very **high energy NP scale**

$Y^\nu \sim \mathcal{O}(1)$ $\quad$ $M_R \sim 10^{14-16}$ GeV

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

leptonic mixing $\approx U_{\text{PMNS}}$
(**unitary** to very good approximation)

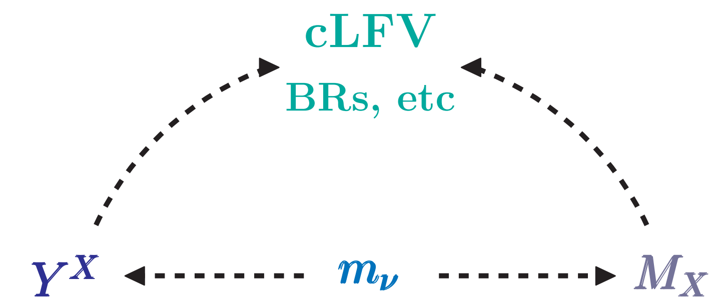
**negligible** active-sterile mixings $(\theta \propto m_D^\dagger M_R^{-1})$

$\Rightarrow$ Decoupled new physics! No contributions for cLFV observables, no resonance within collider reach...

# Type III seesaw and cLFV

- **Mechanisms for neutrino mass generation:** delicate "balance" between sources of flavour violation and masses of new propagators

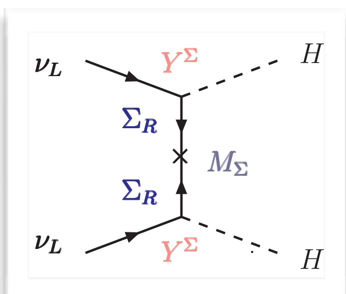
  $\Rightarrow$ account for oscillation data (**observation!**)




- **Type III Seesaw:** extend the SM via SU(2) triplet fermions

  $\rightsquigarrow$ an enlarged spectrum

  $\rightsquigarrow$ extended mixings




$$m_\nu \sim (Y_\Sigma v)^T \frac{1}{M_\Sigma} (Y_\Sigma v)$$

$$\Sigma = \Sigma^+, \Sigma^0, \Sigma^-$$

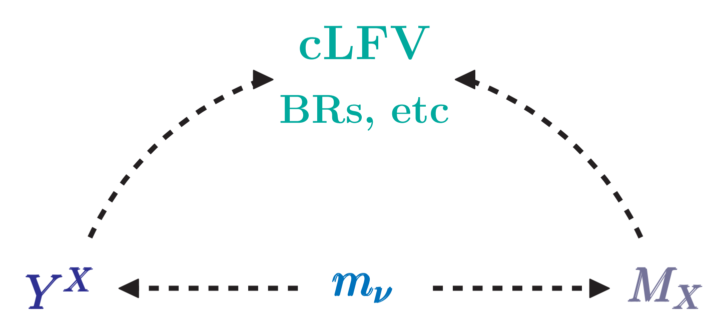
$$\mathscr{L}_{\text{Type III}} \supset v\, Y_\Sigma \Sigma^+ \ell^- + v\, Y_\Sigma \Sigma^0 \nu + M_\Sigma \bar{\Sigma} \Sigma$$

Fermion-triplet mixings: $\Sigma^0 - \nu$ and $\Sigma^{+c} - \ell^-$

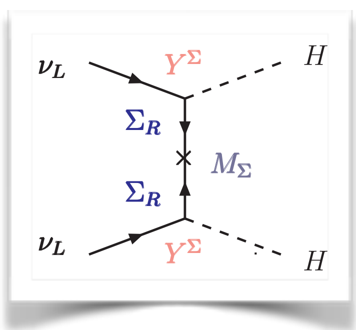
$$\Rightarrow \theta \approx \mathcal{O}(v Y_\Sigma M_\Sigma^{-1})$$

# Type III seesaw and cLFV

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




- **Type III Seesaw:** extend the SM via SU(2) **triplet fermions**




$\rightsquigarrow$ an enlarged spectrum

$\rightsquigarrow$ extended mixings

$$m_\nu \sim (Y_\Sigma v)^T \frac{1}{M_\Sigma} (Y_\Sigma v)$$

$$\Sigma = \Sigma^+, \Sigma^0, \Sigma^-$$

$$\mathscr{L}_{\text{Type III}} \supset v\, Y_\Sigma \Sigma^+ \ell^- + v\, Y_\Sigma \Sigma^0 \nu + M_\Sigma \bar{\Sigma} \Sigma$$

Fermion-triplet mixings: $\Sigma^0 - \nu$ and $\Sigma^{+c} - \ell^-$

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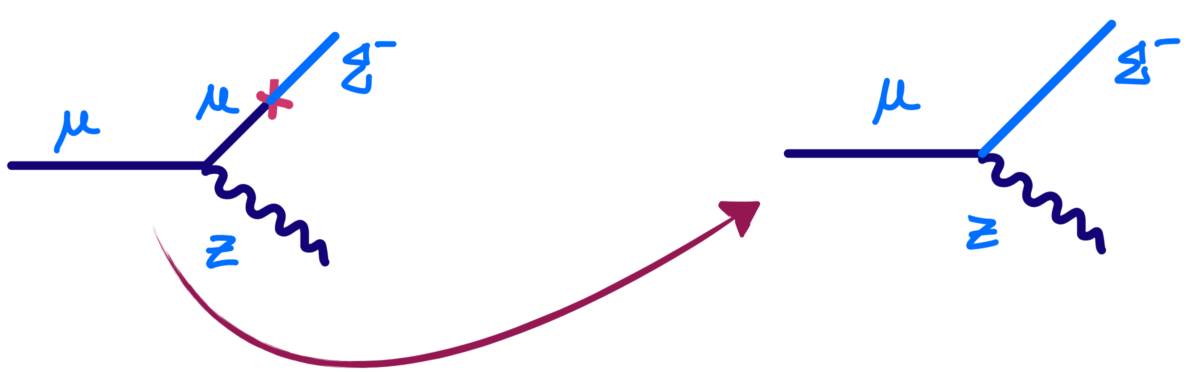
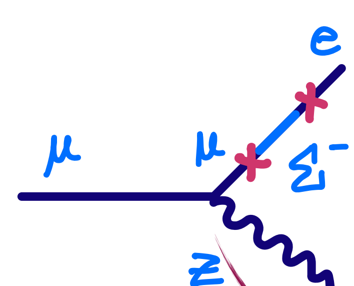
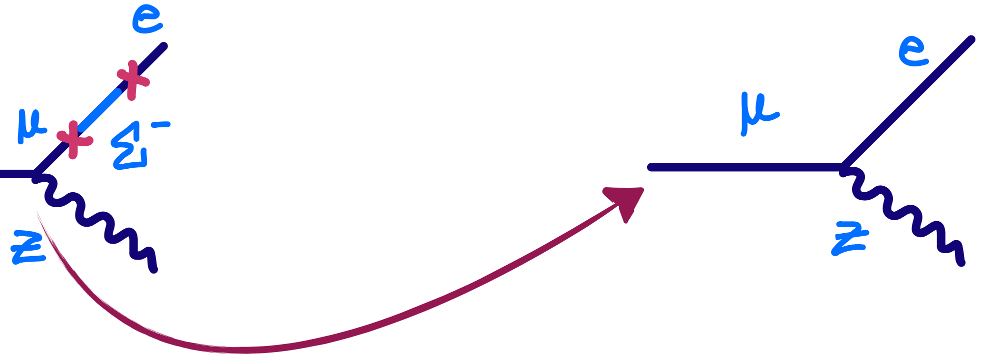


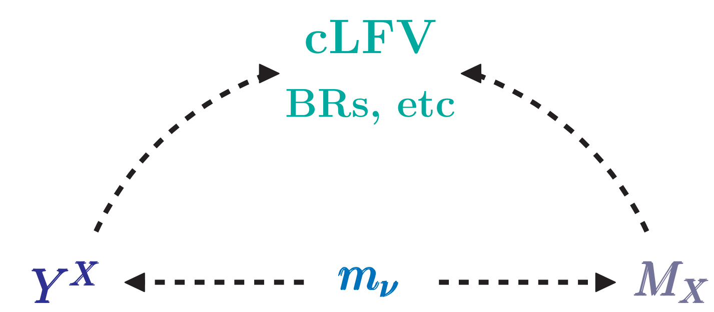



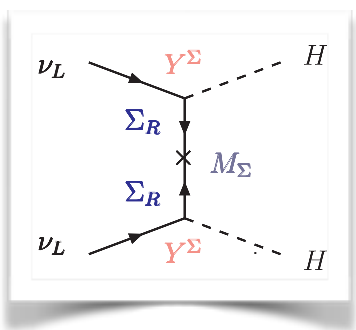

**cLFV neutral currents @ tree!**

# Type III seesaw and cLFV

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




- **Type III Seesaw:** extend the SM via SU(2) **triplet fermions**




$\rightsquigarrow$ an enlarged spectrum

$\rightsquigarrow$ extended mixings

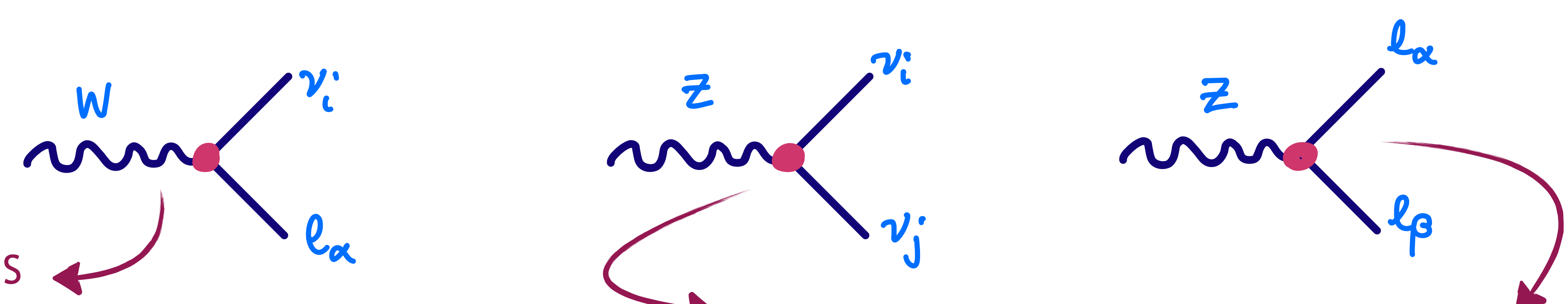
$$m_\nu \sim (Y_\Sigma v)^T \frac{1}{M_\Sigma} (Y_\Sigma v)$$

$$\Sigma = \Sigma^+, \Sigma^0, \Sigma^-$$

$$\mathscr{L}_{\text{Type III}} \supset v\, Y_\Sigma \Sigma^+ \ell^- + v\, Y_\Sigma \Sigma^0 \nu + M_\Sigma \bar{\Sigma} \Sigma$$

Fermion-triplet mixings: $\Sigma^0 - \nu$ and $\Sigma^{+c} - \ell^-$

$$\Rightarrow \theta \approx \mathcal{O}(v Y_\Sigma M_\Sigma^{-1})$$




$\propto (1+\varepsilon) U_{\text{PMNS}}$

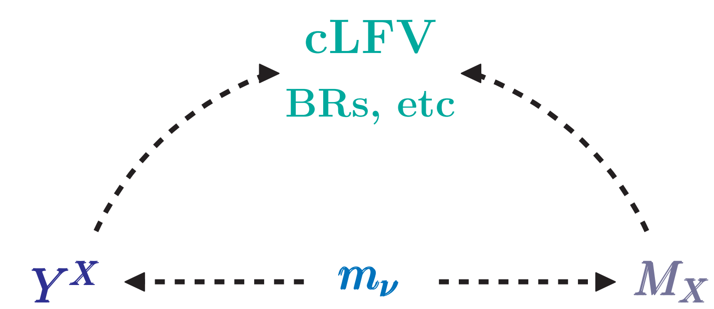
$\propto (1-2\varepsilon) U_{\text{PMNS}}$

$\propto (1+4\varepsilon) U_{\text{PMNS}}$

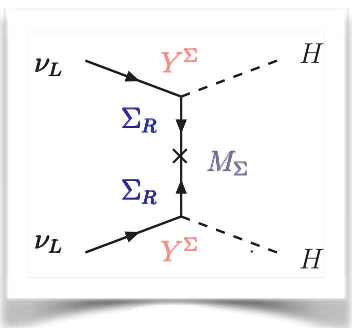
Deviations from unitarity: $\varepsilon = \frac{1}{2} m_\Sigma^\dagger M_\Sigma^{-2} m_\Sigma$

# Type III seesaw and cLFV

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




- **Type III Seesaw:** extend the SM via SU(2) **triplet fermions**




$\rightsquigarrow$ an enlarged spectrum

$\rightsquigarrow$ extended mixings

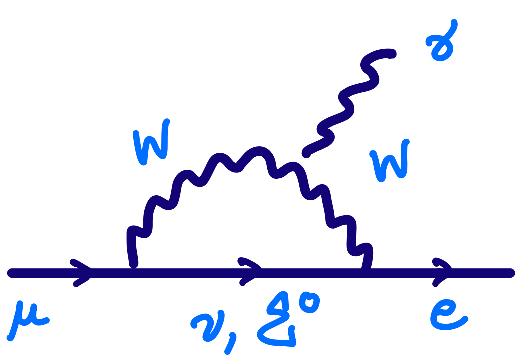
$$\Sigma = \Sigma^+, \Sigma^0, \Sigma^-$$

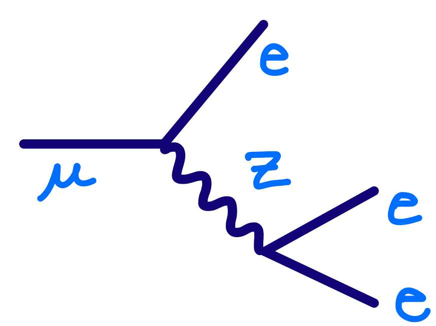
$$m_\nu \sim (Y_\Sigma v)^T \frac{1}{M_\Sigma} (Y_\Sigma v)$$

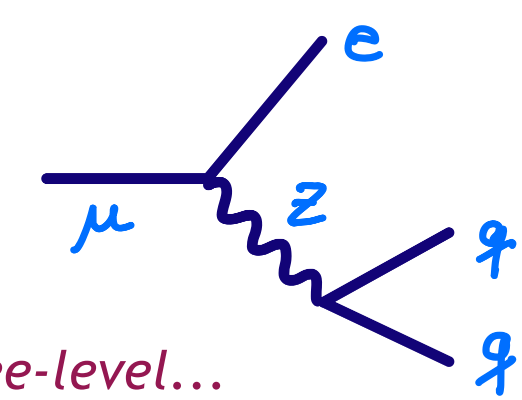
$$\mathscr{L}_{\text{Type III}} \supset v\, Y_\Sigma \Sigma^+ \ell^- + v\, Y_\Sigma \Sigma^0 \nu + M_\Sigma \bar{\Sigma} \Sigma$$

Fermion-triplet mixings: $\Sigma^0 - \nu$ and $\Sigma^{+c} - \ell^-$

$$\Rightarrow \theta \approx \mathcal{O}(v Y_\Sigma M_\Sigma^{-1})$$



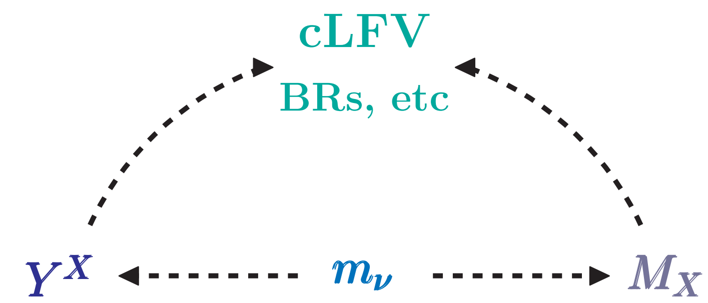




*Tree-body decays and conversion in nuclei @ tree-level... due to the modified $Z\ell_\alpha\ell_\beta$ vertex!*

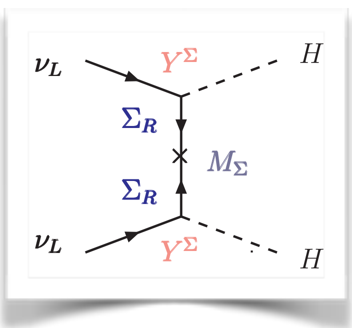
cLFV

# Type III seesaw and cLFV

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




- **Type III Seesaw:** extend the SM via SU(2) triplet fermions
  $\rightsquigarrow$ an enlarged spectrum
  $\rightsquigarrow$ extended mixings




$$m_\nu \sim (Y_\Sigma v)^T \frac{1}{M_\Sigma} (Y_\Sigma v)$$

If **light neutrino masses** generated by "natural" new physics $\Rightarrow$ very **high energy NP scale**

$Y_\Sigma \sim \mathcal{O}(1)$ $\quad M_\Sigma \sim 10^{14-16}$ GeV

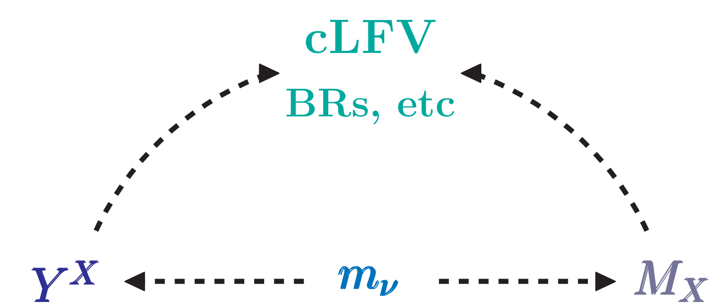
negligible mixings between active neutrinos and NP states ($\theta \propto m_\Sigma^\dagger M_\Sigma^{-1}$)

$\Rightarrow$ Decoupled new physics! Little contributions for cLFV observables, no resonance within collider reach...

