Neutrino physics and charged lepton flavours: synergy at the high-intensity frontier

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Neutrino oscillations: gateway to new physics

- Neutrino oscillations provided the 1st laboratory **evidence of New Physics**

  $\Rightarrow$ **SM must be clearly extended** (or embedded in a larger framework)!

  Smallness of m_ν and unique nature (Dirac vs Majorana)

  $\rightsquigarrow$ **new mechanism of mass generation** and existence of **new fields...**

- **Several** appealing models successfully **account for ν data**

  such extensions might even allow **to address SM observational problems**

  $\rightarrow$ New sources of **CP violation, $\Delta L = 2$** processes, new **"heavy" fields**

  $\Rightarrow$ **BAU from leptogenesis**

  $\rightarrow$ New "comparatively" **light**, (nearly) **stable weakly** interacting states

  $\Rightarrow$ (warm) **Dark Matter candidates**

Neutrino oscillations: gateway to new physics

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  Several **possible models** successfully **account for ν data**

  such extensions might even allow **to address SM caveats**

  hints to the **flavour puzzle ?** **BAU via leptogenesis ?** **DM candidates ?**

- **Extend the SM:** but how? **Hundreths of (motivated) theoretical constructions!!**

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- **Extend the SM:** but how? **Hundreths of (motivated) theoretical constructions!!**

- Gateway to new **experimental signals** (deviation from SM) in the **lepton sector:**

  Lepton Number Violation (if **Majorana**) - **$0\nu2\beta$, meson decays, colliders, ...**

  Electric dipole moments and **Anomalous magnetic moments**

  Charged lepton flavour violation

- **Rare processes searched for at high-intensity facilities**

  ⇒ **Complementary information to direct searches;**

  NP discovery (before LHC!); sensitive to **scales beyond collider reach...**

Brief summary

- **Leptonic high-intensity observables: signs of New Physics**
- **Observables and experimental status (cLFV & some friends)**
  - **Lepton number violation** (observables at high and low energies)
  - **Charged lepton flavour violation**
  - **CP violation:** Electric dipole moments
- **Model-independent approaches to New Physics**
- **Models of neutrino mass generation & more (*): signals at high-intensities**
  - **Ad-hoc extensions**
  - **Seesaw realisations**
  - **Larger frameworks**
- **Overview & discussion**

(*) = focus on GdR HI community!

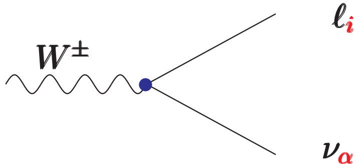
Leptonic observables: signs of New Physics

- In the **Standard Model:** (strictly) **massless neutrinos**
  conservation of total lepton number & lepton flavours
  tiny leptonic EDMs (at 4-loop level.. $d_e^{\mathrm{CKM}} \leq 10^{-38} e$ cm)

- **Extend the SM** to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$

  Assume **most minimal** extension SM_{m_ν}

  [SM_{m_ν} = "ad-hoc" m_ν (Dirac), U_{PMNS}]



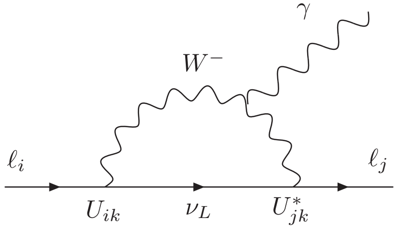
$\bullet \propto U_{\alpha i}^{\mathrm{PMNS}}$

$m_\nu \neq 0$

$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$

- In the SM_{m_ν}: **(total) Lepton number conserved;** what about lepton flavours? And CP?

- SM_{m_ν} - **cLFV possible??**



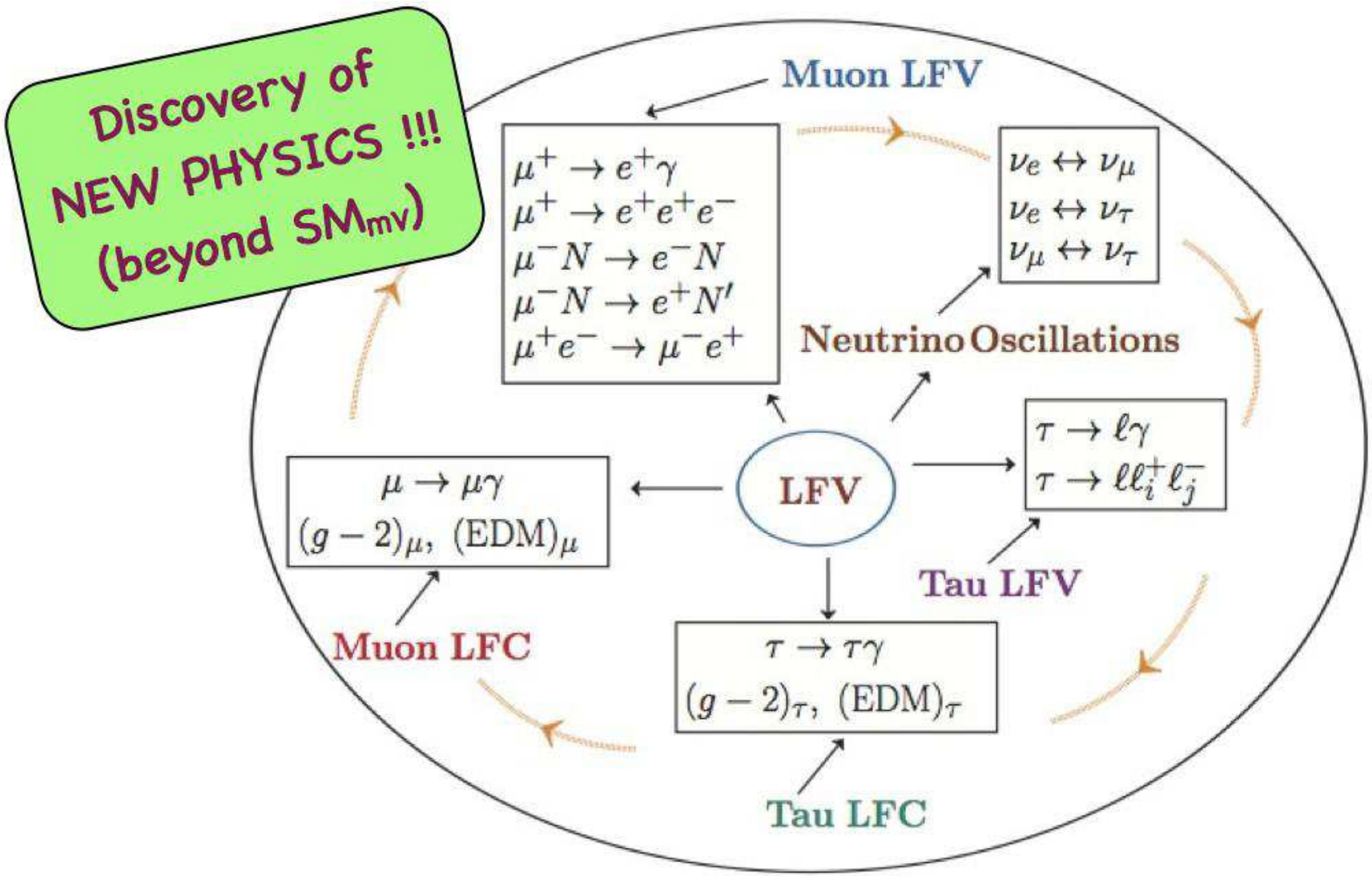
$$\mathrm{BR}(\mu \to e\gamma) \propto \left| \sum U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \sim 10^{-54}$$

[Petcov, '77]

Possible - **yes...** but **not observable!!**

- SM_{m_ν} - **observable EDMs?** Contributions from δ_{CP} (2-loop)... still $d_e^{\mathrm{lep}} \leq 10^{-35} e$ cm

Leptonic observables: signs of New Physics



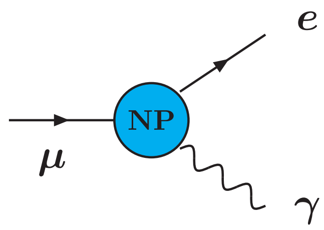
- **Leptonic observables (cLFV and friends): current status**

[$\rightsquigarrow$ **Detailed presentation by F. Kapusta tomorrow!**]

Signals of Lepton Flavour Violation

- Neutrino oscillations [ν-dedicated experiments]

- Rare leptonic decays and transitions [high-intensity facilities]



  $\ell_i \to \ell_j \gamma$, $\ell_i \to 3\ell_j$, mesonic τ decays...

  nucleus assisted $\mu - e$ transitions, Muonium channels...