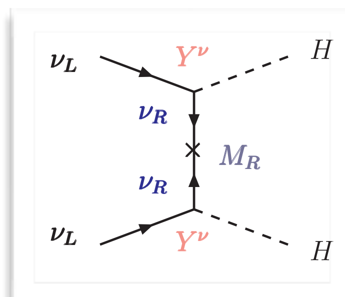
# Fermionic seesaws and cLFV

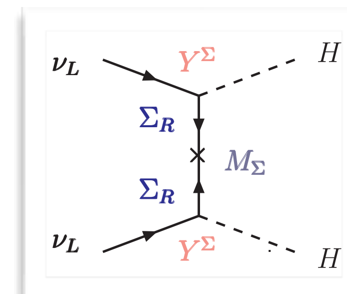
- **Mechanisms for neutrino mass generation:** delicate **"balance"** between **sources of flavour violation** and **masses of new propagators**

  ⇒ account for **oscillation data** (**observation!**)




- **Type I & III Seesaw:** a quick **EFT detour** - *integrate out the heavy mediators* $(N_R, \Sigma)$




**Dimension 5**
(Weinberg operator)

$$Y_\nu^T\, M_R^{-1}\, Y_\nu (\overline{L_L^c}\tilde{\phi}^*)\ (\tilde{\phi}^\dagger L_L)$$

$$Y_\Sigma^T\, M_\Sigma^{-1}\, Y_\Sigma (\overline{L_L^c}\tilde{\phi}^*)\ (\tilde{\phi}^\dagger L_L)$$

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

$$m_\nu \sim (Y_\Sigma v)^T \frac{1}{M_\Sigma} (Y_\Sigma v)$$

[see Broncano et al, 0210271]

[see Abada et al, 0707.4058]

**Dimension 6**

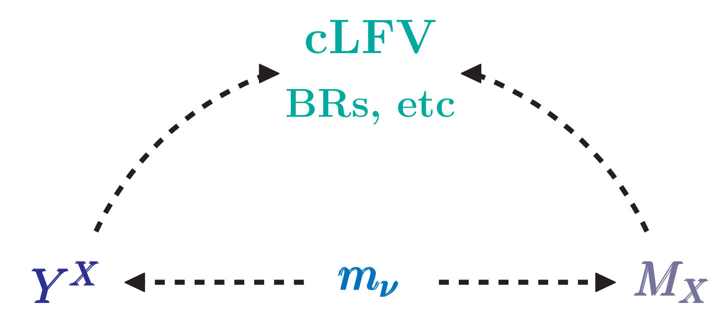
$$Y_\nu^\dagger\, M_R^{-2}\, Y_\nu (\overline{L_L}\tilde{\phi}^*)\, \partial\!\!\!/ (\tilde{\phi}^\dagger L_L)$$

$$Y_\Sigma^\dagger\, M_\Sigma^{-2}\, Y_\Sigma (\overline{L_L}\vec{\tau}\tilde{\phi})\, D\!\!\!\!/\, (\tilde{\phi}^\dagger \vec{\tau} L_L)$$

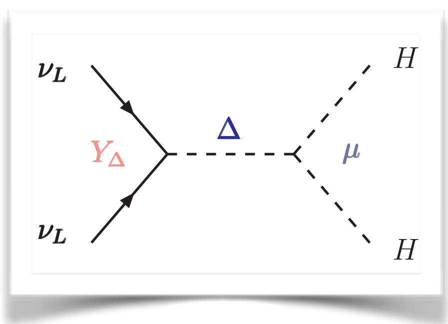
⇒ **suppression** of **"light neutrino masses"** entails strong **suppression of NP effects!**

# Type II seesaw and cLFV

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




- **Type II Seesaw:** extend the SM via SU(2) **triplet scalars**




$\rightsquigarrow$ an enlarged spectrum

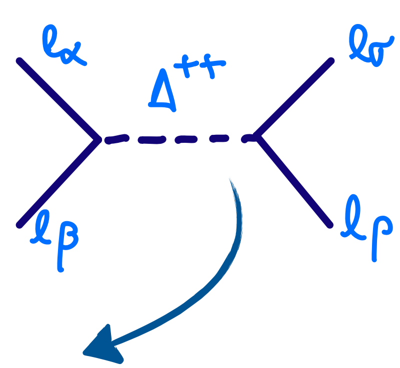
$\rightsquigarrow$ extended mixings

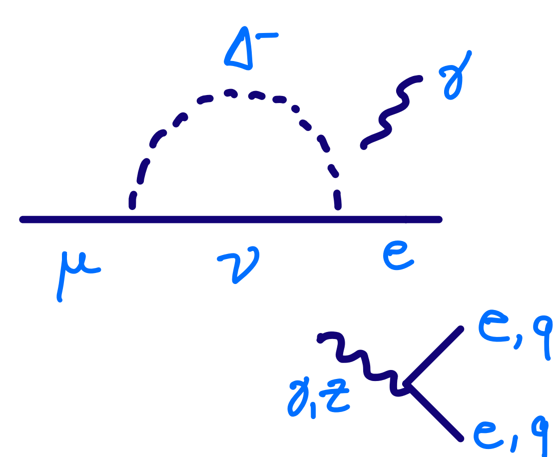
$$\Delta = \Delta^0, \Delta^+, \Delta^{++}$$

$$m_\nu \sim \frac{Y_\Delta \, \mu}{2} \frac{v^2}{M_\Delta^2}$$

$$\mathscr{L}_{\text{Type II}} \supset Y_\Delta \bar{L}_L \vec{\tau} L_L^c \vec{\Delta} + \mu_\Delta \phi^\dagger \vec{\tau} \tilde{\phi} \vec{\Delta}$$

Interactions with **gauge bosons**; **direct cLFV couplings**



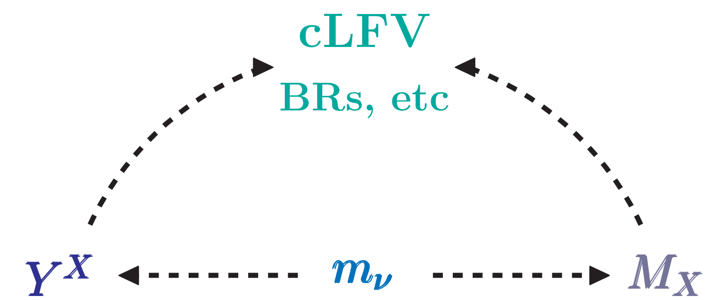




*Tree-body decays @ tree-level...*

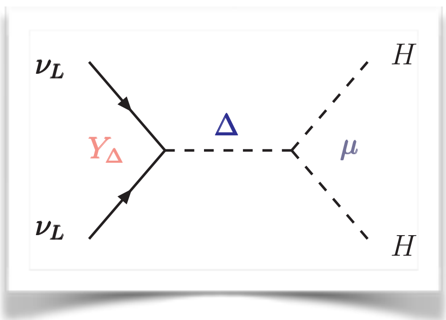
cLFV

# Scalar seesaw and cLFV

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




- **Type II Seesaw:** extend the SM via SU(2) triplet scalars
  ⤳ an enlarged spectrum
  ⤳ extended mixings




$$m_\nu \sim \frac{Y_\Delta \mu}{2} \frac{v^2}{M_\Delta^2}$$

A **different scenario:** additional ingredient!
"natural" new physics $\not\Rightarrow$ very **high energy NP scale**
Smallness of $m_\nu$ **also** from (tiny) $\mu$ coupling
for "natural" $Y_\Delta$ and not "too heavy" $M_\Delta$

[see Abada et al, 0707.4058]

**Dimension 5** $\quad 4\, Y_\Delta\, \mu\, M_\Delta^{-2}\, (\overline{L_L^c} \tilde{\phi}^*)\, (\tilde{\phi}^\dagger L_L)$

**Dimension 6** $\quad Y_\Delta\, Y_\Delta^\dagger\, M_\Delta^{-2}\, (\overline{L_L} \gamma_\mu L_L)\, (\overline{L_L} \gamma^\mu L_L)$

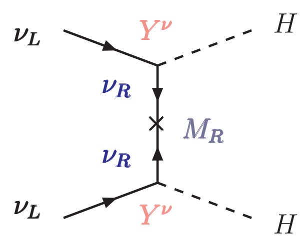
$\Rightarrow$ **suppression** of "light neutrino masses"
decorrelated from **contribution to** NP effects!

# cLFV and the seesaw: peculiar patterns

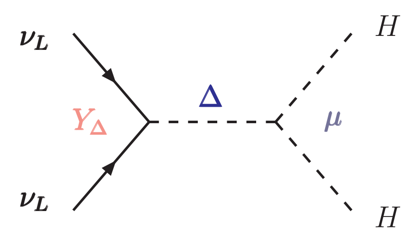
- **Seesaw realisations:** distinctive expectations for numerous **cLFV observables**
  **If observable/measurable cLFV** - what can we learn?

# cLFV and the seesaw: peculiar patterns

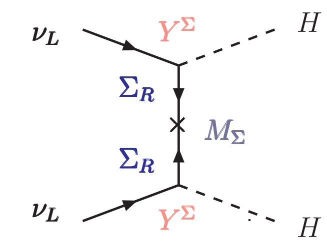
- **Seesaw realisations:** distinctive expectations for numerous **cLFV observables**
  If **observable/measurable cLFV** - what can we learn?



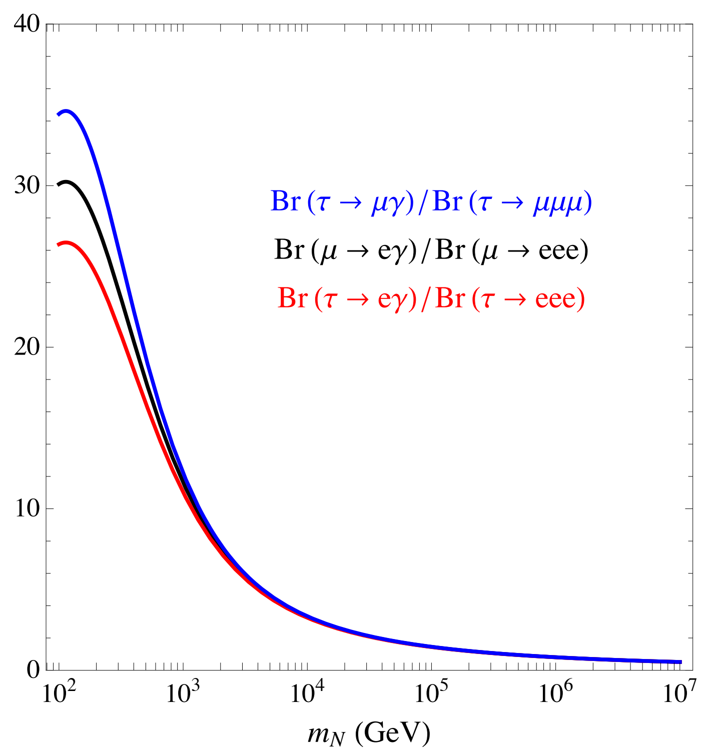

**Type I** (fermion singlet)



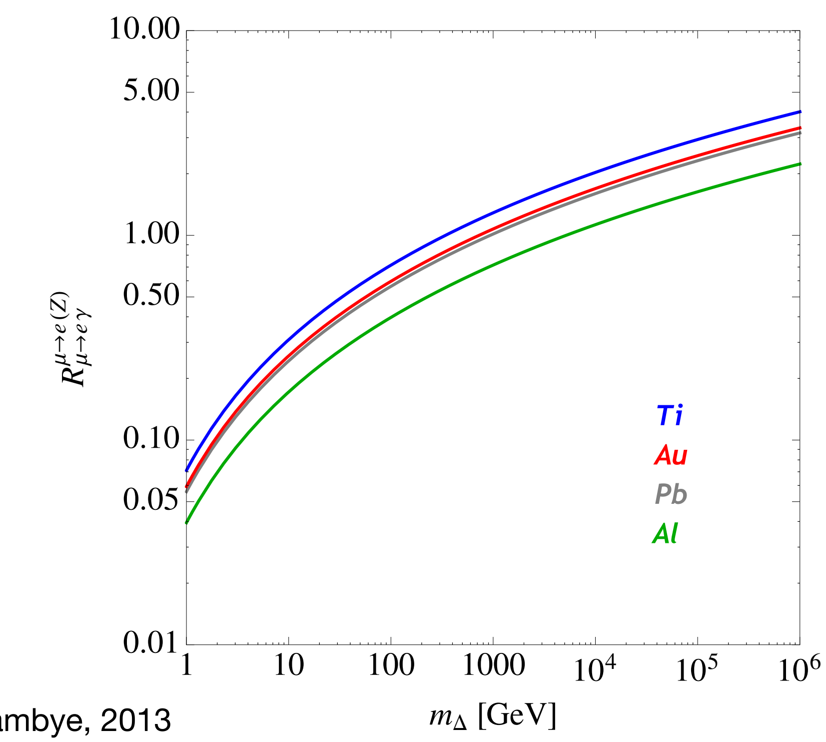

**Type II** (scalar triplet)




**Type III** (fermion triplet)




Hambye, 2013




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

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

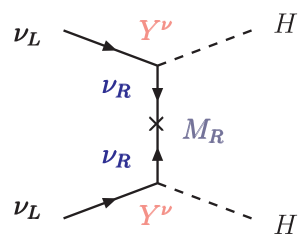
$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{CR}(e-\mu,\mathrm{Ti})} = 3.1\times 10^{-4}$$

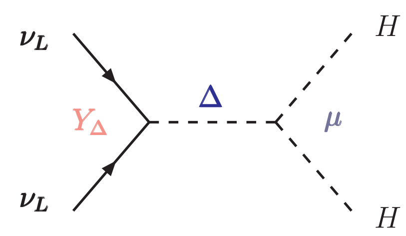
[adapted from Calibbi et al, 1709.00294]

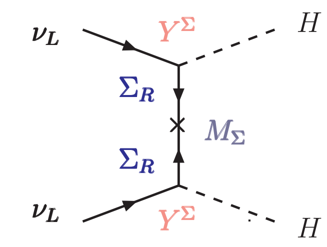
**cLFV patterns** reflect the **topology** of contributions associated with the **new mediators**
(dipole or Z-dominated, tree vs. loop, ...)

# cLFV and the seesaw: peculiar patterns

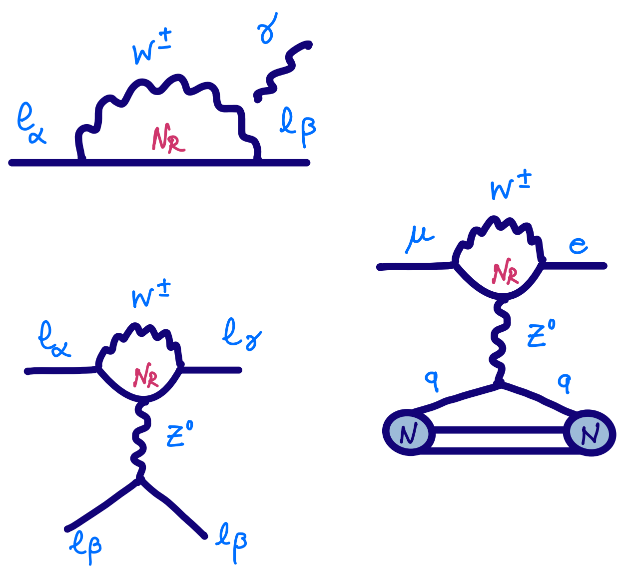
- **Seesaw realisations:** distinctive expectations for numerous **cLFV observables**
  **If observable/measurable cLFV** - what can we learn?

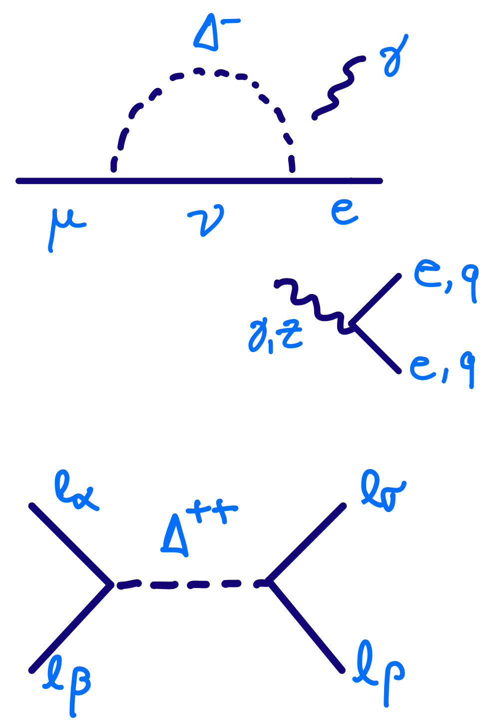


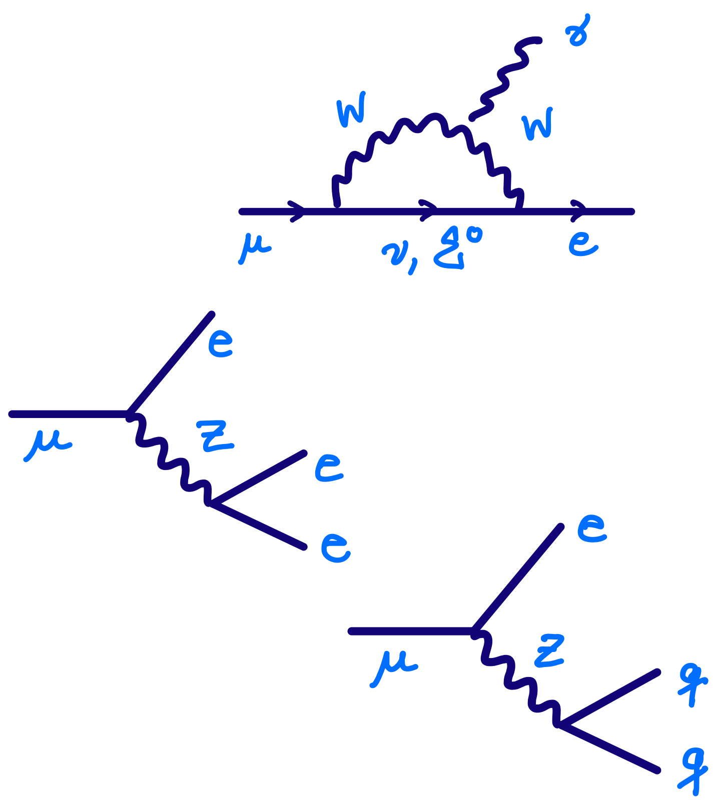




**Type I** (fermion singlet) **Type II** (scalar triplet) **Type III** (fermion triplet)







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

# cLFV and the seesaw: peculiar patterns

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

  $\Rightarrow$ **ratios of observables** to **identify seesaw mediators** & constrain **masses...**

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

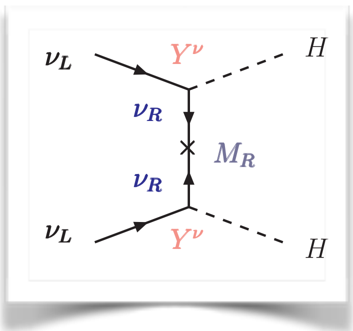
and of $\left.\frac{\mathrm{CR}(\mu - e,\mathrm{N})}{\mathrm{BR}(\mu\to e\gamma)}\right|_{\text{exp}}$ with $\left.\frac{\mathrm{CR}(\mu - e,\mathrm{N})}{\mathrm{BR}(\mu\to e\gamma)}\right|_{\text{NP-th}}$

$\Rightarrow$ **Probe NP model** at the source of **cLFV**

# New Physics paths to cLFV: low-scale seesaws

# Low-scale models of $m_\nu$ generation: type I seesaw

- Addition of **3 "heavy" Majorana** right-handed neutrinos $\nu_R$ to the SM
  but explore **considerably lighter range** for $M_R$ **MeV** $\leq M_R \leq 10^{\text{few}}$ **TeV**




**Type I** (fermion singlet)

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

After EW symmetry breaking, **6 states** in the neutral lepton spectrum

$$\mathcal{M}_\nu^{6\times 6} = \begin{pmatrix} 0 & Y^\nu v \\ (Y^\nu)^T v & M_R \end{pmatrix}$$