- Meson decays: violation of lepton flavour universality (e.g. R_K)

  lepton Number violating decays - $B \to D\,\mu^-\mu^-, \ldots$

  lepton flavour violating decays - $B \to \tau\mu, \ldots$ [high-intensity; LHCb]

- Rare (new) heavy particle decays (typically model-dependent) [colliders]

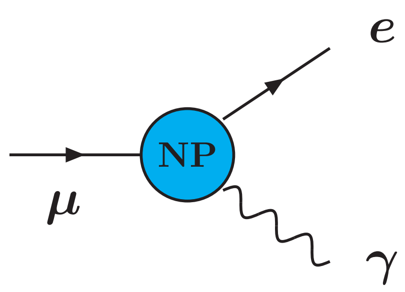
  SM boson decays: $H \to \tau\mu$, $Z \to \ell_i \ell_j$

  SUSY $\tilde{\ell}_i \to \ell_j \chi^0$; FV KK-excitation decays; ...

  LFV final states: for example, $e^\pm e^- \to e^\pm \mu^- + E_{\text{miss}}$

- And many others ... **all absent in the SM!**

cLFV in muon channels: radiative decays



- cLFV decay: $\mu^+ \to e^+ \gamma$
- Event signature: $E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)

  Back-to-back e^+ - γ ($\theta \sim 180°$); Time coincidence

- Backgrounds ⇒ prompt physics & accidental

  Prompt: radiative μ decays $\mu \to e\nu_e\nu_\mu\gamma$ (very low E_ν) $[\propto R_\mu]$

  Accidental: coincidence of γ with positron from Michel decays $\mu \to e\nu_e\nu_\mu$; photon from $\mu \to e\nu_e\nu_\mu\gamma$; photon from in flight e^+e^- annihilation $[\propto R_\mu^2]$

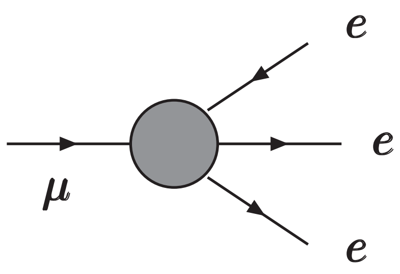
- **Current status:**

Collaboration	year	BR($\mu \to e\gamma$) 90% C.L.
LAMPF/MEGA	1999	1.2×10^{-11}
PSI/MEG	2011	2.8×10^{-11}
PSI/MEG	**2016**	$\mathbf{4.2 \times 10^{-13}}$

- **Future prospects: MEG II PSI** (proposal 2013) **sensitivity** $\mathbf{4 \times 10^{-14}}$

  ... intense proton beams: CERN (NuFact), FNAL, JPARC, ...

cLFV in muon channels: 3-body decays



- **cLFV decay:** $\boldsymbol{\mu^+ \to e^+ e^- e^+}$
- **Event signature:** $\sum E_e = m_\mu$; $\sum \vec{P}_e = \vec{0}$

  common vertex; Time coincidence

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

  Physics: $\mu \to ee\nu\nu e$ decay (very low E_ν)

  Accidental: Bhabha scattering of Michel e^+ from $\mu \to e\nu\nu$ with atomic e^+e^-;
  Michel positrons with e^+e^- from γ conversion...

- **Current status:**

Collaboration	year	BR($\mu \to eee$) 90% C.L.
LAMPF/Crystal Box	1988	3.5×10^{-11}
PSI/SINDRUM	**1988**	$\mathbf{1.0 \times 10^{-12}}$
JINR	1991	3.6×10^{-11}

- **Future prospects: Mu3e Experiment** at **PSI**

  Phase I ($\sim$ 2017): $\mathbf{10^{-15}}$ (πE5 μ source) $\Rightarrow$ **Phase II ($>$ 2018): $\mathbf{10^{-16}}$** (H.I. μ-beam)

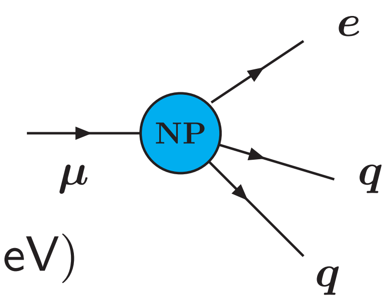
cLFV in "muonic" atoms: $\mu - e$ conversion

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

SM processes: $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ (decay in orbit); $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$ (nuclear capture)

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

coherent conversion, increases with Z (maximal for $30 \leq Z \leq 60$)



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

$$E_{\mu e}^{\mathrm{N}} = m_\mu - E_B(A, Z) - E_R(A, Z), \qquad E_{\mu e}^{\text{Al, Pb, Ti}} \approx \mathcal{O}(100 \text{ MeV})$$

- **Backgrounds** ⇒ only **physics** (e.g. μ decay in orbit); beam (purity), cosmic rays, ...

- **Experimental status (present bounds and future prospects):**

CR($\mu - e$, N) bound	material	year
$\mathbf{4.3 \times 10^{-12}}$	**Ti**	1993
$\mathbf{4.6 \times 10^{-11}}$	**Pb**	1996
$\mathbf{7 \times 10^{-13}}$	**Au**	2006

Experiment (material)	future sensitivity	year
Mu2e (Al)	$\mathbf{3 \times 10^{-17}}$	$\sim$ 2021
COMET (Al) - Phase I (II)	$\mathbf{10^{-15}}$ ($\mathbf{10^{-17}}$)	$\sim$ 2018(21)
PRISM/PRIME (Ti)	$\mathbf{10^{-18}}$	
DeeMe (SiC)	10^{-14}	

- And also LNV ($\Delta L = 2$) $\mu^- - e^+$ conversion: $\boldsymbol{\mu^- + (A, Z) \to e^+ + (A, Z-2)^*}$

cLFV in "muonic" atoms: Coulomb enhanced decays

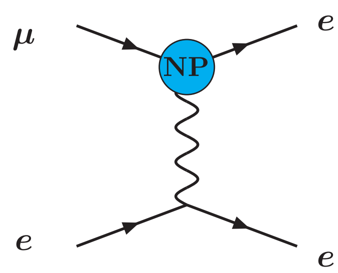
- **Muonic atom decay:** $\mu^- e^- \to e^- e^-$ [Koike et al, '10]

  Initial μ^- and e^-: 1s state bound in Coulomb field of the **muonic atom's nucleus**

- **Coulomb interaction** increases overlap between

  Ψ_{μ^-} and Ψ_{e^-} wave functions

  $$\Gamma(\mu^- e^- \to e^- e^-, \text{ N}) \propto \sigma_{\mu e \to ee} v_{\text{rel}} \left[(Z-1)\,\alpha\, m_e\right]^3/\pi$$



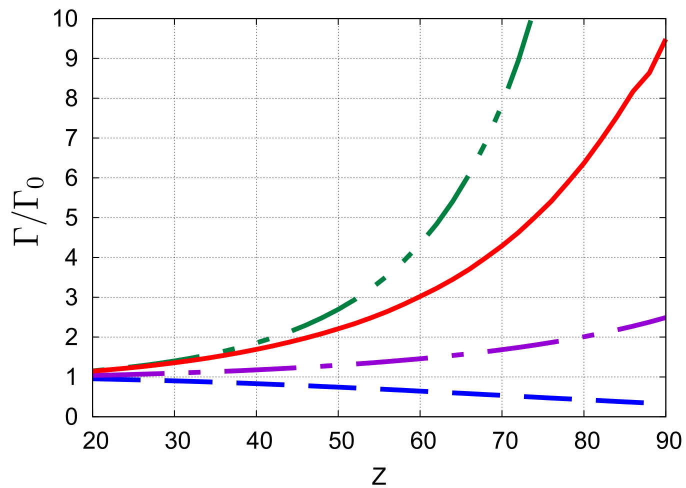
- **Clean experimental signature:** back-to-back electrons, $E_{e^-} \approx m_\mu/2$

  larger phase space than $\mu \to 3e$

- **Rate strongly enhanced** in **large Z atoms**

  $$\Gamma/\Gamma_0 \gtrsim (Z-1)^3$$ [Uesaka et al, '15-'16]