**3 light neutrinos** $m_\nu \approx -v^2 Y_\nu^T M_R^{-1} Y_\nu$

**3 heavy states** $m_N \approx M_R$

**Enlarged** $6 \times 6$ **mixing matrix** $U^T \mathcal{M}_\nu^{6\times 6} U$ = diag($m_{\nu_i}$)

$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix}$$

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

**Non-unitary** leptonic mixing $\tilde{U}_{\text{PMNS}}$

**Low-scale realisations** of the **Type I seesaw** open door to a **very rich phenomenology** from **cLFV signals**, to collider searches

**Similar implications** for **low-scale Type III**
(but important direct/indirect constraints due to the *non-singlet nature of new states...*)

# Low-scale models of $m_\nu$ generation: type I seesaw

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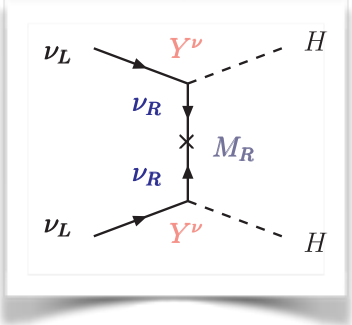
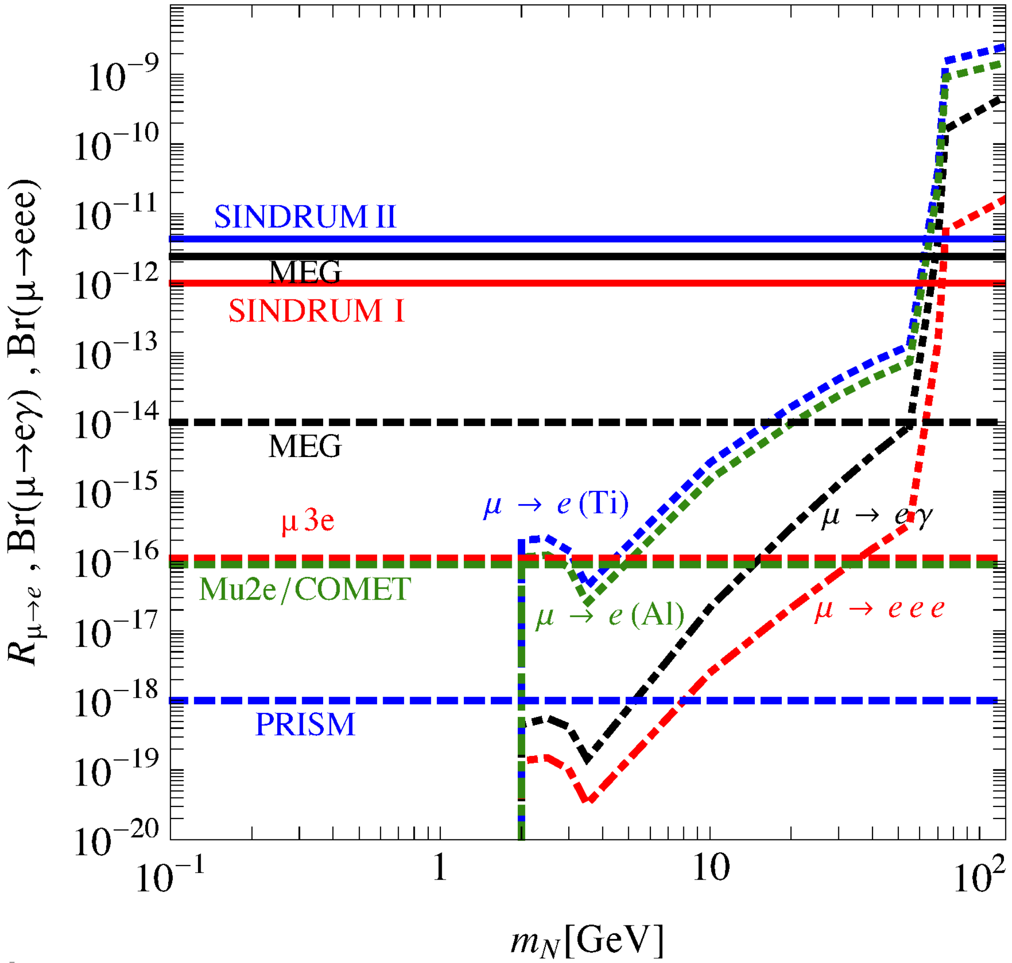
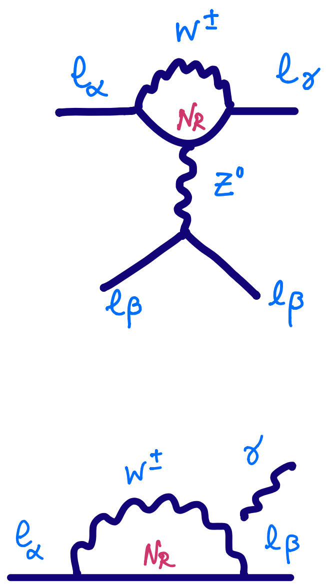
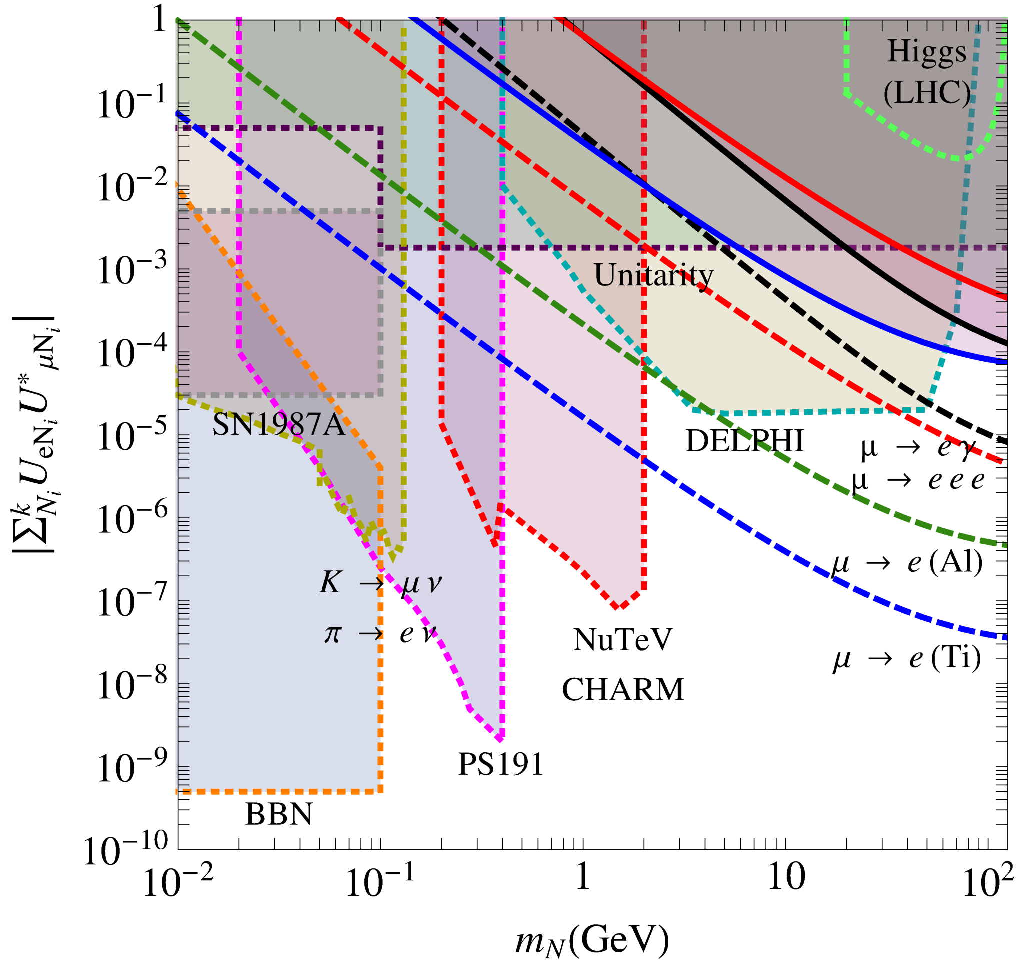



**Low-scale realisations** of the **Type I seesaw: very rich phenomenology**

$\Rightarrow$ **cLFV signals** *(more promising than collider searches)*




Alonso, Dehn, Gavela, Hambye [1209.2679]

# Low-scale models for $m_\nu$: Inverse Seesaw

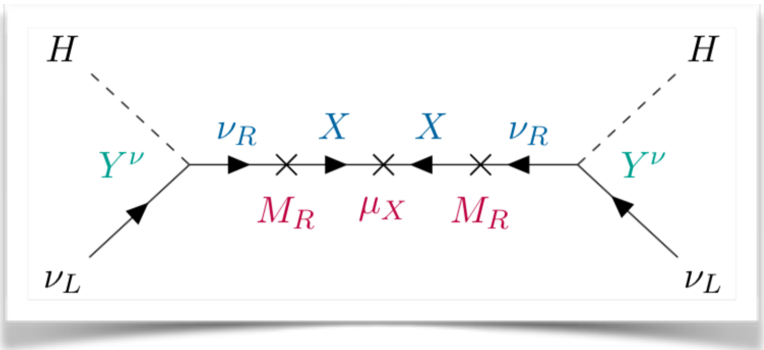
- **Variants** of type I seesaw aiming at a natural realisation of a low-scale $m_\nu$ mechanism
- Addition of **two new species** of **fermionic gauge singlets**

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

$$\mathscr{L}^{(3,3)}_{\text{ISS}} = - Y^\nu \bar{L}\,\tilde{H}\,\nu_R - M_R\,\bar{\nu}^c_R\,X - \frac{1}{2}\,\mu_X\,\bar{X}^c X$$

[Mohapatra and Valle, '86]

lepton number violating!




*ISS(3,3)*

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

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

Interplay of **two scales** driving smallness of $m_\nu$: $M_R$ and $\mu_X$

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

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

small values of $\mu_X$ (around eV - keV)

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

**Symmetry protected "smallness" of $m_\nu$ - approximate LNC**

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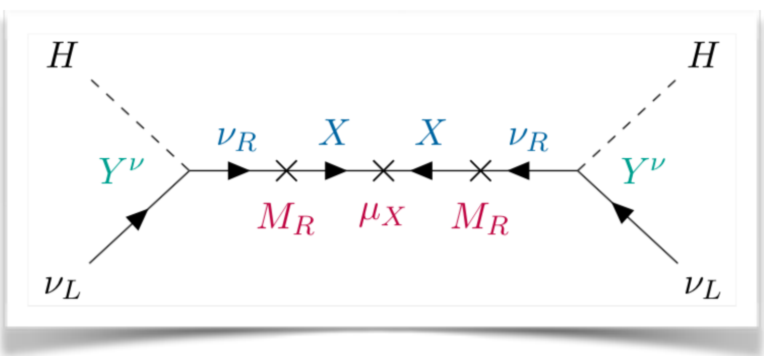


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For **natural values** of $Y^\nu \sim \mathcal{O}(1)$

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

small values of $\mu_X$ (around eV - keV)

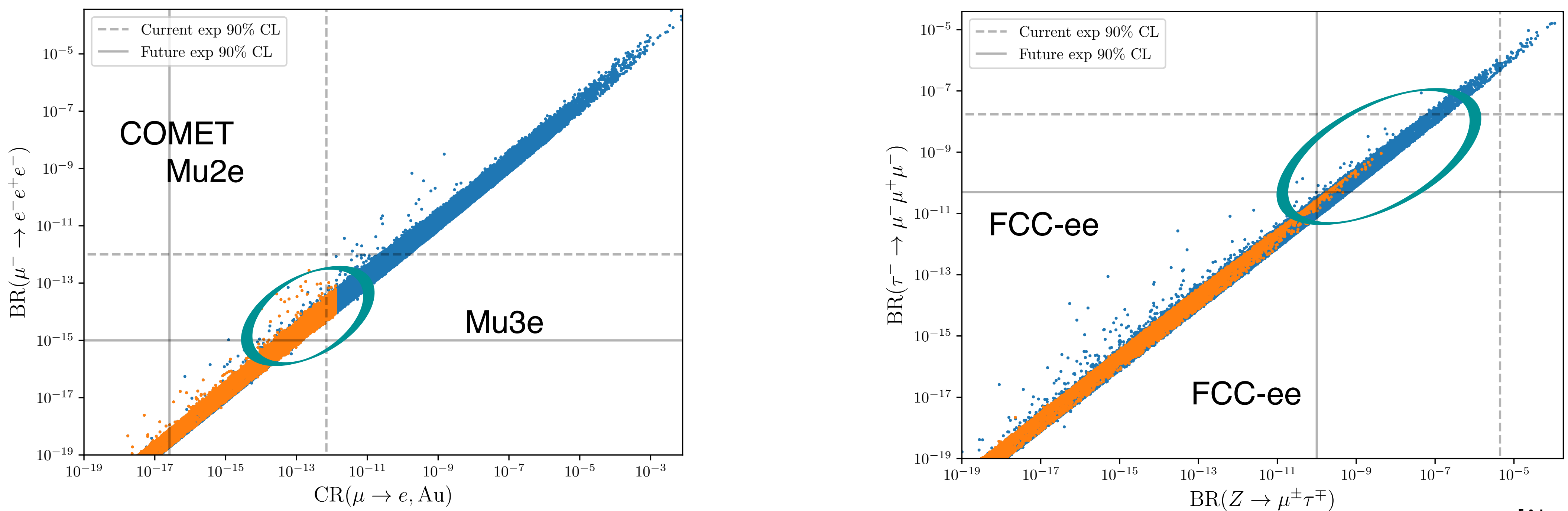
$\Rightarrow$ Despite **small** $m_\nu \sim \mu_X \frac{m_D^2}{M_R^2}$, a "low" NP scale $\sim M_R$, and **sizeable mixings** ($\theta \propto m_D^\dagger M_R^{-1}$) !

# cLFV and EW precision in the ISS

# Low-scale models for $m_\nu$: Inverse Seesaw

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

**ISS(3,3) $\Rightarrow$ SM + 3 $\nu_R$ + 3 $X$** *(rich phenomenology $\Rightarrow$ **testability!**)*




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

$\Rightarrow$ **Abundant "flavour" signals: cLFV** transitions (at low and high energies)

Regimes *already disfavoured* from current bounds!

cLFV actively constrains parameter space of **ISS**

$\Rightarrow$ **Opportunities** to observe cLFV in (near-)future facilities:

$\mu - e$ sector @ Mu3e, COMET & Mu2e

$\tau - \mu$ sector @ Belle II, FCC-ee, ...

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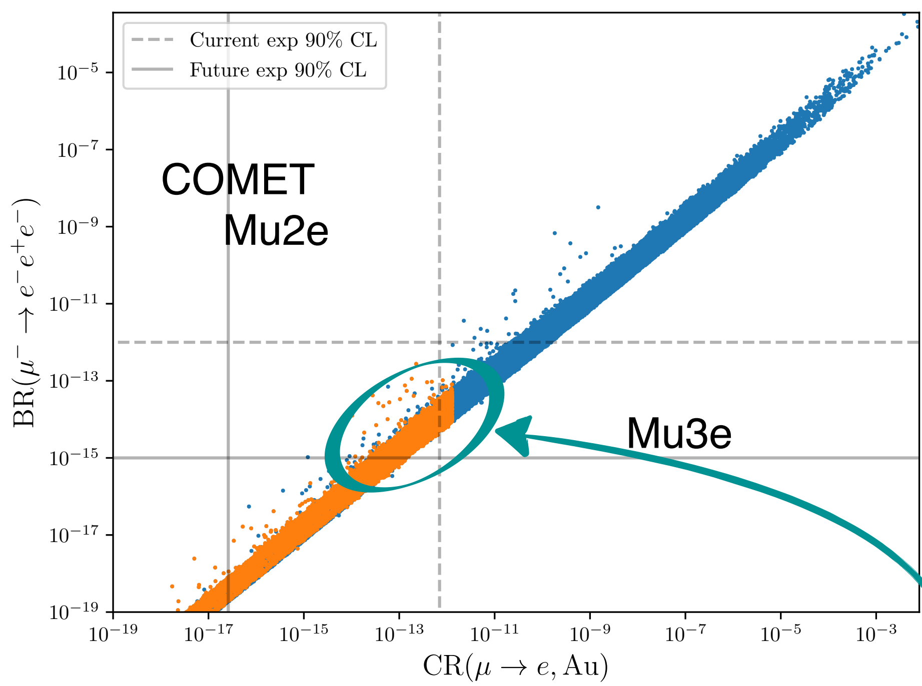


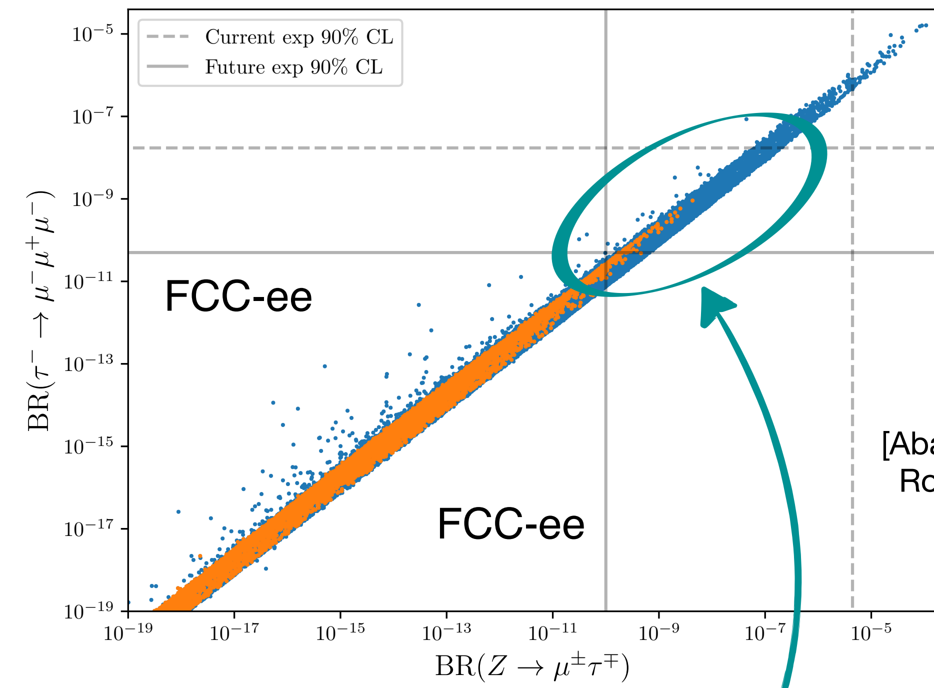


[Abada, Kriewald, Pinsard, Rosauro, AMT, '23]