  Consider experimental setups for **Pb, U !?**



- **Experimental status: New observable!**

  Hopefully included in **COMET**'s Physics programme

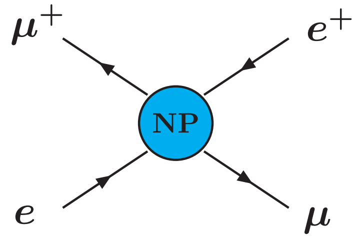
cLFV in "muonic" atoms: Muonium

- **Muonium:** hydrogen-like **Coulomb bound state** $(e^-\mu^+)$; free of hadronic interactions!

- **Mu – $\overline{\text{Mu}}$ conversion**

  Spontaneous conversion of a $(e^-\mu^+)$ into $(e^+\mu^-)$

  Reflects a **double lepton number violation:** $\Delta L_e = \Delta L_\mu = 2$



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

- **cLFV Mu decay:** Mu $\to e^+e^-$

  clear signal compared to SM decay Mu $\to e^+e^-\bar{\nu}_\mu\nu_e$ (no missing energy)

- **Experimental status:** no clear roadmap (nor bounds)...

  Hopefully included in **COMET**'s Physics programme

Rare lepton processes: cLFV tau decays

- **Tau production and decay:** $e^+e^- \to \tau^+\tau^-$ $\rightsquigarrow$ signal hemisphere
  $\rightsquigarrow$ tagging hemisphere: e.g. $\tau \to \bar{\nu}_\tau \nu_e e$

- **Radiative decay:** $\boldsymbol{\tau^\pm \to \ell^\pm \gamma}$
  - **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 γ (ISR, FSR); mistagging

Process	BR (BaBar, 2010)
$\boldsymbol{\tau \to e\gamma}$	$\mathbf{3.3 \times 10^{-8}}$
$\boldsymbol{\tau \to \mu\gamma}$	$\mathbf{4.4 \times 10^{-8}}$

- **3-body decays:** $\boldsymbol{\tau^\pm \to \ell_i^\pm \ell_j^\mp \ell_k^\pm}$
  - **Event signature:** $E_{3\ell} - \sqrt{s}/2 \sim 0;\ M_{3\ell} \sim m_\tau$
  - **Backgrounds** $\Rightarrow$ **No irreducible backgd!**
    small backgd from $q\bar{q}$ and Bhabha pairs...

3ℓ final state	BR (BaBar)	BR (Belle)
$\boldsymbol{e^-e^+e^-}$	2.9×10^{-8}	$\mathbf{2.7 \times 10^{-8}}$
$\mu^-e^+e^-$	2.2×10^{-8}	1.8×10^{-8}
$\mu^-e^-e^-$	1.8×10^{-8}	1.5×10^{-8}
$e^+\mu^-\mu^-$	2.6×10^{-8}	1.7×10^{-8}
$e^-\mu^+\mu^-$	3.2×10^{-8}	2.7×10^{-8}
$\boldsymbol{\mu^-\mu^+\mu^-}$	3.3×10^{-8}	$\mathbf{2.1 \times 10^{-8}}$

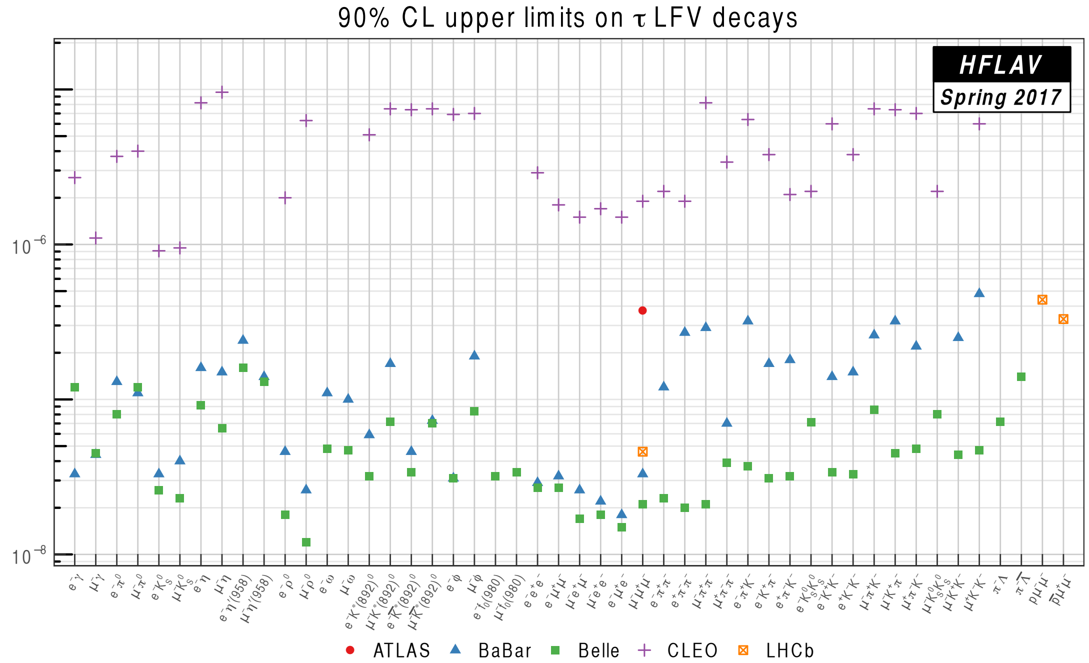
- **Future experimental prospects: SuperB (Belle II) and/or Tau-Charm factories**

  BR$(\tau \to \ell\gamma) \leq 1 - 3 \times 10^{-9}$ **BR**$(\tau \to 3\ell) \leq 1 - 2 \times 10^{-10}$

Rare processes: (semi)leptonic decays

cLFV tau decays into mesons: "large" τ mass $\Rightarrow$ possible to have semi-leptonic decays

- **Meson(s) & charged lepton:** $\tau \to \ell h^0$; $\tau \to \ell h_i h_j$
- **cLFV exotic modes:** $\tau^- \to \ell^+ h_i^- h_j^-$; $\tau \to p \mu \mu$



Meson decays: excellent testing grounds for lepton flavour dynamics - **cLFV** & **LNV**

- **K, D and B meson decays:** **abundant data [LHCb, BNL, KTeV, BaBar, Cleo, Belle, ...]**

$$\text{BR}(K_L \to \mu e) < 4.7 \times 10^{-12}; \quad \text{BR}(K^+ \to \pi^+ \mu^+ e^-) < 2.1 \times 10^{-11}$$

$$\text{BR}(D^0 \to \mu e) < 1.5 \times 10^{-8}; \quad \text{BR}(B \to \mu e) < 2.8 \times 10^{-9}, \; \ldots.$$

cLFV signatures at high energies: SM & NP decays

- **In-flight lepton conversion: $\ell_i \to \ell_j$** $\rightsquigarrow$ $\mu \to \tau$ conversion [few GeV, dense target]

  Possibly studied at high-intensity facilities: Muon or Linear colliders, COMET...

- **Z boson decays: $Z \to \ell_i \ell_j$** $\rightsquigarrow$ Zs abundantly produced at **LEP** and at the **LHC**
  - **Current bounds:** BR$(Z \to e\mu) < 7.5 \times 10^{-7}$ [ATLAS, 2014]

    BR$(Z \to \mu\tau) < 1.2 \times 10^{-5}$; BR$(Z \to e\tau) < 9.8 \times 10^{-6}$ [OPAL & DELPHI]

- **Higgs boson decays: $H \to \ell_i \ell_j$** $\rightsquigarrow$ "Higgs-factory" at LHC - study rare processes...
  - **Current data:** **BR$(H \to \mu\tau) \lesssim 0.0025$** [CMS]; **BR$(H \to e\tau) \lesssim 0.0061$** [CMS]

- **Production of "on-shell" NP states** $\Rightarrow$ **new interactions** induce **cLFV decays**

  Multiplicity, composition, E_{miss}, ...: properties of final state strongly model-dependent...

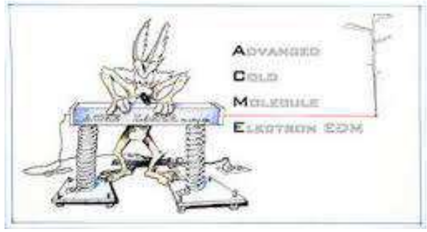
- **Future experimental prospects:** **Exciting ones from LHC Run 2 !!**

  Linear Collider / FCC-ee running at ZZ, HH, tt thresholds

cLFV “NP friends”: Leptonic dipole moments

- **Electric dipole moments of charged leptons** $\mathcal{L}_{\text{EDM}} = -i/2\, d_\ell\, \bar{\ell}\sigma^{\mu\nu}\gamma_5 \ell F_{\mu\nu}$

EDM (e cm)	Current bounds	Future sensitivity
$\mathbf{|d_e|}$	$\mathbf{8.7 \times 10^{-29}}$ [ACME]	$\mathbf{\mathcal{O}(10^{-30})}$ [ACME]
$|d_\mu|$	1.9×10^{-19} [Muon g-2]	$\mathcal{O}(10^{-21})$ [g-2/EDM Coll.]
$|\text{Re}(d_\tau)|$	4.5×10^{-17} [Belle]	–
$|\text{Im}(d_\tau)|$	2.5×10^{-17} [Belle]	–



- **(Anomalous) magnetic moments of charged leptons** $\vec{\mu} = g_\ell \frac{e}{2\,m_\ell}\vec{S} \Rightarrow a_\ell = \frac{1}{2}(g_\ell - 2)$

a_e : Best **determination of α...**

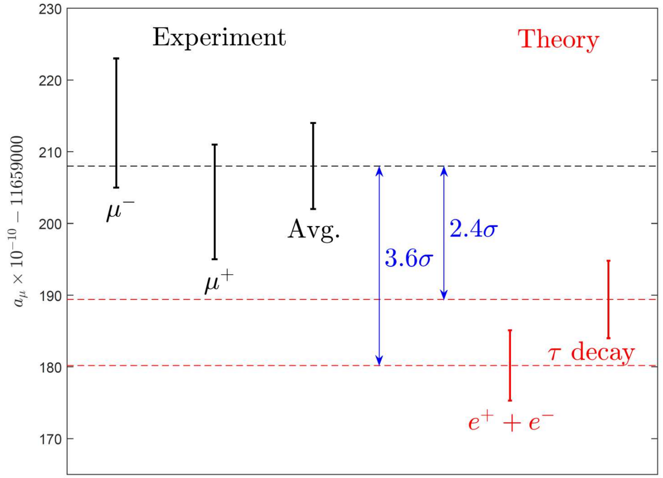
$a_e^{\text{the}} = 0.001159652181643(764) \rightsquigarrow 5^{\text{th}}$ order in QED (12,672 diags)!

$a_e^{\text{exp}} = 0.00115965218073(28)$

a_μ : Current **tension** between **theory and experiment** $\longrightarrow$

Very **sensitive probe of New Physics** close to Λ_{EW}

If δa_μ confirmed $\rightsquigarrow$ **discrepancies** for $a_{e,\tau}$ and d_ℓ!



a_τ : Short **tau lifetime...**

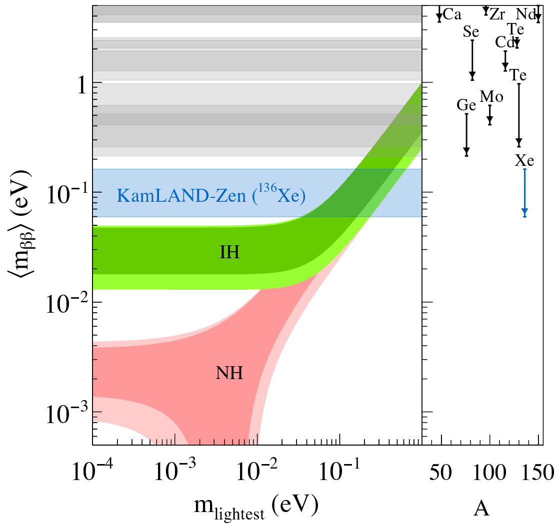
$a_\tau^{\text{the}} = 0.00117721(5)$ [0701260]

$-0.007 < a_\tau^{\text{exp}} < 0.005$ [1601.07987]

[0801.1134]

Further "friends": LNV ($\Delta L = 2$) observables and searches

▶ Neutrinoless double beta decays



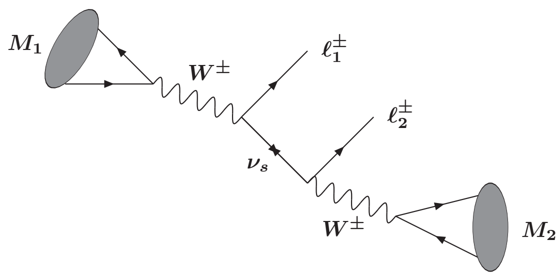
[KamLAND-Zen, '15]

Experiment	$\lvert m_{ee}\rvert$ (eV)
EXO-200 (4 yr)	0.075 - 0.2
nEXO (5 yr)	0.012 - 0.029
nEXO (5 yr + 5 yr w/ Ba tagging)	0.005 - 0.011
KamLAND-Zen (300 kg, 3 yr)	0.045 - 0.11
GERDA phase II	0.09 - 0.29
CUORE (5 yr)	0.051 - 0.133
SNO+	0.07 - 0.14
SuperNEMO	0.05 - 0.15
...	...