$\Rightarrow$ **Correlated observables!** $\mu \to 3e$ vs. $\mu - e$ conversion

and $Z \to \mu\tau$ vs. $\tau \to 3\mu$

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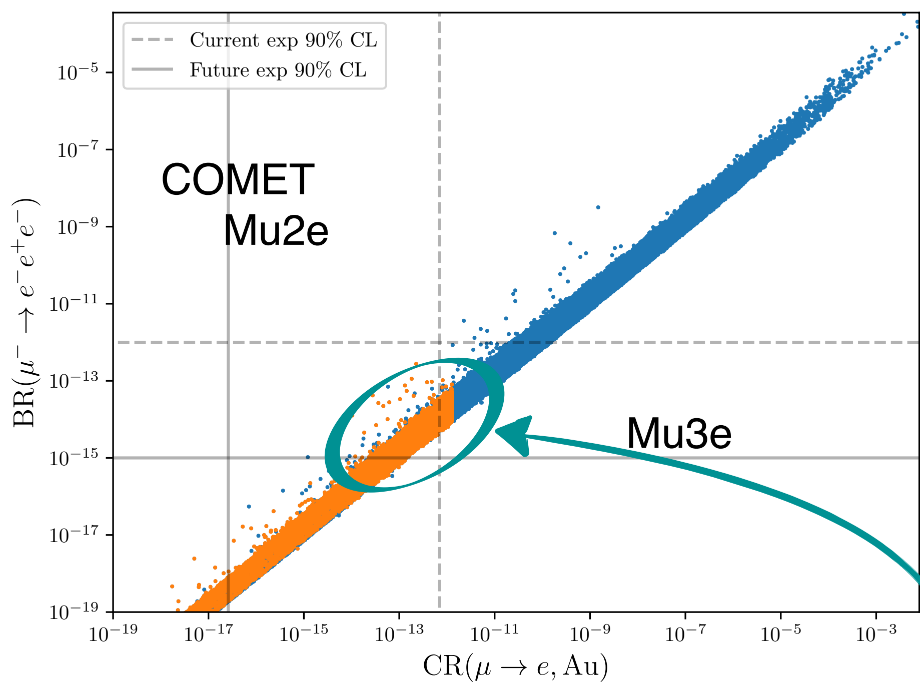
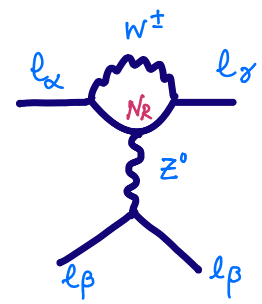
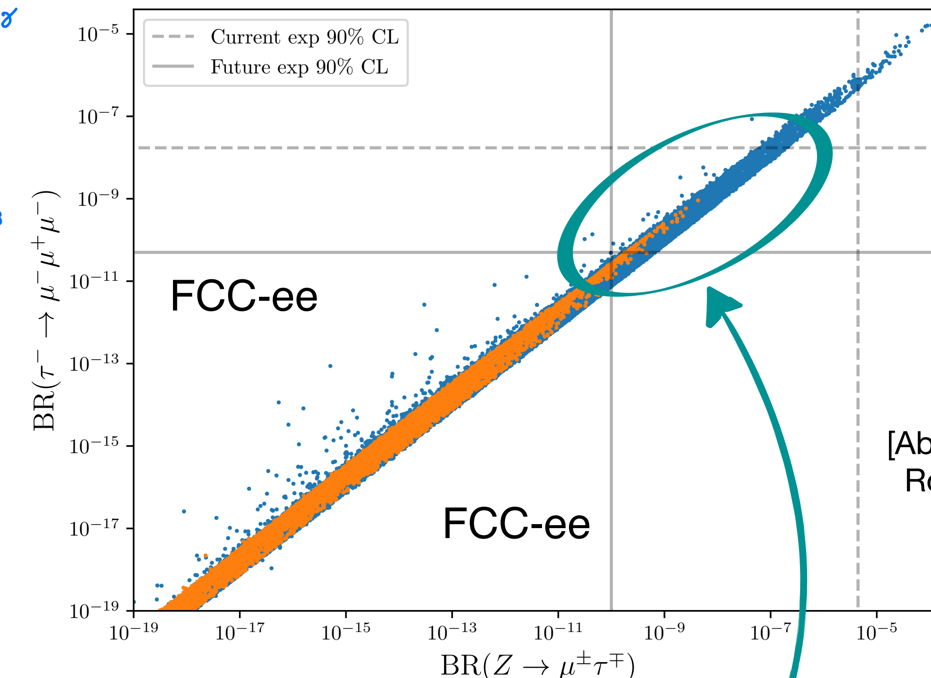
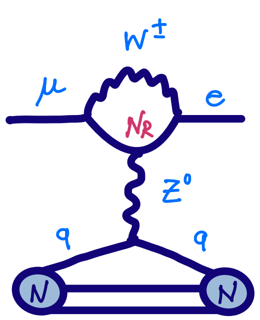
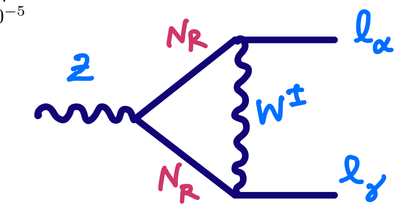



[Abada, Kriewald, Pinsard, Rosauro, AMT, '23]




$\Rightarrow$ **Correlated observables!** $\mu \to 3e$ vs. $\mu - e$ conversion

and $Z \to \mu\tau$ vs. $\tau \to 3\mu$

A consequence of the **dominant contribution of Z-penguins** in the 3-body decays and in neutrinoless conversion in nuclei (for the most "observable" regimes...)

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

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

*testability!?*

# Low-scale models for $m_\nu$: Inverse Seesaw

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

ISS(3,3) $\Rightarrow$ SM + 3 $\nu_R$ + 3 $X$ *(rich phenomenology $\Rightarrow$ **testability!**)*

$\Rightarrow$ **Abundant "flavour" signals: cLFV** transitions (at low and high energies)

$\Rightarrow$ **Precision tests: electroweak observables** and **lepton flavour universality**

**LFUV-sensitive:** $R_Z^{\alpha\beta} = \frac{\Gamma(Z \to \ell_\alpha^+ \ell_\alpha^-)}{\Gamma(Z \to \ell_\beta^+ \ell_\beta^-)}, \quad R_Z^{\alpha\beta}\Big|_{\text{SM}} \simeq 1$ & $R_W^{\alpha\beta} = \frac{\Gamma(W \to \ell_\alpha \nu)}{\Gamma(W \to \ell_\beta \nu)}, \quad R_W^{\alpha\beta}\Big|_{\text{SM}} \simeq 1$

**EWPO:** $\Gamma(Z \to \text{inv.})$, oblique parameters, …

**New parametrisation** (beyond Casas-Ibarra) to access key-regimes of **large LFUV**

*(escaping cLFV constraints!)*

$$\mu_X = M_R^T \, m_D^{(-1)} \, U^*_{\text{PMNS}} \, m_\nu^{\text{diag}} \, U^\dagger_{\text{PMNS}} \, (m_D^T)^{(-1)} \, M_R \,, \quad Y_D = y_i^d \, \mathscr{V} M_R^\dagger$$

**Massive (semi-)analytical computation** of form-factors, renormalisation, …

[Abada, Kriewald, Pinsard, Rosauro, AMT, 2307.02558]

**Non-negligible NLO corrections** to **ISS** vertices! $Z\ell\ell$, $Z\nu\nu$ and $W\ell\nu$

# Low-scale models for $m_\nu$: Inverse Seesaw

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

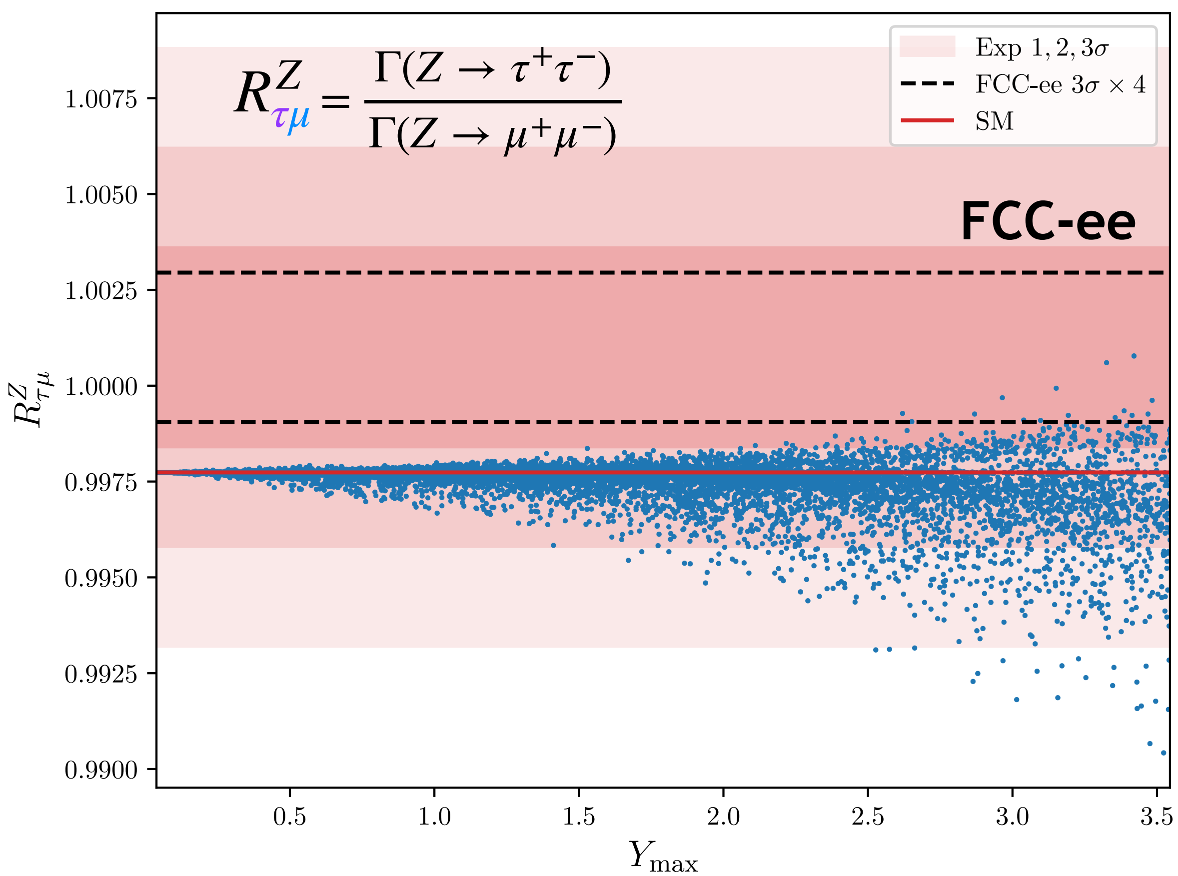
**ISS(3,3) ⇒ SM + 3 $\nu_R$ + 3 $X$** *(rich phenomenology ⇒ **testability!**)*

⇒ **Abundant "flavour" signals: cLFV** transitions (at low and high energies)

⇒ **Precision tests: LFUV** in **$Z$ decays**

large **deviations** from **SM** possible (sizeable NLO corrections)

[Abada, Kriewald, Pinsard, Rosauro, AMT, 2307.02558]




$$R^Z_{\tau\mu} = \frac{\Gamma(Z \to \tau^+\tau^-)}{\Gamma(Z \to \mu^+\mu^-)}$$

Contributions around **SM prediction**
(already in tension with measurement)

**Large deviations for sizeable Yukawas**
(corresponding to masses ~ 5 TeV)

**Significant NLO corrections to LFU in $Z$ decays!**

⇒ **FCC-ee** expected to probe these regimes
(increase in experimental precision)

# Low-scale models for $m_\nu$: Inverse Seesaw

Inverse seesaw: well-motivated low-scale mechanism of neutrino mass generation

ISS(3,3) ⇒ SM + 3 $\nu_R$ + 3 $X$ (rich phenomenology ⇒ *testability!*)

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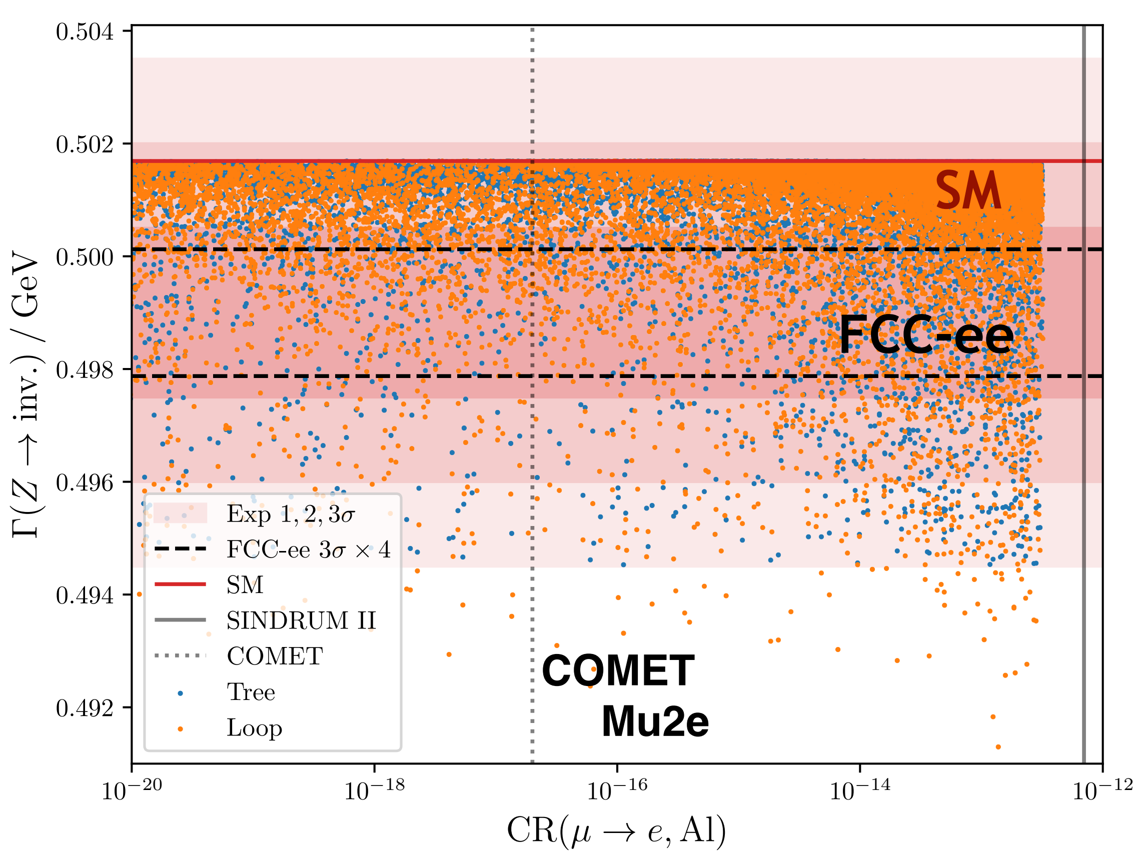
⇒ **(EW) precision tests: Invisible $Z$ decays**

[Abada, Kriewald, Pinsard, Rosauro, AMT, EPJC 84 (2024) 2]




**Large deviations from SM prediction**

**Significant NLO corrections** to **invisible** $Z$ decays!

$\Gamma_{\text{tree}}(Z \to \text{inv.}) - \Gamma_{\text{loop}}(Z \to \text{inv.})$ up to 5 MeV!

*(current exp. uncertainty 1.5 MeV...)*

**NLO corrections:** master **theory uncertainties,** on par with experiment!

⇒ **FCC-ee** expected to probe important regimes (increase in experimental precision)

# Low-scale models for $m_\nu$: Inverse Seesaw

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

**ISS(3,3) $\Rightarrow$ SM + 3 $\nu_R$ + 3 $X$** *(rich phenomenology $\Rightarrow$ **testability!**)*

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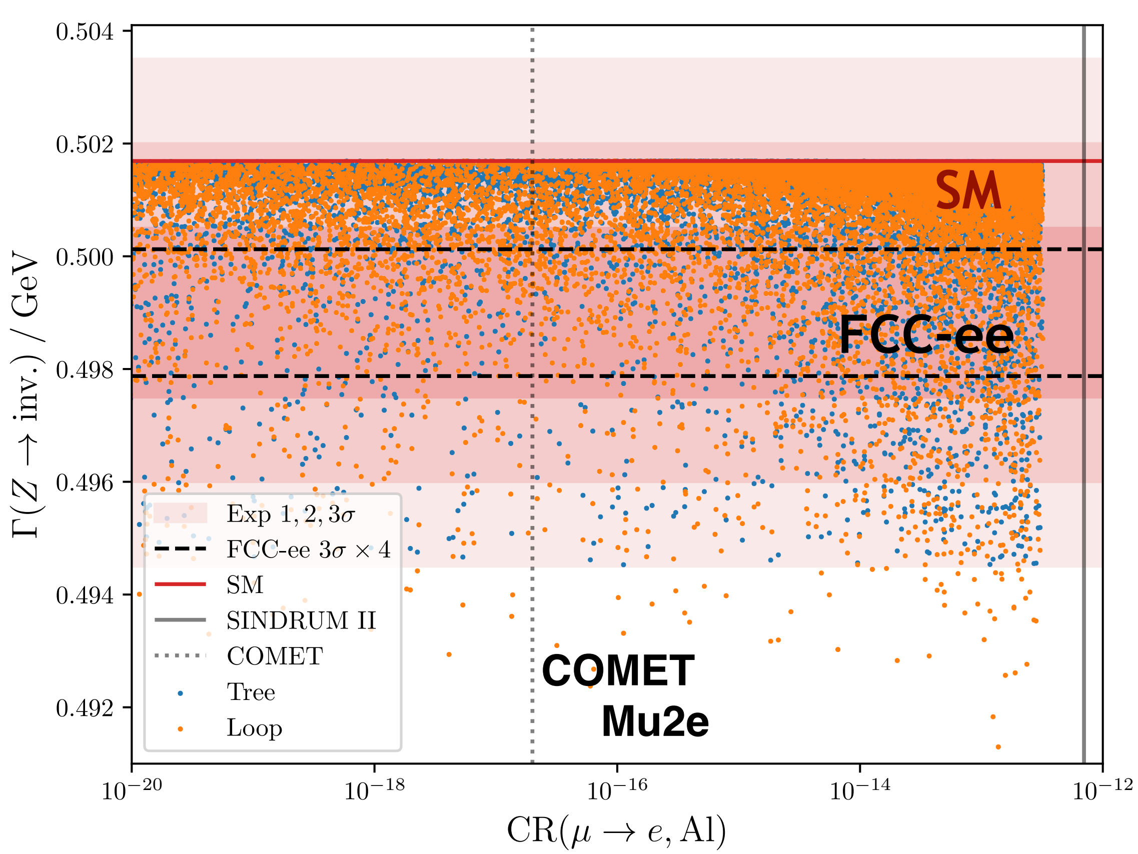
[Abada, Kriewald, Pinsard, Rosauro, AMT, EPJC 84 (2024) 2]




**EWPO vs. cLFV - complementary probes**

**cLFV** in $\mu - e$: usually **most stringent** constraints (e.g. $\mu \to e\gamma$, $\mu - e$ conversion...)

**Invisible $Z$ decays @ FCC-ee**

$\Rightarrow$ explore **regimes beyond cLFV future reach**

$\Rightarrow$ **probe ISS(3,3)** regimes with **sizeable or negligible cLFV!**

# New Physics paths to cLFV:
# neutrino masses beyond "standard seesaw"

# Beyond "standard" seesaw realisations

**Seesaw** (and its variants) - one of the most appealing mechanisms for **$m_\nu$ generation**

Further ways to account for **tiny neutrino masses: higher order, higher dimension!**