▶ LNV in semileptonic tau and/or meson decays

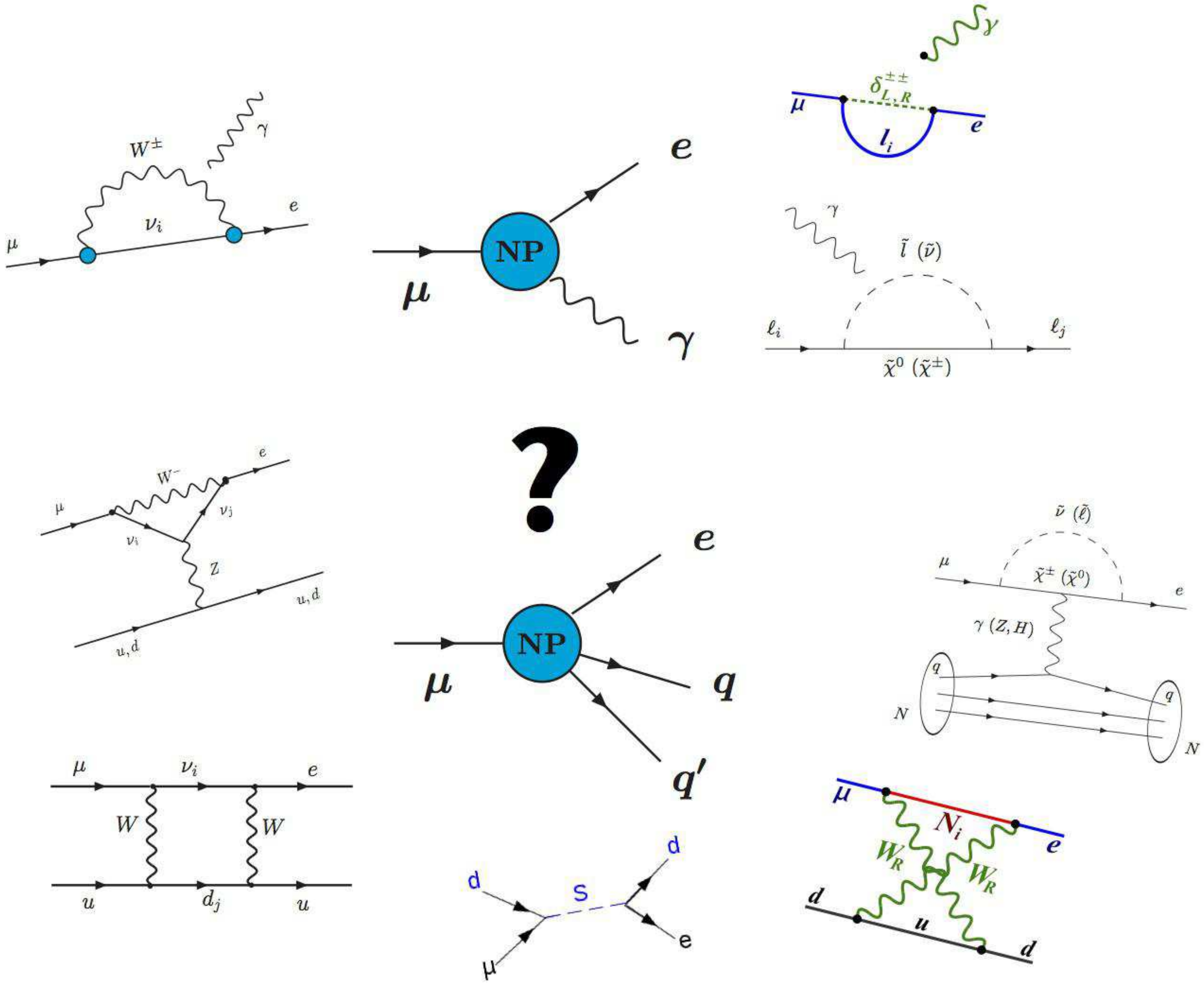
LNV decay	Current Bound	
	$\ell = e,\ \ell' = e$	$\ell = \mu,\ \ell' = \mu$
$K^- \to \ell^- \ell'^- \pi^+$	6.4×10^{-10}	1.1×10^{-9}
$D^- \to \ell^- \ell'^- \pi^+$	1.1×10^{-6}	2.2×10^{-8}
$D^- \to \ell^- \ell'^- K^+$	9.0×10^{-7}	1.0×10^{-5}
$B^- \to \ell^- \ell'^- \pi^+$	2.3×10^{-8}	4.0×10^{-9}
$B^- \to \ell^- \ell'^- K^+$	3.0×10^{-8}	4.1×10^{-8}
$B^- \to \ell^- \ell'^- \rho^+$	1.7×10^{-7}	4.2×10^{-7}
$B^- \to \ell^- \ell'^- D^+$	2.6×10^{-6}	6.9×10^{-7}

LNV decay	Current Bound	
	$\ell = e$	$\ell = \mu$
$\tau^- \to \ell^+ \pi^- \pi^-$	2.0×10^{-8}	3.9×10^{-8}
$\tau^- \to \ell^+ \pi^- K^-$	3.2×10^{-8}	4.8×10^{-8}
$\tau^- \to \ell^+ K^- K^-$	3.3×10^{-8}	4.7×10^{-8}



- **After the experiments: which New Physics model?**

Many models to one observable?



Interpreting data - how??

- Pheno approaches:
  - Effective approach (model-independent)
  - Model dependent (specific NP scenario)

- Different from quark FV!

  No SM "TH background"...

- **cLFV (and friends): effective approach**

The effective approach

- $\mathcal{L}^{\text{eff}}$ - **"vestigial" (new) interactions** of **"heavy" fields** with **SM** at **low-energies**

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

- Apply **experimental** bounds on **(leptonic) observables** to **constrain** $\frac{\mathcal{C}^6_{ij}}{\Lambda^2}$ **(cLFV)**

Hypotheses on:

1. **size** of **"new couplings"**

   ⇒ **Natural couplings**

   $\mathcal{C}^6_{ij} \sim \mathcal{O}(1)$

2. **scale** of **"new physics"**

   ⇒ **Natural scale** - delicate..

   direct discovery $\Lambda \sim$ TeV

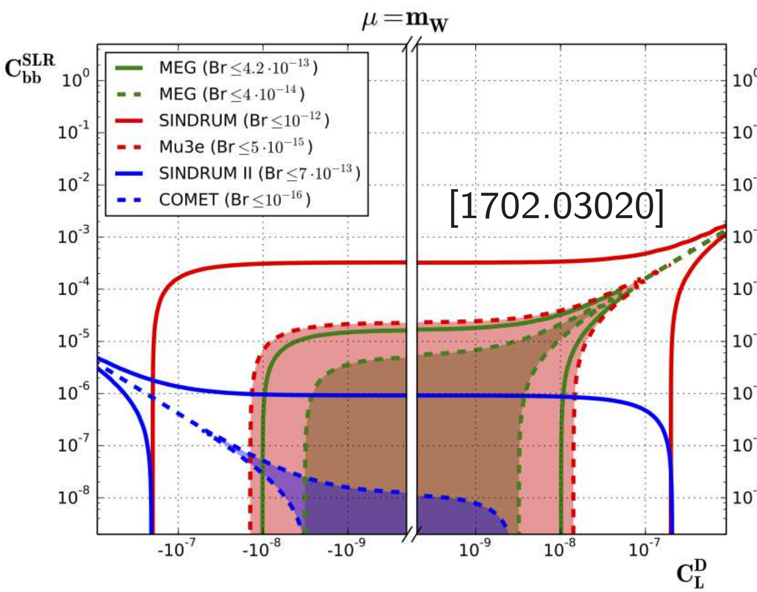
Effective coupling (example)	Bounds on Λ (TeV) (for $\lvert\mathcal{C}^6_{ij}\rvert = 1$)	Bounds on $\lvert\mathcal{C}^6_{ij}\rvert$ (for $\Lambda = 1$ TeV)	Observable
$\mathcal{C}^{\mu e}_{e\gamma}$	6.3×10^4	2.5×10^{-10}	$\mu \to e\gamma$
$\mathcal{C}^{\tau e}_{e\gamma}$	6.5×10^2	2.4×10^{-6}	$\tau \to e\gamma$
$\mathcal{C}^{\tau\mu}_{e\gamma}$	6.1×10^2	2.7×10^{-6}	$\tau \to \mu\gamma$
$\mathcal{C}^{\mu eee}_{\ell\ell,ee}$	207	2.3×10^{-5}	$\mu \to 3e$
$\mathcal{C}^{e\tau ee}_{\ell\ell,ee}$	10.4	9.2×10^{-5}	$\tau \to 3e$
$\mathcal{C}^{\mu\tau\mu\mu}_{\ell\ell,ee}$	11.3	7.8×10^{-5}	$\tau \to 3\mu$
$\mathcal{C}^{\mu e}_{(1,3)H\ell}$, $\mathcal{C}^{\mu e}_{He}$	160	4×10^{-5}	$\mu \to 3e$
$\mathcal{C}^{\tau e}_{(1,3)H\ell}$, $\mathcal{C}^{\tau e}_{He}$	≈ 8	1.5×10^{-2}	$\tau \to 3e$
$\mathcal{C}^{\tau\mu}_{(1,3)H\ell}$, $\mathcal{C}^{\tau\mu}_{He}$	≈ 9	$\approx 10^{-2}$	$\tau \to 3\mu$

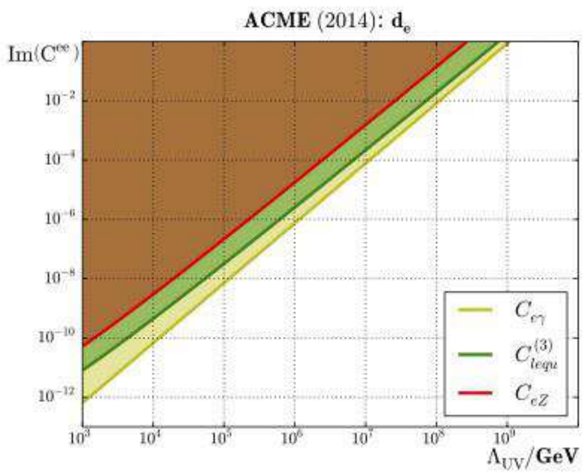
[Feruglio et al, 2015]

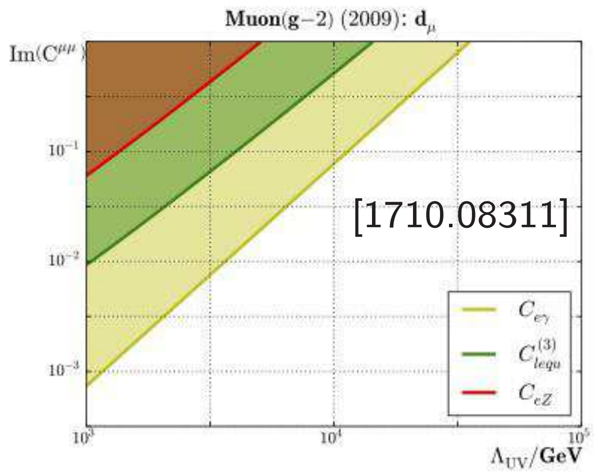
- **Despite its generality, caution in interpreting limits from effective approach!**

Experimental bounds and $\mathcal{L}^{\text{eff}}$

- **Despite its generality, caution in taking "naïve limits"!**
  - limits assume **dominance of one operator; NP leads to several (interference...)**
  - contributions from **higher order operators** may be non-negligible if $\mathbf{\Lambda}$ **is low...**
  - **multiple "new physics" scales:** $\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{1}{\Lambda_{\text{LNV}}}\, \mathcal{C}^5(m_\nu) + \frac{1}{\Lambda^2_{\text{LFV}}}\, \mathcal{C}^6(\ell_i \leftrightarrow \ell_j) + \ldots$
- **Full analyses!** threshold & RGE effects; correlations, higher-order contributions...
- Recent reviews of effective approach of $\mu - e$ transitions (RGE improved) [Crivellin et al, '16-'17]







$$\Gamma(\mu - e, N) = \frac{m_\mu^5}{4\Lambda^4} \Big| e C_L^D D_N + $$

$$+4 \left\{ G_F m_\mu m_p S_N^{(p)} \left(\sum_q \frac{C_{qq}^{S\,LL} + C_{qq}^{S\,LR}}{m_\mu m_q G_F} f_{S\,p}^{(q)} + \tilde{C}_{gg}^L f_{G\,p} \right) + V_N^{(p)} \left(\sum_q (C_{qq}^{V\,RL} + C_{qq}^{V\,RR}) f_{V\,p}^{(q)} \right) + p \to n \right\} \Big|^2$$

- **Accounting for neutrino masses and mixings:**

  SM extensions ...

  ... and high-intensity observables

Theoretical frameworks

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

  "ad-hoc" construction (no specific assumption on mechanism of mass generation)

  encodes the effects of N additional sterile states (well-motivated NP candidates)

  in a **single one** **[... Not to be confused with oscillation anomaly solution!...]**

- **Complete SM extensions (accounting for ν masses and mixings)**

  - **Standard seesaws** [type I, type II, type III] & **variants**

    Low-scale, νMSM, Inverse Seesaw (ISS), ...

  - **Additional states: Multi-Higgs doublet models,**

    leptoquarks, Z', vector-like, ...

  - **Extended frameworks: extra dimensions, ...**

    SUSY seesaw,

    Left-Right models, GUTs, ...

- **High-intensity probes to distinguish between them!**

- **Minimal toy-model: SM + ν_s**

Assuming that New Physics is encoded into such a simple model, what can we expect and learn?

"Toy model" for phenomenological analyses: SM + ν_s

- **Assumptions:** 3 active neutrinos + 1 sterile state $\quad n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s^c)^T$

  interaction basis $\leftrightsquigarrow$ physical basis $\quad n_L = U_{4\times 4}\, \nu_i$

  $U^T_{4\times 4}\, M\, U_{4\times 4} = \text{diag}(m_{\nu_1}, ..., m_{\nu_4})$ $\quad$ "**Majorana** mass": $\mathcal{L}_{\text{toy}} \sim n_L^T C M n_L$

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

  rectangular matrix $\leftarrow \mathbf{U} = U|_{3\times 4}$

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

  3×3 sub-block, non-unitary!

$$U_{4\times 4} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- **Physical parameters:** **4 masses** [**3 light (mostly active)** + **1 heavier (mostly sterile)** states]

  6 mixing angles [θ_{12}, θ_{23}, θ_{13}, & θ_{i4}] and **6 phases** [(3 Dirac and 3 Majorana)]

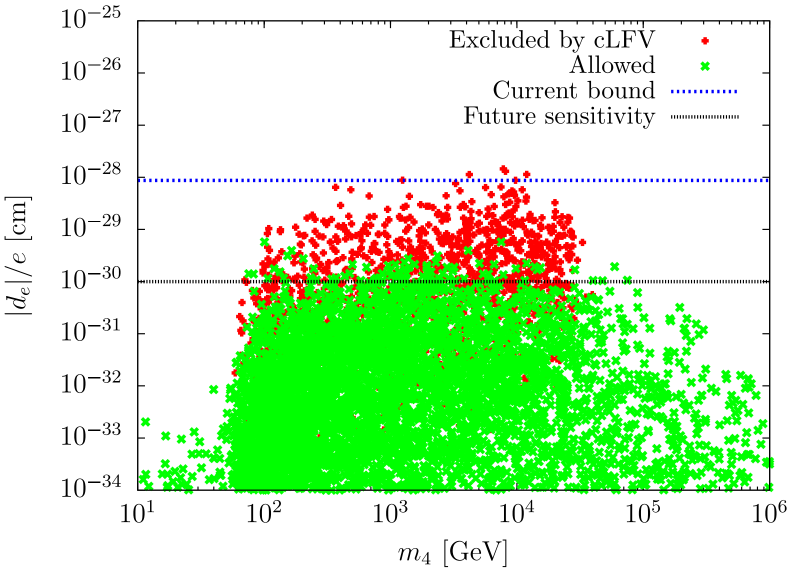
- **Modified charged ($W^\pm$) and neutral (Z^0) current interactions:**

$$\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+n_S} \mathbf{U}_{\alpha i}\, \bar{\ell}_\alpha\, \gamma^\mu\, P_L\, \nu_i$$

$$\mathcal{L}_{Z^0} \sim -\frac{g_w}{2\cos\theta_w} Z_\mu \sum_{i,j=1}^{3+n_S} \bar{\nu}_i\, \gamma^\mu \left[P_L\, (\mathbf{U}^\dagger \mathbf{U})_{ij} - P_R\, (\mathbf{U}^\dagger \mathbf{U})^*_{ij} \right] \nu_j$$

Sterile neutrinos: impact for lepton properties

▶ **Leptonic CP violation: electric dipole moments**



▶ Majorana (and Dirac) phases ⇒ **lepton EDMs**

▶ **Non-vanishing** contributions: at least **two sterile ν**

▶ $|d_e|/e \geq 10^{-30}$ **cm** for $m_{\nu_{4,5}} \sim$ [100 GeV, 100 TeV]

[Abada and Toma, '15]

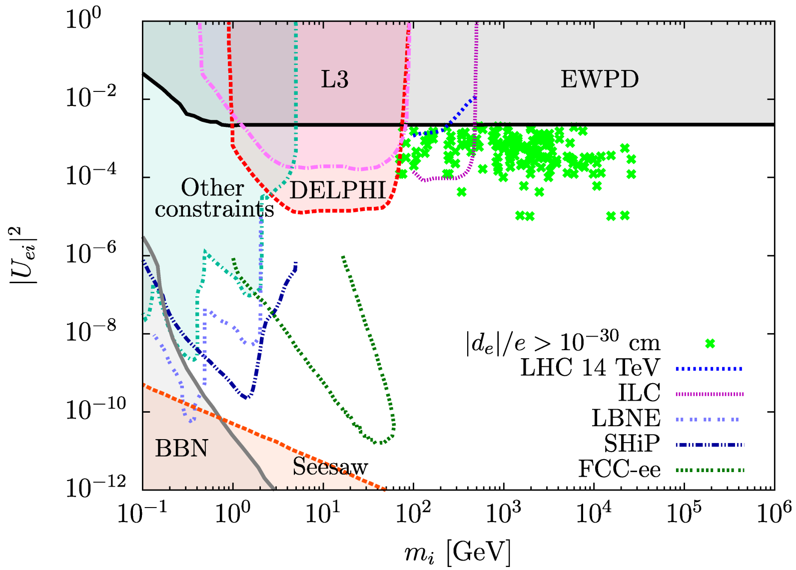
▶ **Independent of active-sterile mixings**

Majorana contribution is dominant!