Tree → n loops

**Higher order contributions:**
loop-suppressed $(1/16\pi^2)$

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=5} + \delta\mathscr{L}^{(1)}_{d=5} + \delta\mathscr{L}^{(2)}_{d=5} + \cdots\right]$$
$$+ \frac{1}{\Lambda^3_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=7} + \delta\mathscr{L}^{(1)}_{d=7} + \delta\mathscr{L}^{(2)}_{d=7} + \cdots\right]$$
$$+ \frac{1}{\Lambda^5_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=9} + \delta\mathscr{L}^{(1)}_{d=9} + \delta\mathscr{L}^{(2)}_{d=9} + \cdots\right]$$
$$+ \frac{1}{\Lambda^7_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=11} + \delta\mathscr{L}^{(1)}_{d=11} + \delta\mathscr{L}^{(2)}_{d=11} + \cdots\right]$$
$$+ \cdots$$

**Type I-II-III seesaw**
*(dim5 @tree level)*

LNV operators dim >5

**Higher order operators:**
dim=7, 9, 11...

Several **other** interesting and theoretically **well-motivated possibilities exist:**

**Tree-level** realisations via **higher-dimension** operators, **dynamical "seesaws"**, ...

**Higher order realisations** (Dirac/Majorana): from first **Zee model**, to **$R_P$V SUSY**, ...

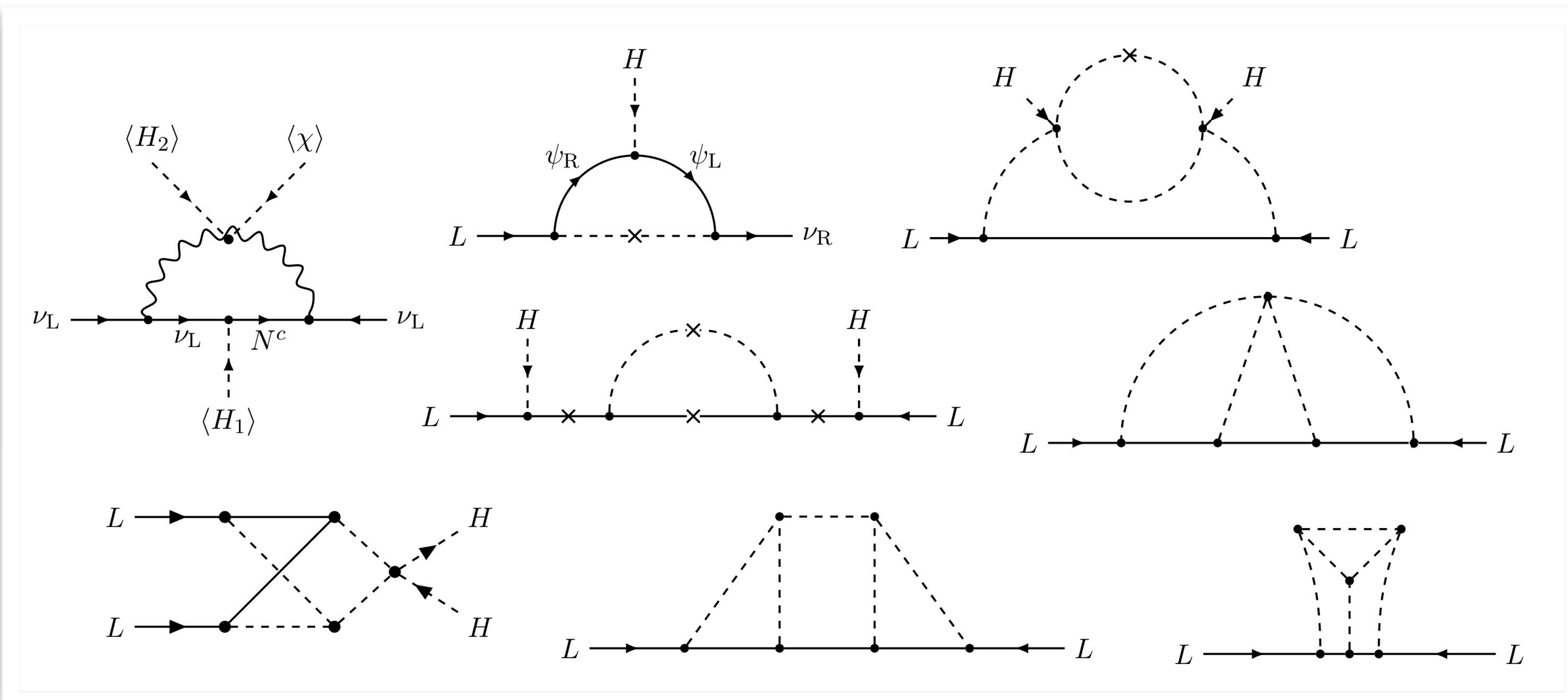
**scotogenic** models, to **3-loops and more!**

# Beyond "standard" seesaw realisations

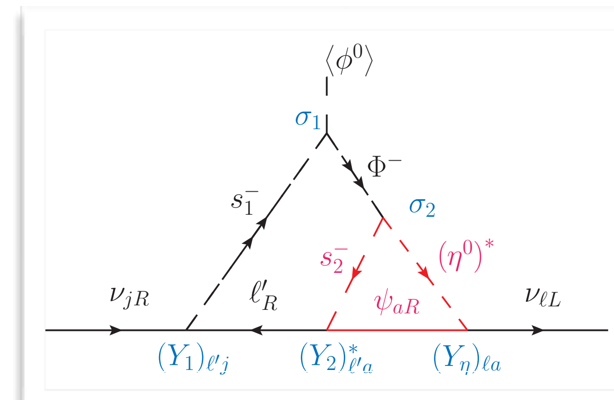
**Seesaw** (and its variants) - one of the most appealing mechanisms for $m_\nu$ **generation**

Several **other** interesting and theoretically **well-motivated possibilities exist:**

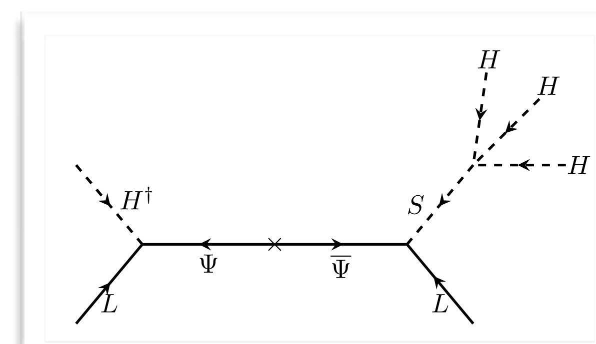
often aiming at addressing $m_\nu$ and other SM observational issues...




[Cai et al, 1706.08524]




Enomoto et al [1904.07039]




[Arbelaez et al, 2007.11007]

$\Rightarrow$ $m_\nu$ from large NP scale, small **couplings**, approximate **symmetries**, **loop** suppression

cnrs
IN2P3
Les deux infinis

# cLFV and EW precision in scotogenic models

IN2P3
50 ANS

# Low-scale models for $m_\nu$: DM connection (?)

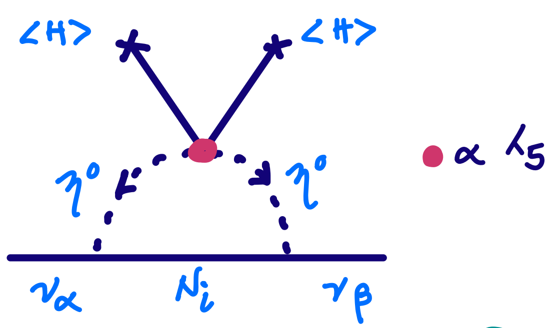
**Scotogenic models:** a link between **neutrino mass** generation and **dark matter!**

[Ma, 2006] Additional $Z_2$ symmetry: stabilises dark matter candidate ... but

$\Rightarrow$ neutrino masses @ 1-loop

[Review on phenomenology of generalised scotogenic models: Hagedorn et al, 1804.04117]

A minimal realisation: extend SM by **inert scalar doublet** $\eta$ and **RH neutrinos** $N_R$

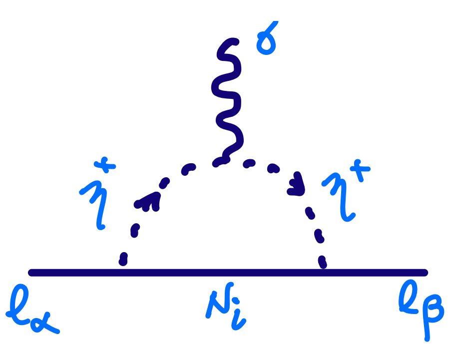


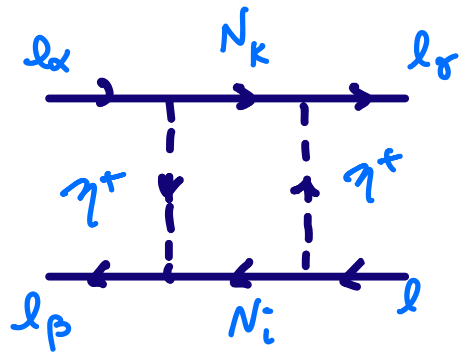

$$\mathcal{M}^\nu_{ij} \simeq \frac{\lambda_5}{16\pi^2} \frac{2\, Y^\eta_{ik} Y^\eta_{jk}\, v^2}{M^2_{N_i}} \left[ \frac{M^2_{N_k}}{m_0^2 - M^2_{N_k}} + \frac{M^4_{N_k}}{(m_0^2 - M^2_{N_k})^2} \log\left( \frac{M^2_{N_k}}{m_0^2} \right) \right]$$

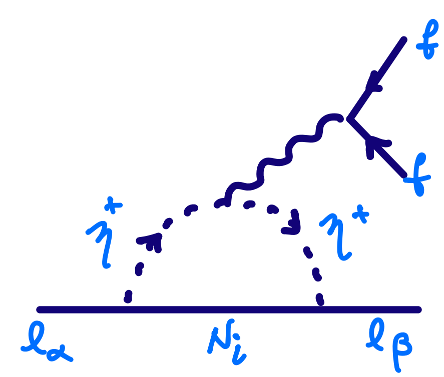
(for $\lambda_5 \ll 1$, with $m_0 = m_{\eta_R} \sim m_{\eta_I}$)

*Suppression of neutrino masses:*
*smallness of $\lambda_5$ and **loop** factors!*

**cLFV observables:** numerous contributions from $\eta$ and/or $N_R$







[Toma and Vicente, 1312.2840]

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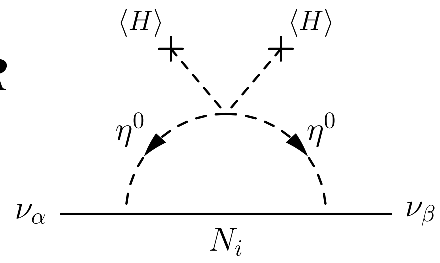
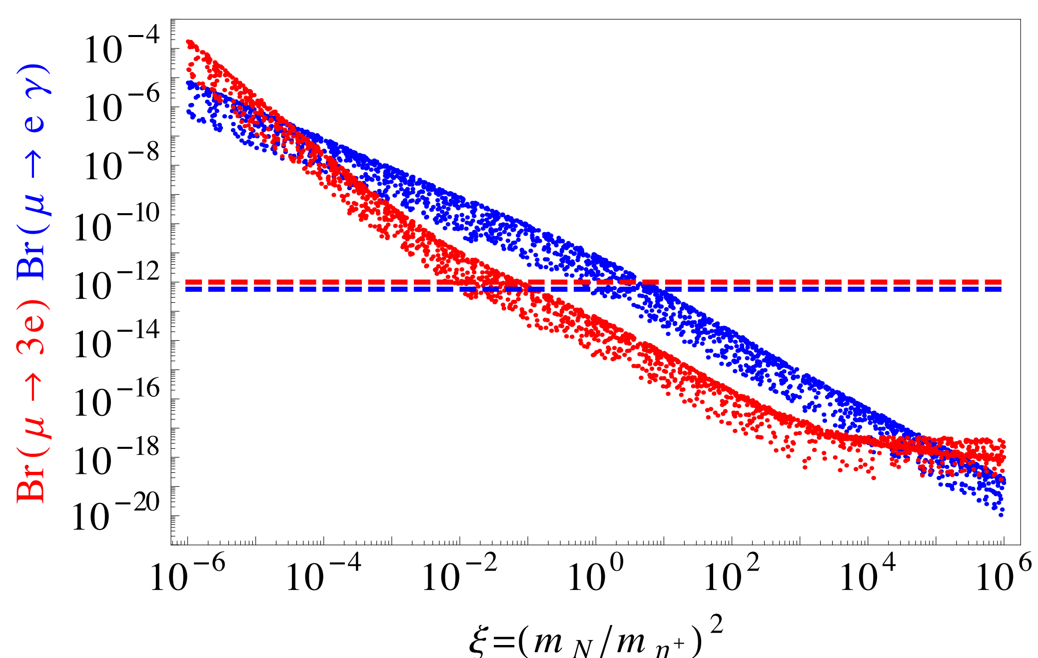
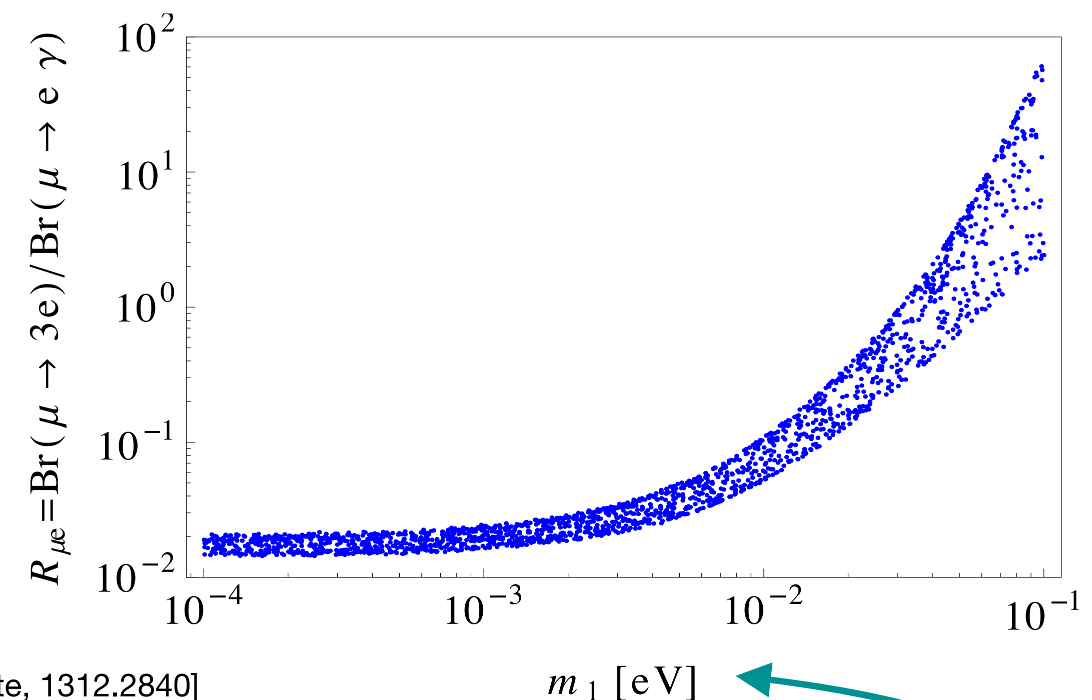



**cLFV observables:** hints on the **nature of the DM candidate** (**$\eta$** or **$N_R$**) and $\nu$ **mass scale**




[Toma and Vicente, 1312.2840]

Determination of $\boldsymbol{R_{\mu e}}$ = BR($\mu \to 3e$)/BR($\mu \to e\gamma$) $\Rightarrow$ hints on **lightest neutrino mass $m_{\nu_1}$**

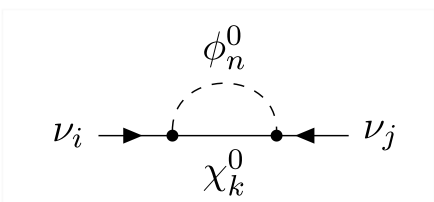
# Low-scale models for $m_\nu$: DM connection (?)

**Scotogenic models:** a link between neutrino mass generation and **dark matter!**

[Ma, 2006]

Additional $Z_2$ symmetry: stabilises dark matter candidate ... but

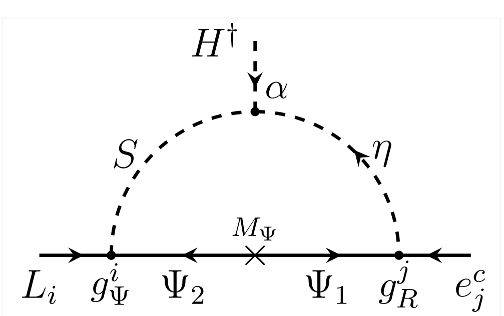
$\Rightarrow$ neutrino masses @ 1-loop



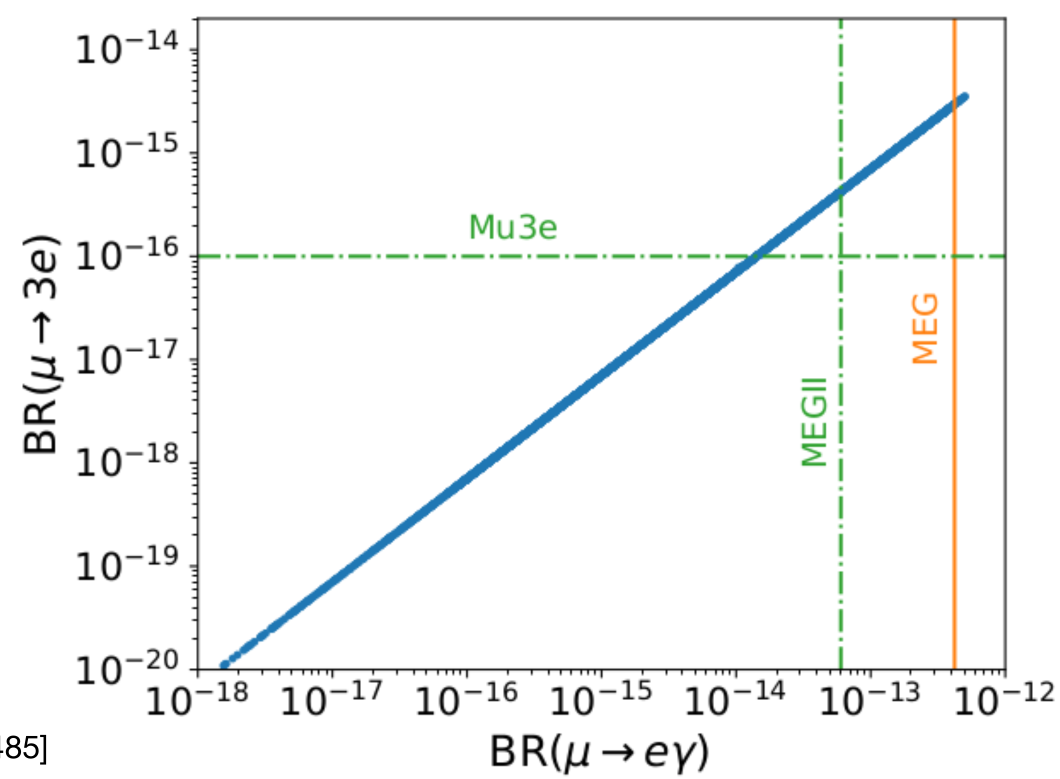

**"T1-2-A" variant:** SM extended by $SU(2)_L$ **Weyl fermions, Majorana singlets & extra scalars**

$\Rightarrow$ **$\nu$ mass generation, DM candidates,** $(g-2)_\mu$ and BAU via leptogenesis

[Alvarez et al, 2301.08485]




[Alvarez et al, 2301.08485]




**cLFV observables - strict correlation** between

BR($\mu \to e\gamma$), BR($\mu \to 3e$)

[dipole dominated]

muon cLFV decays

$\Rightarrow$ **falsify model**

**@ MEG II** and **Mu3e !**

# Low-scale models for $m_\nu$: DM connection (?)

**Scotogenic models:** a link between **neutrino mass** generation and **dark matter!**

[Ma, 2006] Additional $Z_2$ symmetry: stabilises dark matter candidate ... but

$\Rightarrow$ **neutrino masses** @ 1-loop

**"T1-2-A" variant:** SM extended by $SU(2)_L$ **Weyl fermions, Majorana singlets & extra scalars**

[Alvarez et al, 2301.08485]

*Relax certain (driving) assumptions* $\Rightarrow$ $\nu$ **masses, DM candidates** (scalar and fermionic)

$\Rightarrow$ generic $\Delta a_\mu$ - from *SM-like* to *NP* (at ~$5\sigma$) ; no BAU

Avoid **theoretically disfavoured** regimes (large hierarchical "Yukawas" & scalar couplings)?

Thorough exploration of flavoured and electroweak precision observables!

$\Rightarrow$ **cLFV decays:** leptonic, $Z \to \ell_\alpha \ell_\beta$, $H \to \ell_\alpha \ell_\beta$

$\Rightarrow$ **EW observables:** sensitive **probes** of **new interactions** (scalar, vector, fermion...)

$Z \to$ inv, LFUV in $Z \to \ell_\alpha \ell_\alpha$ *(in progress)*

New contributions to $H \to \ell_\alpha \ell_\alpha$ [Darricau, Lee, Orloff, AMT to appear soon]

Full computation of **NLO** contributions to $Z$ and Higgs interactions!

[see e.g. Grimus et al, 0802.4353]

# Low-scale models for $m_\nu$: DM connection (?)

**Scotogenic models:** a link between neutri… s generation and **dark matter!**

[Ma, 2006]

Addition… bilises dark matter candidate … but

…neutrino masses @ 1-loo…

"T1-2-A" variant: S… calars

…2301.08485]

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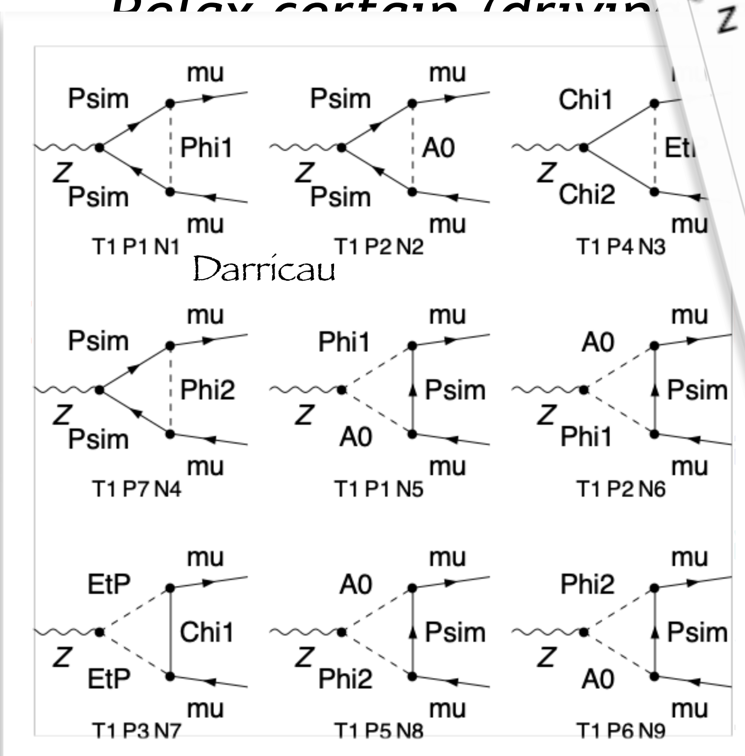
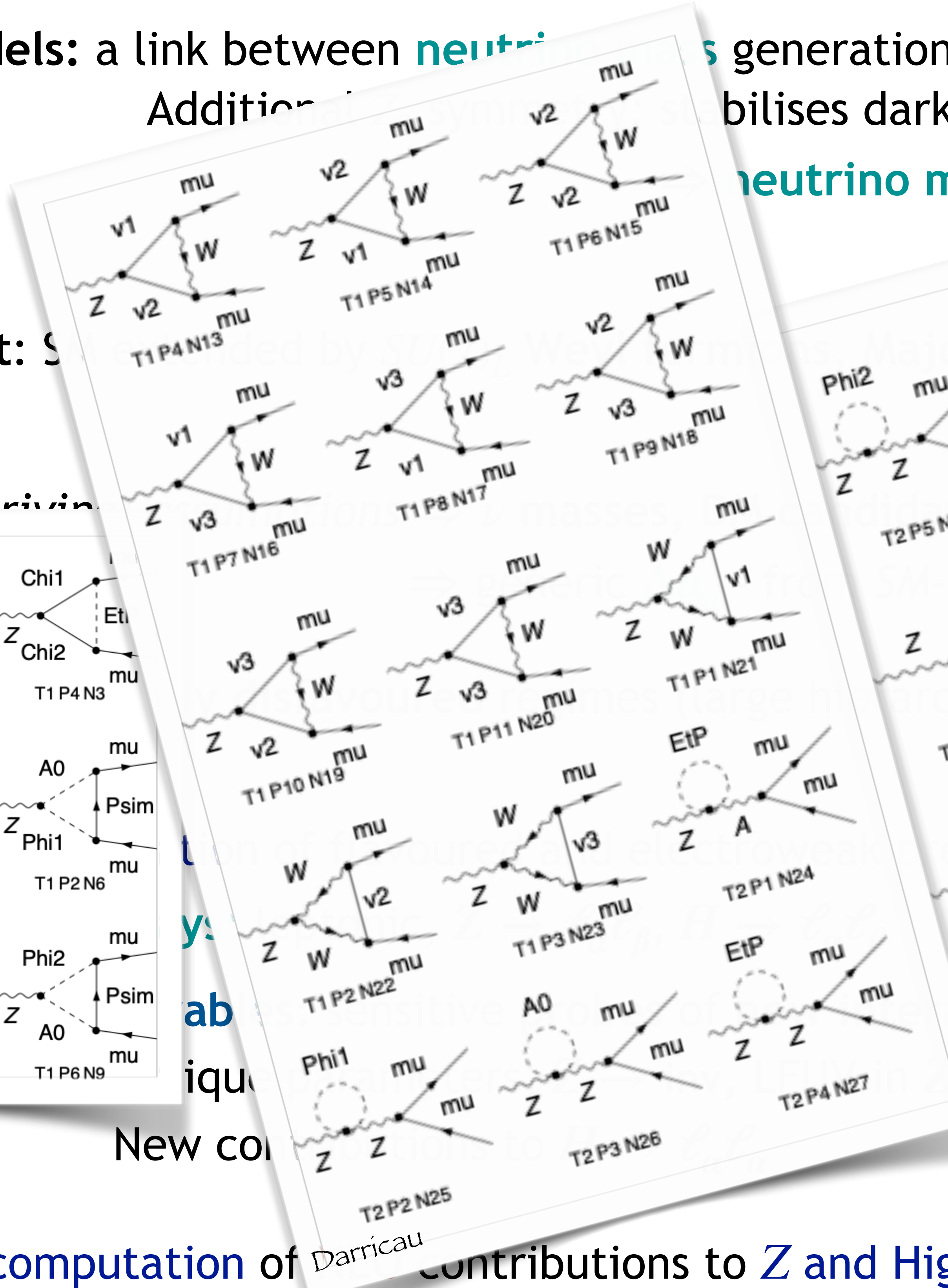
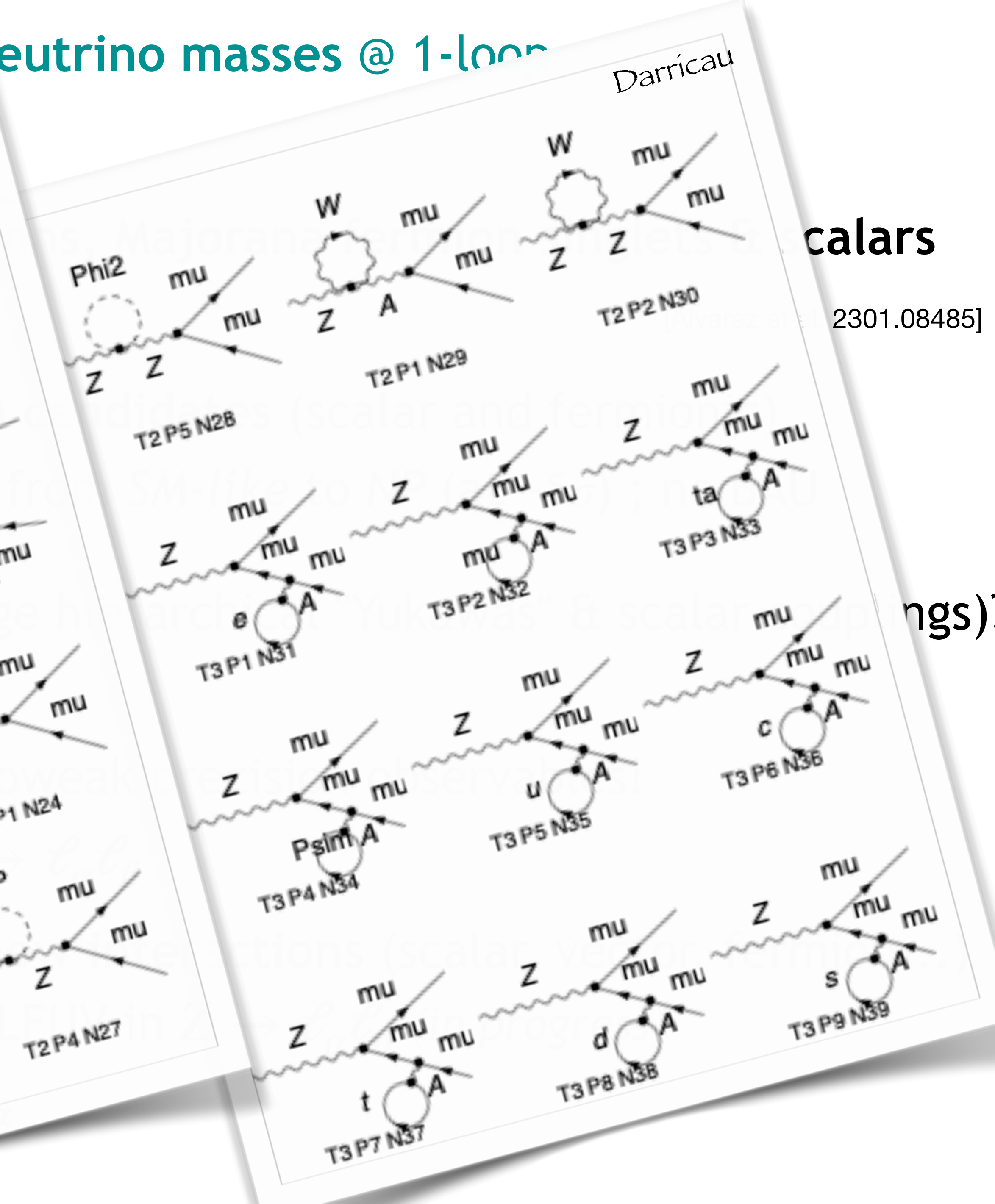


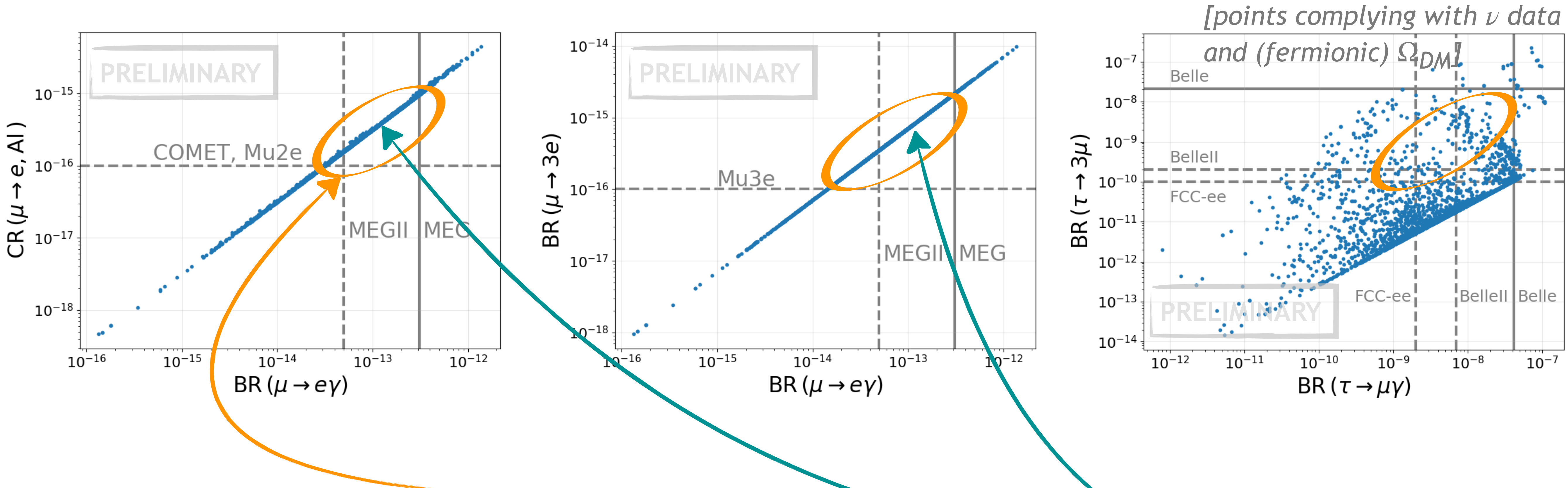

Full computation of … contributions to $Z$ and Higgs interactions!

[Darricau, Lee, Orloff, AMT to appear soon]

# Low-scale models for $m_\nu$: DM connection (?)

- **Scotogenic models: a link between neutrino mass generation and dark matter!**

- cLFV leptonic decays:
  - ⇒ **correlated muon-electron decays** (dipole dominance)
  - ⇒ sizeable **box**-contributions for **3-body tau decays**




- ⇒ well within **future reach!**
- ⇒ **muon cLFV decays** ⤳ **test & falsify model @ MEG II, Mu3e, Mu2e & COMET**

[Darricau, Lee, Orloff, AMT, to appear soon]

# Low-scale models for $m_\nu$: DM connection (?)

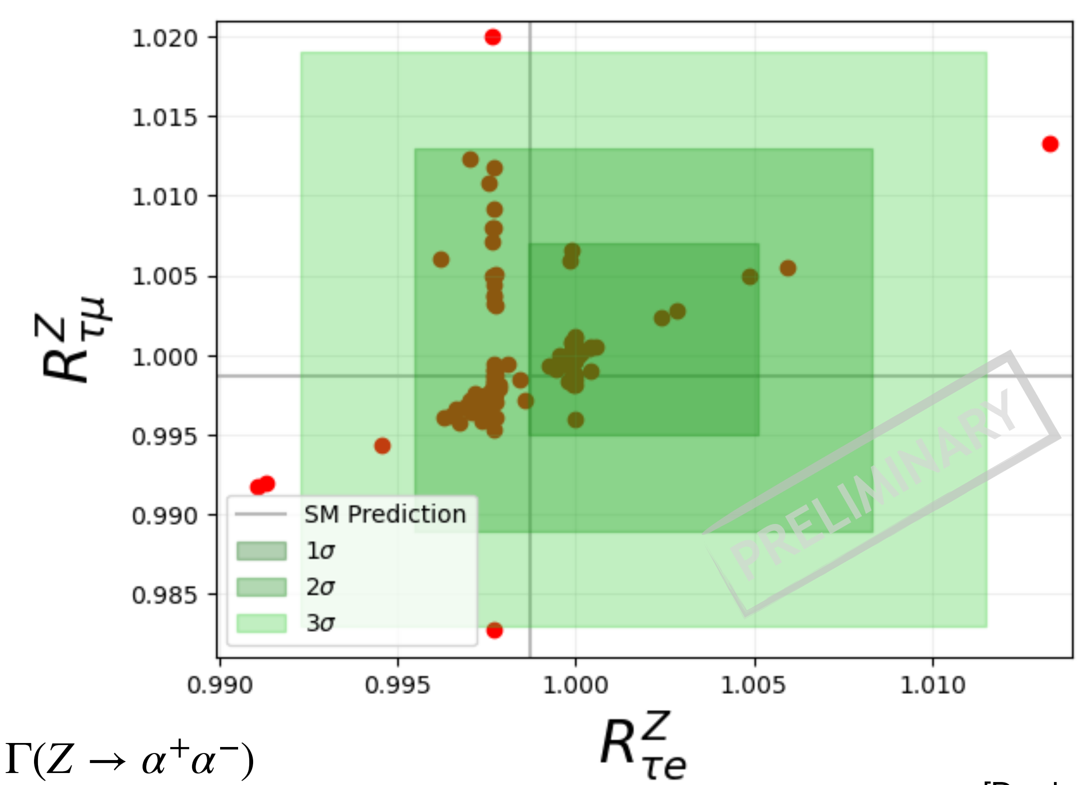
- **Scotogenic models: a link between neutrino mass generation and dark matter!**