▶ **EDM observation:** suggest new sources of CPV

⇒ **Majorana νs? ⇝ Leptogenesis??**

▶ Sterile states beyond (direct) collider reach...



Sterile neutrinos: impact for LNV observables

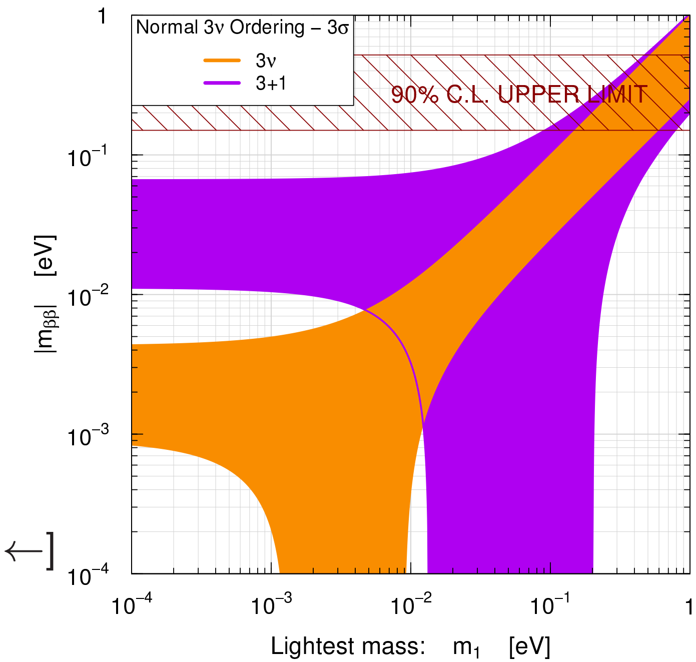
- **Lepton number violation: $0\nu2\beta$ decays**
  - ν_s can strongly impact **predictions for $|m_{ee}|$**

    $\Rightarrow$ **augmented ranges** for effective mass *(IO and NO)*

  - **Observation of $0\nu2\beta$ signal** in future experiments

    does not imply Inverted Ordering for light νs

[Abada, De Romeri and AMT, '14; ...; Giunti et al, '15 ←]

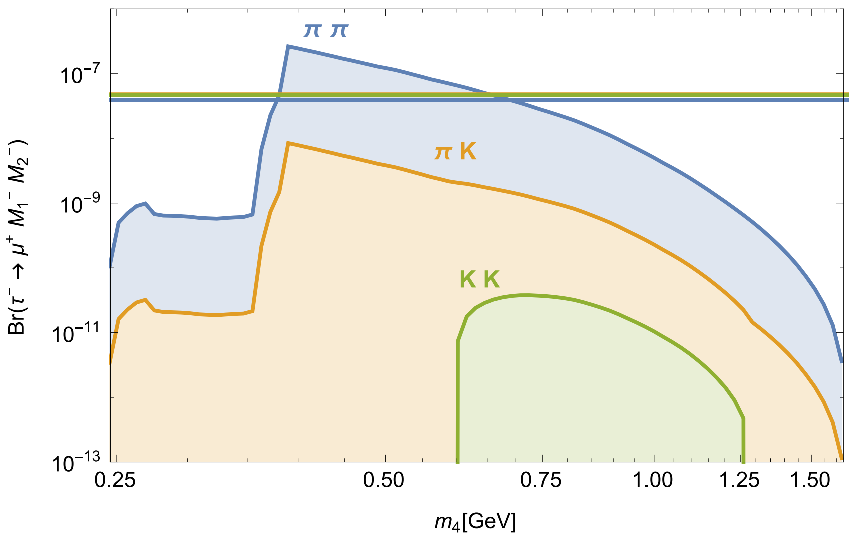


- **Lepton Number Violation in meson and τ decays**
  - **If ν_s produced on-shell,**

    resonant enhancement of **LNV decays**

    $M_1^- \to M_2^+ \ell^- \ell^-$ and $\tau^- \to \ell^+ M_1^- M_2^-$

[Abada, De Romeri, Lucente, Toma, AMT, '17]