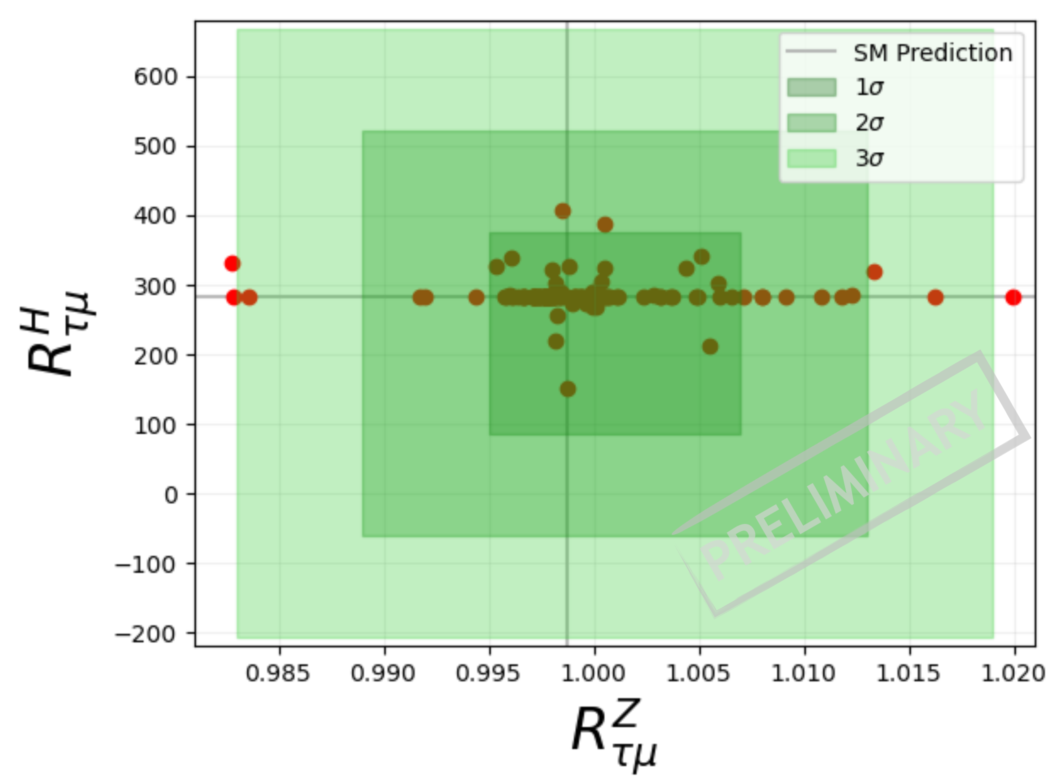
- **cLFV leptonic decays: well within future reach!**

  **muon cLFV decays ⇝ test model @ MEG II, Mu3e, Mu2e & COMET**

- **LFUV in $Z$ decays (and Higgs)**

  ⇒ Typically within $2\sigma$ (although certain regimes in stronger tension)




$$R^Z_{\alpha\beta} = \frac{\Gamma(Z \to \alpha^+\alpha^-)}{\Gamma(Z \to \beta^+\beta^-)}$$

[Darricau, Lee, Orloff, AMT, to appear soon]

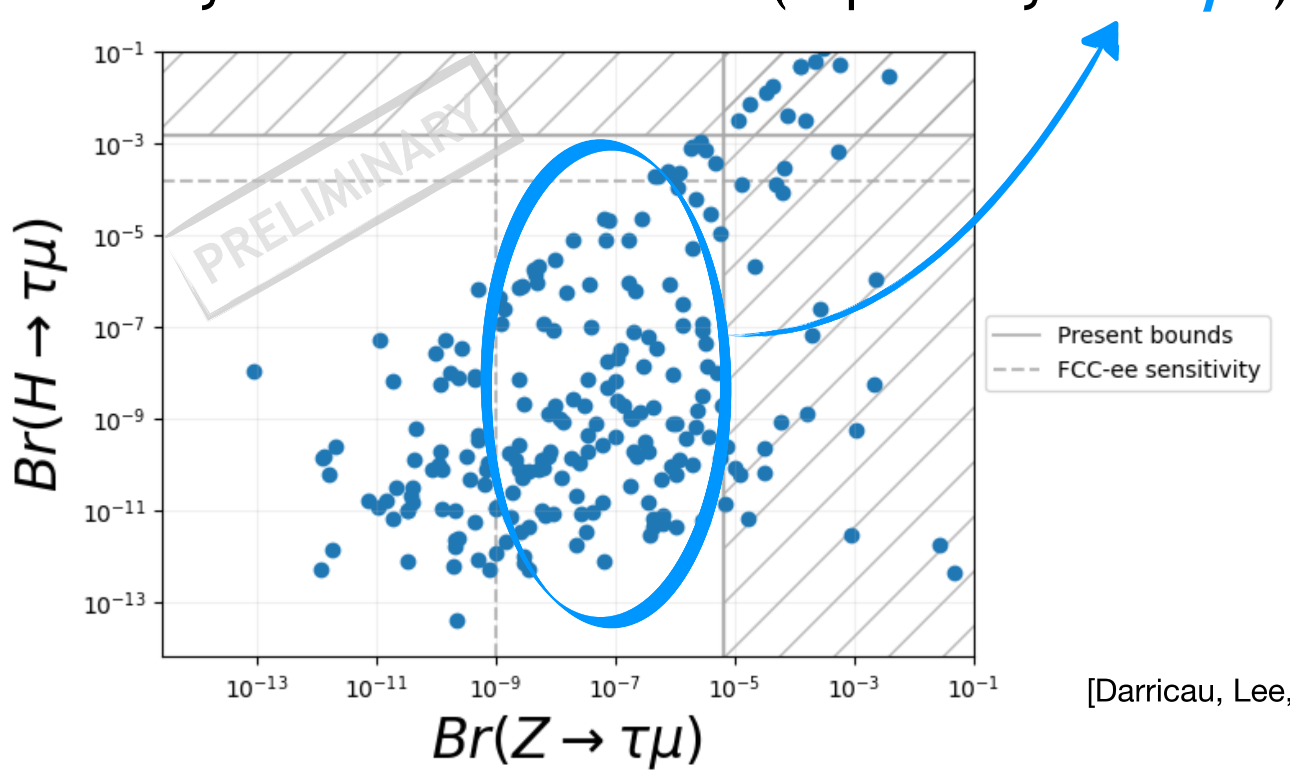
# Low-scale models for $m_\nu$: DM connection (?)

- **Scotogenic models: a link between neutrino mass generation and dark matter!**

- **cLFV leptonic decays: well within future reach!**
  **muon cLFV decays ⤳ test model @ MEG II, Mu3e, Mu2e & COMET**

- **LFUV in $Z$ decays (and Higgs)**
  $\Rightarrow$ Typically within $2\sigma$ (although certain regimes in stronger tension)

- **cLFV in $Z$ and Higgs decays (and Higgs)**
  $\Rightarrow$ Constraints on certain regimes!
  $\Rightarrow$ Potentially **testable at FCC-ee** (especially $Z \to \mu\tau$)




[Darricau, Lee, Orloff, AMT, to appear soon]

# cLFV beyond (minimal) neutrino masses...

# NP models of flavour: so many possibilities!

**Extensive contributions in recent years** - driven by **NP hints** ($m_\nu$, AMMs, B-anomalies…)

⇒ exploring *flavoured signatures of BSM* realisations

**Neutrino mass generation** and the **BAU**

**Higgs portal** to flavours

**DM** flavoured portals

**Symmetry**-enforced

**sterile fermions**

**vector-like quarks & leptons**

**additional Higgs**

$Z'$

**leptoquarks**

*Majorons*

…

**axion-like particles**

**extra scalars**

*flavons*

**UV-complete models: GUTs, Supersymmetry, extra dimensions**, …

**Ultimately addressing all (several) SM problems,** and **testable** (via flavours?!) **??**

Can **lepton flavours** help us disentangle the **NP model at work?**

Or **falsify** candidates?

# NP models of flavour: so many possibilities!

**Extensive contributions in recent years** - driven by **NP hints** ($m_\nu$, AMMs, B-anomalies...)

$\Rightarrow$ exploring *flavoured signatures of BSM* realisations

| | AC | RVV2 | AKM | $\delta$LL | FBMSSM | LHT | RS |
|---|---|---|---|---|---|---|---|
| $D^0 - \bar{D}^0$ | ★★★ | ★ | ★ | ★ | ★ | ★★★ | ? |
| $\epsilon_K$ | ★ | ★★★ | ★★★ | ★ | ★ | ★★ | ★★★ |
| $S_{\psi\phi}$ | ★★★ | ★★★ | ★★★ | ★ | ★ | ★★★ | ★★★ |
| $S_{\phi K_S}$ | ★★★ | ★★ | ★ | ★★★ | ★★★ | ★ | ? |
| $A_{CP}(B \to X_s\gamma)$ | ★ | ★ | ★ | ★★★ | ★★★ | ★ | ? |
| $A_{7,8}(B \to K^*\mu^+\mu^-)$ | ★ | ★ | ★ | ★★★ | ★★★ | ★★ | ? |
| $A_9(B \to K^*\mu^+\mu^-)$ | ★ | ★ | ★ | ★ | ★ | ★ | ? |
| $B \to K^{(*)}\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★ | ★ |
| $B_s \to \mu^+\mu^-$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★ | ★ |
| $K^+ \to \pi^+\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★★★ | ★★★ |
| $K_L \to \pi^0\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★★★ | ★★★ |
| $\mu \to e\gamma$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $\tau \to \mu\gamma$ | ★★★ | ★★★ | ★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $\mu + N \to e + N$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $d_n$ | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | ★ | ★★★ |
| $d_e$ | ★★★ | ★★★ | ★★ | ★ | ★★★ | ★ | ★★★ |
| $(g-2)_\mu$ | ★★★ | ★★★ | ★★ | ★★★ | ★★★ | ★ | ? |

[Altmannshofer et al, '10]

**AC:** RH currents & U(1) flavour sym
**RVV2:** SU(3)-flavoured MSSM
**AKM:** RH currents & SU(3) family sym
**$\delta$LL:** CKM-like currents
**FBMSSM:** flavour-blind MSSM
**LHT:** Little Higgs (T-parity)
**RS:** Warped extra dimensions

Expected **impact** for **observables:**

★★★ large effects
★★ small, but visible
★ unobservable

**Densely** populated sector!

**cLFV transitions** amongst the most **sensitive observables** to numerous **NP models!**

# Geometric flavour: RS warped extra dimensions

- Embed **4dim space-time** into **5dim AdS space** (extra dim compactified on orbifold)

  **Two branes** (UV, IR) and **bulk** between them

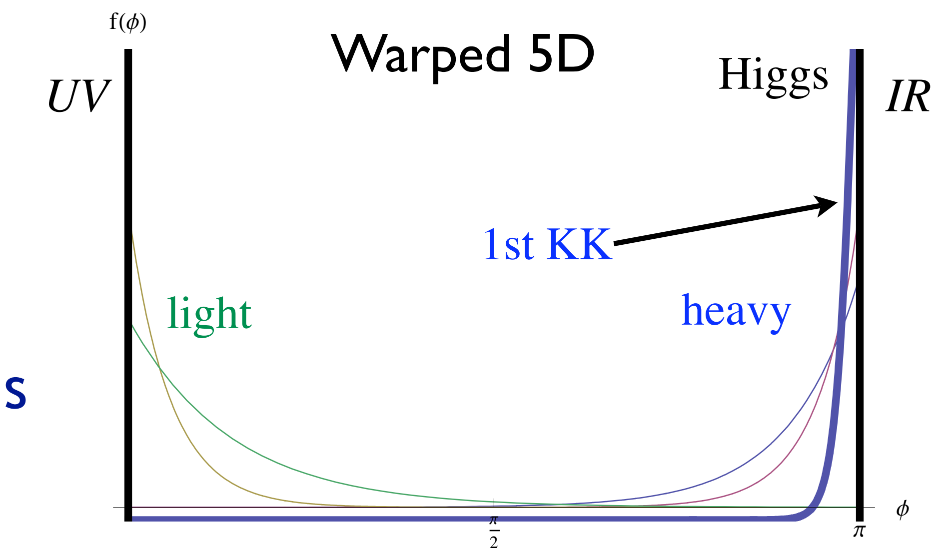
  **Localise fields:** **Higgs** close to *IR brane*

  **SM fermions** & **gauge bosons** on *bulk*

  **KK excitations** close to *IR brane*

  **Interactions** ⇝ **overlap of wave functions**

  **(L)FV** from **couplings** of light fermions to **KK excitations**




$$M_{\mathrm{TeV}} \simeq M_{\mathrm{Planck}}\, e^{-\pi k L_5}$$

**Geometrical distribution** of **fermions in bulk:**

reproduce **hierarchy** in **4dim Yukawas** from **"anarchic" $\mathcal{O}(1)$ dim5 couplings!**

*Non-negligible phenomenological issues:*

enlarge bulk symmetry to prevent violation of custodial SU(2) symmetry

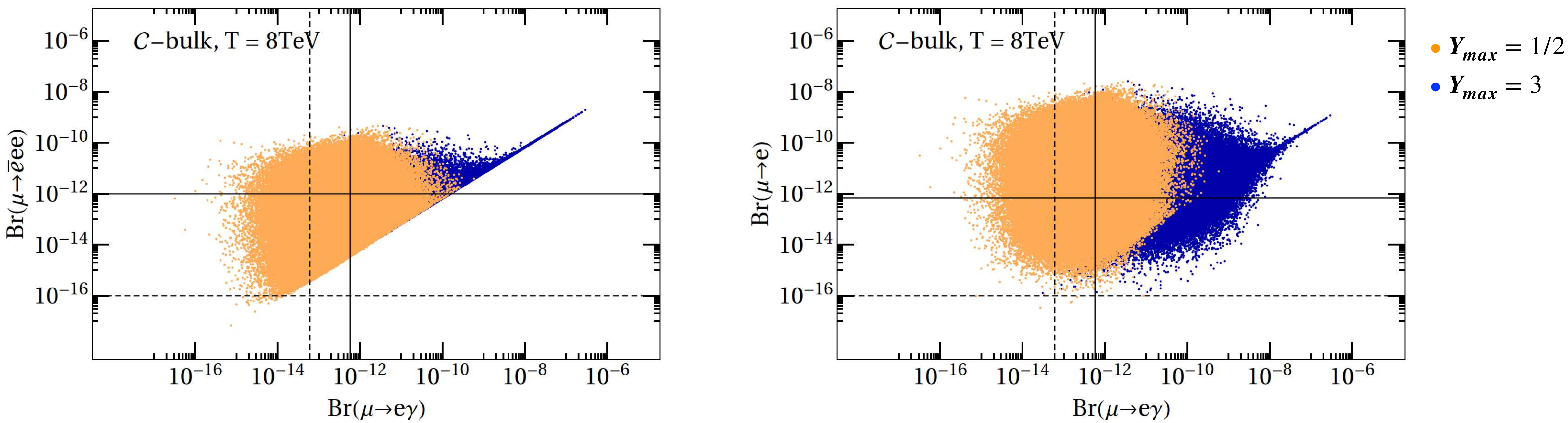
additional "rescue" strategies to avoid excessive FCNCs,

to protect EW precision observables, ..., among other issues

[Burdman, ’02; Agashe et al, ’04; Csaki et al, ’08; Blanke et al & Buras et al, ’08-’09; Bauer et at, ’10; Vempati et al, ’12; Beneke et al, ’12-’15; and many others...]

# Geometric cLFV: RS warped extra dimensions

- *Example*: **custodially protected** model, full inclusion of **all dim-6 cLFV** operators
  **generical anarchic Yukawa** couplings
  new gauge fields & KK-excitations of lepton fields ⇒ **cLFV transitions**




[Beneke et al, 1508.01705]

**Most stringent constraints** from $\mu \to e\gamma$ and $\mu - e$ **conversion**

$\tau$ decays comparatively less restrictive

Current $\mu - e$ **cLFV bounds** constrain **NP scale to be very heavy**, **beyond LHC reach**

$T_{KK} \gtrsim$ **4 TeV** (corresponding to $m^1_{KK} \gtrsim 10$ TeV)

**Future $\mu - e$ sensitivities: exclude anarchic RS models** (without additional symmetries) up to **8 TeV** (corresponding to KK gluon masses around $20$ TeV)

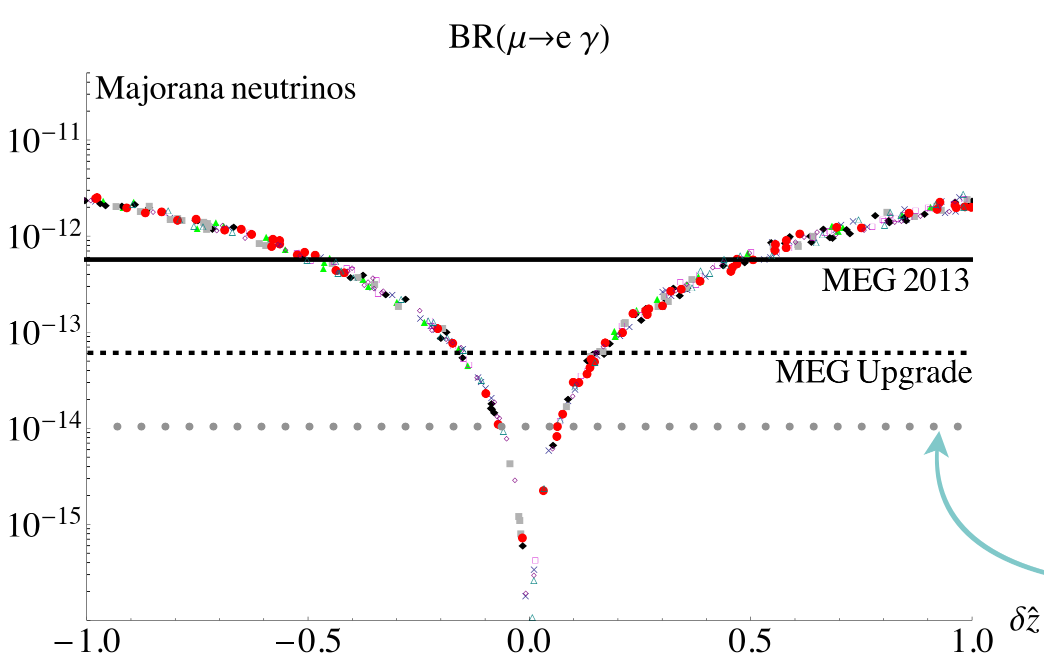
# Composite Higgs and warped extra dimensions

- **Holographic composite Higgs** model based on enlarged symmetry, $\mathcal{G}_{SM} \times G_f$

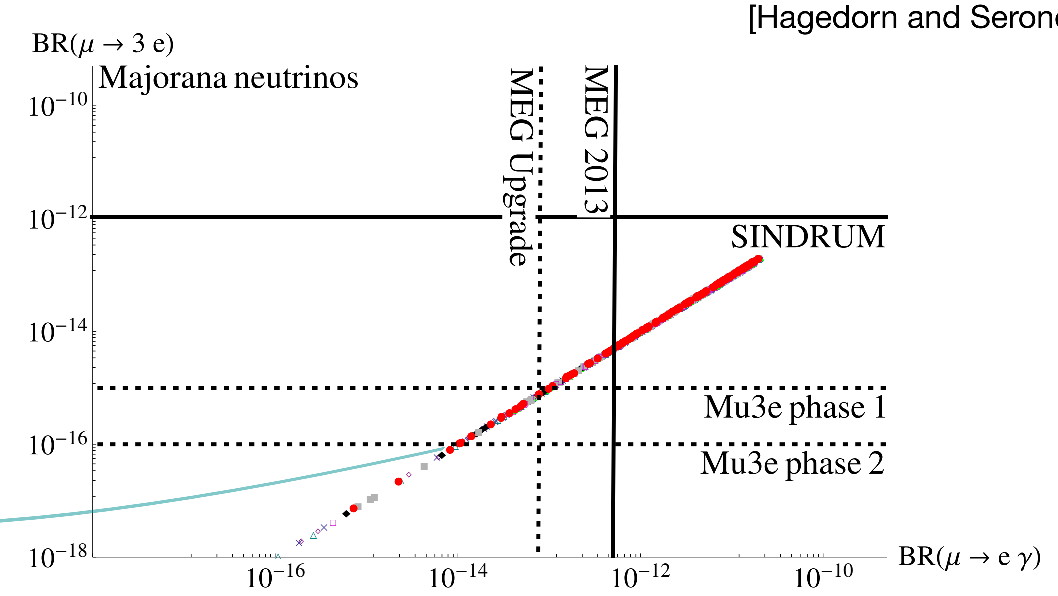
$$G_f = X \times Z_N, \text{ with } X = S_4, A_4, \Delta(96,384)$$

(Discrete) symmetries - predict the lepton mixing pattern (masses unconstrained)

Applied to **5dim** model in warped space; both cases of Dirac and Majorana neutrinos




[Hagedorn and Serone, '11-'12]




cLFV observables (as well as EDMs) typically **below experimental bounds** ($m^1_{KK} \sim 3 - 4$ TeV)

**MEG (I & II) bounds** on $\mu \to e\gamma \rightsquigarrow$ constrain the size of boundary kinetic terms!

Important role played in the future by Mu3e data

$\Rightarrow$ cLFV allows to infer relevant information on fundamental parameters

# Concluding remarks

# Outlook

**Confirmed observations** and several **"tensions"** suggest the need to go **beyond the SM**

In the **lepton sector, $\nu$-masses** provided the 1st laboratory **evidence of NP**

Many experimental **"tensions"** nested in **lepton-related observables**

**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!**

**(Synergy of) lepton observables** can provide **information on the underlying NP model**

**New Physics is there! Lepton physics** might be a perfect **portal** to address SM problems

⇒ First hints on **preferred paths** to NP from **EFT approach**

⇒ Attempt at **identifying the underlying model** capable of accounting for ***all* SM problems** ($m_\nu$, **DM** and **BAU**) and further **"tensions" with observation!**

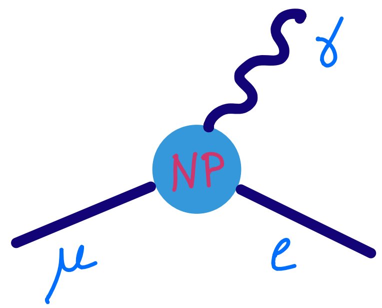
**cLFV** emerges as extremely **powerful probe** to test and falsify **NP in the lepton sector**

**Explore different paths**, and **profit from amazing experimental prospects in the near future!**

# Additional material

# cLFV observables

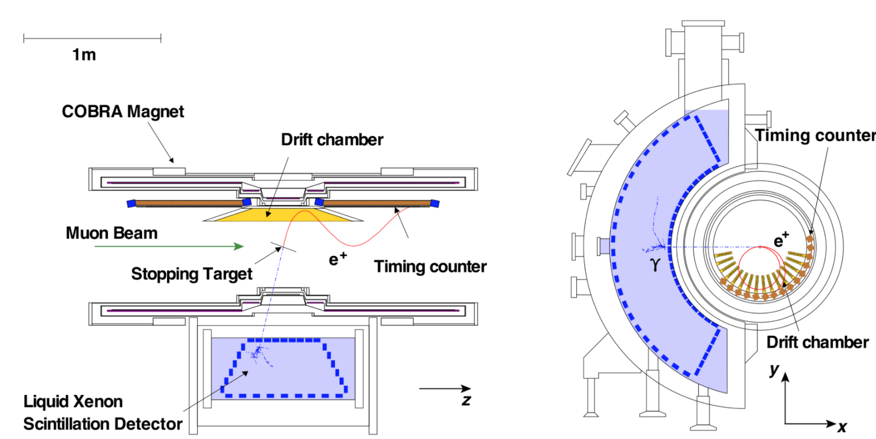
# cLFV muon channels: radiative decays




- cLFV decay: $\mu^+ \to e^+ \gamma$
- **Event signature:** $E_e = E_\gamma = m_\mu/2 \quad (\sim 52.8$ MeV)
  Back-to-back $e^+ - \gamma \quad (\theta \sim 180^\circ)$; Time coincidence

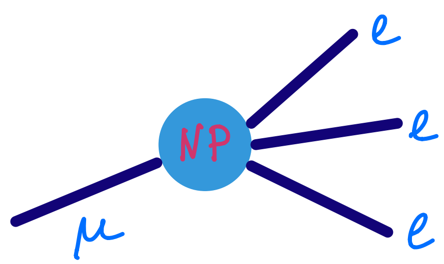
- **Backgrounds** $\Rightarrow$ prompt physics & accidental
  Prompt: radiative $\mu$ decays ($\mu \to e\,\bar{\nu}_e \nu_\mu \gamma$, very low $E_\nu$) $[\propto R_\mu]$
  Accidental: coincidence of $\gamma$ with positron from Michel decays $\mu \to e\,\bar{\nu}_e \nu_\mu$ :
  photon from $\mu \to e\,\bar{\nu}_e \nu_\mu \gamma$ ; $\gamma$ from in-flight $e^+e^-$ annihilation $[\propto R_\mu^2]$

- **Experimental status:**
  *First searches (!) in 1940's* [MEG Coll., 1605.05081]
  Advent of intense muon beams in 2000's MEG @ PSI
  BR($\mu^+ \to e^+\gamma$) $\leq 4.2 \times 10^{-13}$ (90% CL)




- **Future prospects:** [MEG II Coll., 2201.008200]
  MEG II (@ PSI): BR($\mu^+ \to e^+\gamma$) $\leq 6 \times 10^{-14}$
  *very hard to go beyond* $10^{-15}$ *without conceptually different approach*

# cLFV muon channels: 3-body decays




- cLFV decay: $\mu^+ \to e^+ e^- e^+$
- **Event signature:** $\Sigma E_e = m_\mu ; \Sigma \vec{P}_e = \vec{0}$
  common vertex; Time coincidence

- **Backgrounds** $\Rightarrow$ physics & accidental

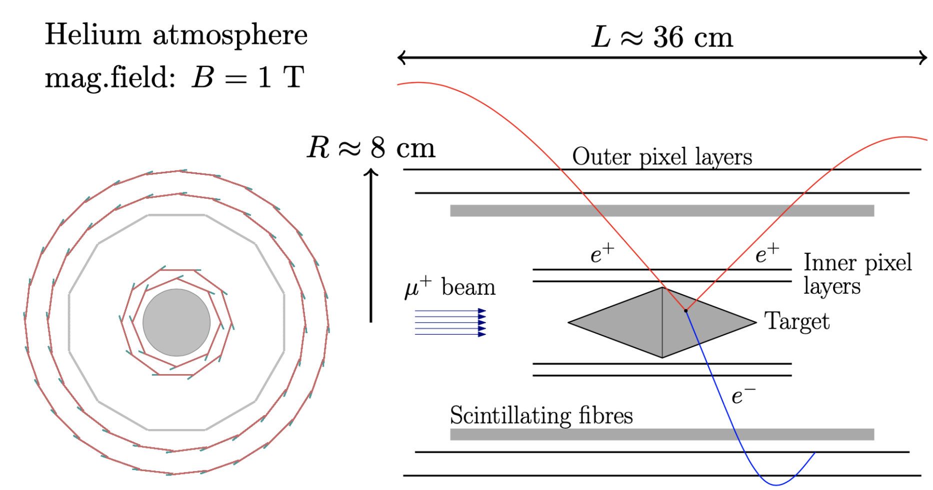
  Physics: multi-body $\mu$ decays ($\mu \to e \bar{\nu}_e \nu_\mu e^+ e^-$, very low $E_\nu$)

  Accidental: Bhabha scattering of Michel $e^+$ from $\mu \to e \bar{\nu}_e \nu_\mu$ decays with atomic $e^+ e^-$
  Michel positrons with $e^+ e^-$ from $\gamma$ conversion

- **Experimental status:**

  SINDRUM @ PSI [SINDRUM Coll., '88]

  $\mathrm{BR}(\mu^+ \to e^+ e^- e^+) \leq 1.0 \times 10^{-12}$ (90% CL)




- **Future prospects:** [Mu3e Coll., 2009.11690]

  Mu3e (@ PSI): expected sensitivity $\mathcal{O}(10^{-15})$ for Phase I
  with HIMB, $\mathcal{O}(10^{-16})$ for Phase II [Aiba et al, 2111.05788]

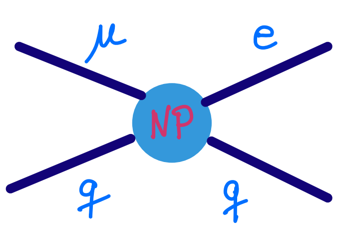
# cLFV in muonic atoms: $\mu - e$ conversion

- **Muonic atoms:** 1s bound state formed when $\mu^-$ 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

  $$E_{\mu e} = m_\mu - E_B(A, Z) - E_R(A, Z)$$

  For Aluminium, Lead, Titanium $\rightsquigarrow E_{\mu e} \approx \mathcal{O}(100\text{ MeV})$

  *Which target?** For coherent conversion, maximal rates for* $30 \leq Z \leq 60$

- **Backgrounds** $\Rightarrow$ Only physics! $\mu$ decay in orbit, beam purity, cosmic rays, …

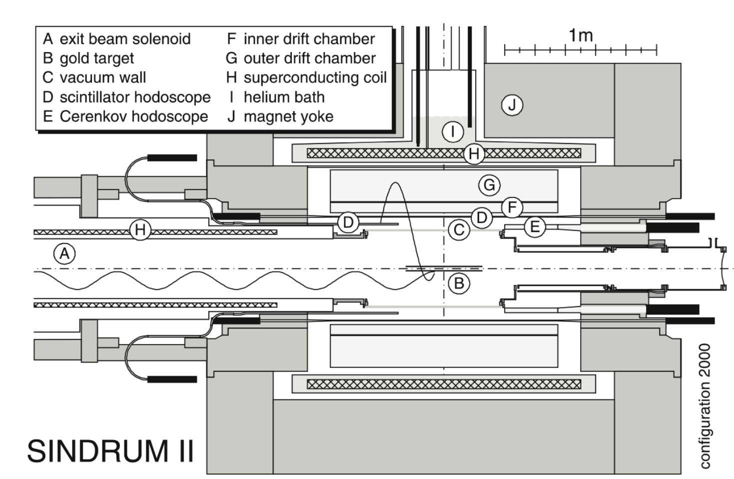
- **Experimental status:** [SINDRUM II Coll., '06]

  SINDRUM @ PSI: CR($\mu^- - e^-$, Au) $\leq 7.1 \times 10^{-13}$ (90% CL)

- **Future prospects:**

  Mu2e (@ FNAL) - $\mathcal{O}(10^{-17})$, [Bartoszek et al, 1501.05241]

  [Abramishvili et al, '20] COMET (@ JPARC) - $\mathcal{O}(10^{-15} - 10^{-17})$, …



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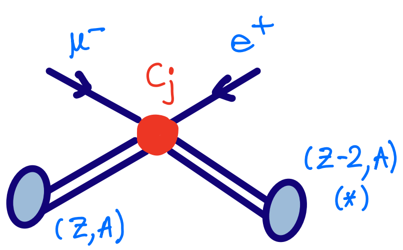
  nuclear capture $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$

- In the presence of **New Physics** - cLFV & LNV $(\Delta L = 2)$ neutrinoless $\mu^- - e^+$ conversion

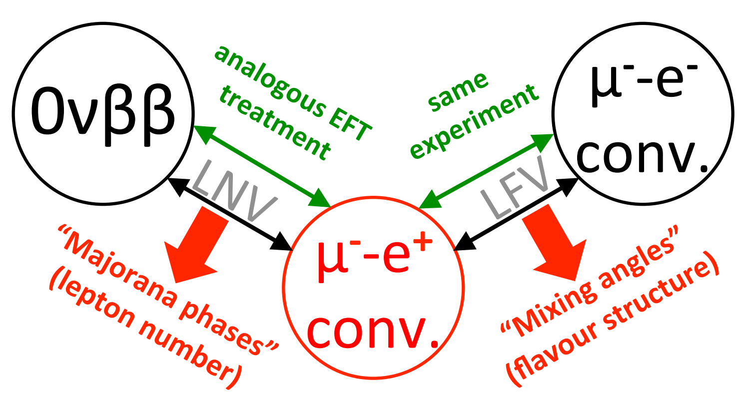
$$\boldsymbol{\mu^- + (A, Z) \to e^+ + (A, Z-2)^*}$$




$\mu^- - e^-$ conversion: coherent process, single nucleon, nuclear ground states

$\mu^- - e^+$ conversion: 2 nucleons $(\Delta Q = 2)$, possibly excited final state

A **unique connection** between LNV (in association with Majorana nature and possibly, neutrino mass generation) and cLFV




LNV-Alternatives:
$\mu^-$-$\mu^+$ conversion
$K^+ \longrightarrow \pi^+\mu^-\mu^-$

LFV-Alternatives:
$\mu \longrightarrow e+\gamma$
$\mu \longrightarrow 3e$

[see e.g. Geib et al, 1609.09088]

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

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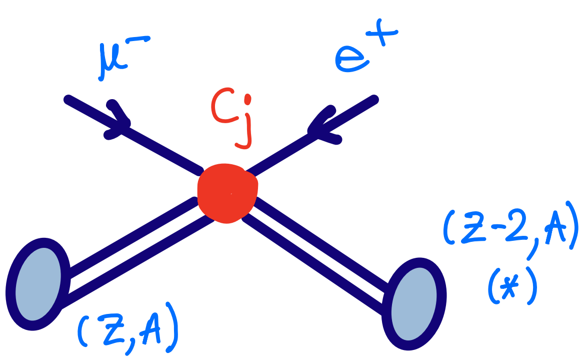



- **Event signature:** single positron - but complex energy spectrum

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

  For Aluminium (giant dipole resonance) $\rightsquigarrow E_{\mu^- e^+}^{\text{Al, GDR}} \approx \mathcal{O}(83.9\text{ MeV})$

- **Experimental status:**

| Collaboration | year | Process | Bound |
|---|---|---|---|
| PSI/SINDRUM | 1998 | $\mu^-$+Ti$\to e^+$+Ca$^*$ | $3.6 \times 10^{-11}$ |
| PSI/SINDRUM | 1998 | $\mu^-$+Ti$\to e^+$+Ca | $1.7 \times 10^{-12}$ |

- **Future prospects:**

  Best sensitivity expected for Ca, S and Ti targets (possibly $\sim \mathcal{O}(\text{few} \times 10^{-15})$)

[Yeo et al,'17]

# cLFV in muonic atoms: Coulomb enhanced decay

- **Muonic atoms:** 1s bound state formed when $\mu^-$ stopped in target

- In the presence of **New Physics** - cLFV muonic atom decay $\mu^- e^- \to e^- e^-$

  Initial $\mu^-, e^-$: 1s states bound in Coulomb field of muonic atom's nucleus

  Coulomb interaction increases wave function overlap

  rate strongly enhanced in large $Z$ atoms, $\Gamma \gtrsim (Z-1)^3$

  Larger phase space (compared with $\mu \to 3e$)

- **Event signature:** back-to-back electrons, $E_{e^-} \approx m_\mu/2$

- **Backgrounds** $\Rightarrow$ similar to neutrinoless conversion

- Experimental status - new observable!

  possibly included in future physics runs (e.g. COMET)

# cLFV muonium decays

- **Muonium: $\mu^+ e^-$**

  **Hydrogen-like** Coulomb bound state, free of hadronic interactions!

  Powerful laboratory for **EW** tests and cLFV

- In the presence of **New Physics** - Muonium oscillations and Muonium decays

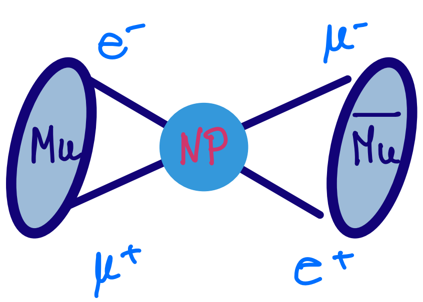
  - **Mu-$\overline{\text{Mu}}$ oscillation**

    Spontaneous conversion $\mu^+ e^- \leftrightsquigarrow \mu^- e^+$

    Reflects a double (individual) lepton number violation $|\Delta L_e| = |\Delta L_\mu| = 2$

    Rate (typically) suppressed by external magnetic fields

    **Detection:** reconstruct Michel electron from $\mu^-$ decays and shell positron




    **Experimental status:** MACS - $P(\text{Mu} - \overline{\text{Mu}}) < 8.3 \times 10^{-11}$ [Willmann et al, 1999]

    **Future prospects:** MACE, AMF (@FNAL)

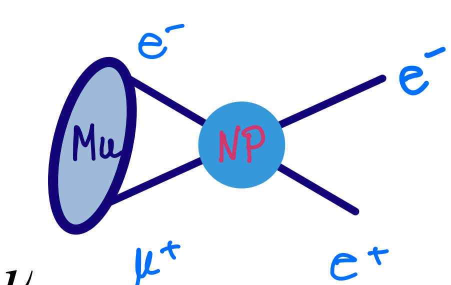
    [Bai et al, 2203.11406]

- **Mu decays**

  $\mu^+ e^- \to e^+ e^-$

  Clear signal compared to SM-allowed muonium decay, Mu $\to e^+ e^- \bar{\nu}_\mu \nu_e$

  No available bounds, no clear roadmap...



# 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. $\tau^+ \to \bar{\nu}_\tau \nu_e e^+$)

- **cLFV tau decays:** abundant modes! Pure leptonic, semileptonic (2- and 3-body), ...

- **Radiative decay: $\tau^\pm \to \ell^\pm \gamma$**
  - **Event signature:** $E_{\text{final}} - \sqrt{s}/2 = \Delta E \sim 0$ ; $M_{\text{final}} = M_{\ell\gamma} \sim m_\tau$
  - **Backgrounds** $\Rightarrow$ coincidence of isolated leptons with $\gamma$ (ISR, FSR); mistagging

- **3-body leptonic decay: $\tau^\pm \to \ell_i^\pm \ell_j^\mp \ell_k^\pm$**
  - **Event signature:** $E_{3\ell} - \sqrt{s}/2 \sim 0$ ; $M_{3\ell} \sim m_\tau$
  - **Backgrounds** $\Rightarrow$ No irreducible backgrounds!

    Small background from $q\bar{q}$ and Bhabha pairs, ...

# 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. $\tau^+ \to \bar{\nu}_\tau \nu_e e^+$)

- **cLFV tau decays:** abundant modes! Pure leptonic, semileptonic (2- and 3-body), ...

- **Semi-leptonic cLFV tau decays**
  - **2-body** final state: $\tau \to \ell h^0$ (pseudoscalar, scalar or vector neutral meson)
  - **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)
  - $\tau^- \to \ell^+ h_i^\pm h_j^\pm$ $(h \leftrightsquigarrow \pi^\pm, K^\pm)$ $\Rightarrow$ LNV
  - $\tau^- \to \Lambda h^-$ $(h \leftrightsquigarrow \pi^\pm, K^\pm)$ $\Rightarrow$ LNV & BLV
  - $\tau \to p \ell_i \ell_j$ $\Rightarrow$ LNV & BLV