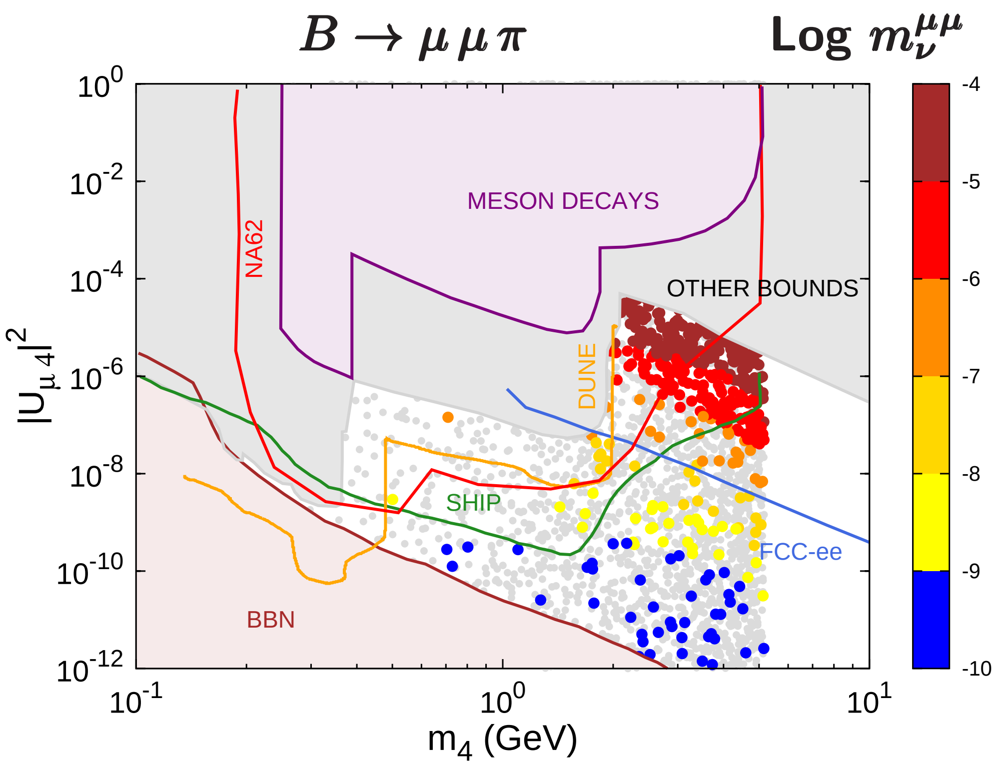


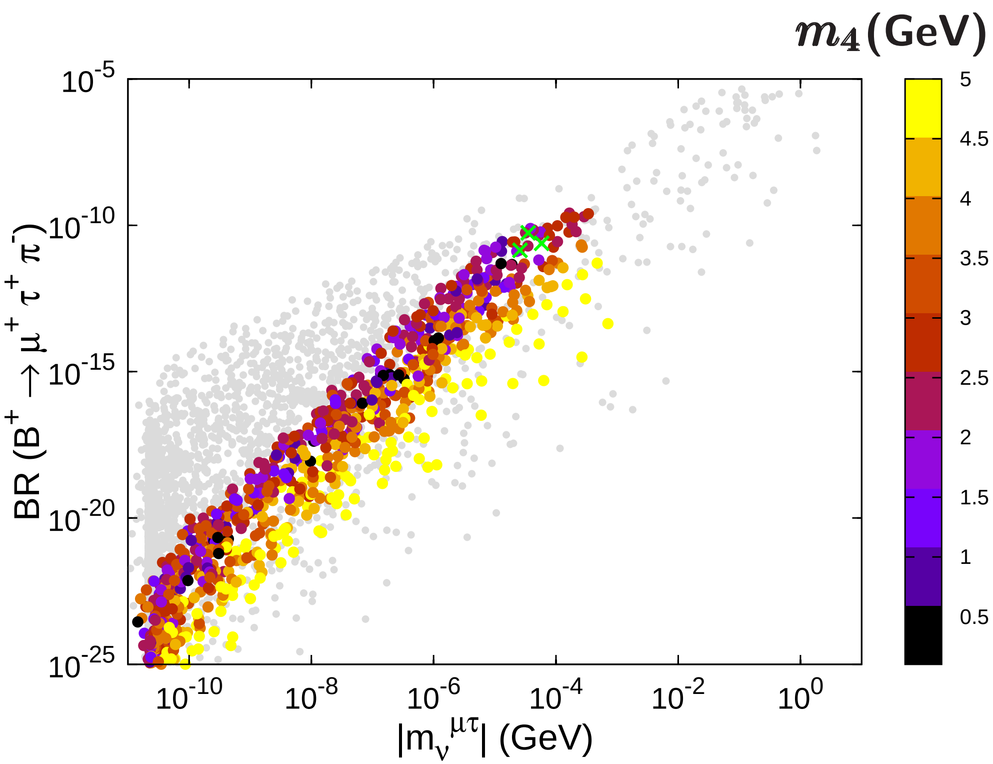
Sterile neutrinos: impact for LNV meson and tau decays

▶ In addition to **further constraining** the **active-sterile mixings** **[future sensitivities...]**

LNV meson and tau decays offer possibility to **infer information** on $m_\nu^{\ell_i \ell_j}$

$$m_\nu^{\ell_\alpha \ell_\beta} \equiv \left| \sum_{i=1}^{4} \frac{U_{\alpha i}\, m_i\, U_{\beta i}}{1 - m_i^2/p_{12}^2 + i\, m_i \Gamma_i / p_{12}^2} \right|$$

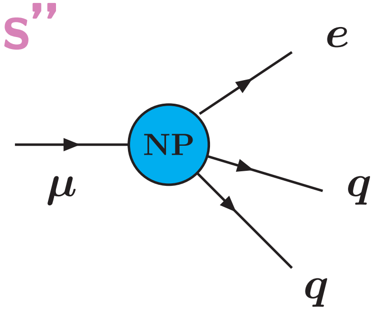




[Abada, De Romeri, Lucente, Toma, AMT, 1712.03984]

Sterile neutrinos: cLFV in "muonic atoms"

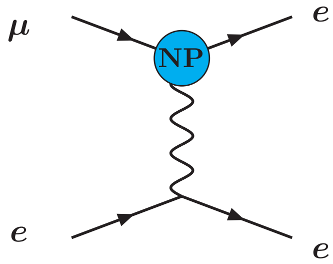
- **cLFV $\mu^- - e^-$ conversion:** $\mu^- + (A, Z) \to e^- + (A, Z)$



- **Muonic atom decay:** $\mu^- e^- \to e^- e^-$ [Koike et al, '10]

  Coulomb interaction increases overlap between Ψ_{μ^-} and Ψ_{e^-}

  Rate strongly enhanced in **large Z atoms** [Uesaka et al, '15-'16]



- **cLFV in muonic atoms from ν_s:**

  $\mu^- e^- \to e^- e^-$ (■) vs

  $\mu - e$ **conversion** (■) in Aluminium

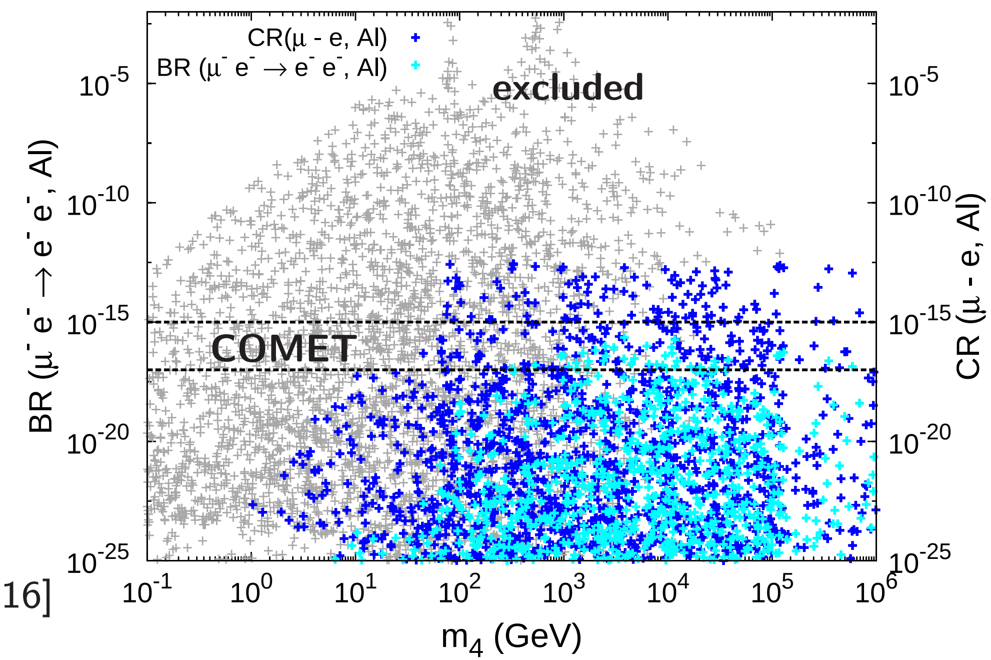
- For **Aluminium**, **CR($\mu - e$)** has

  stronger experimental potential

  .. consider **"heavy" targets** to probe

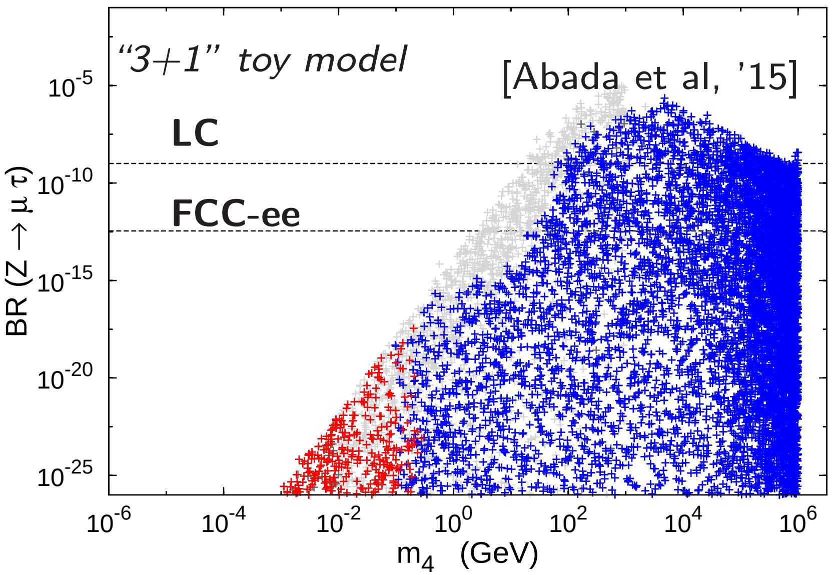
  BR($\mu^- e^- \to e^- e^-$)

"3+1" toy model [Abada, De Romeri and AMT, '16]

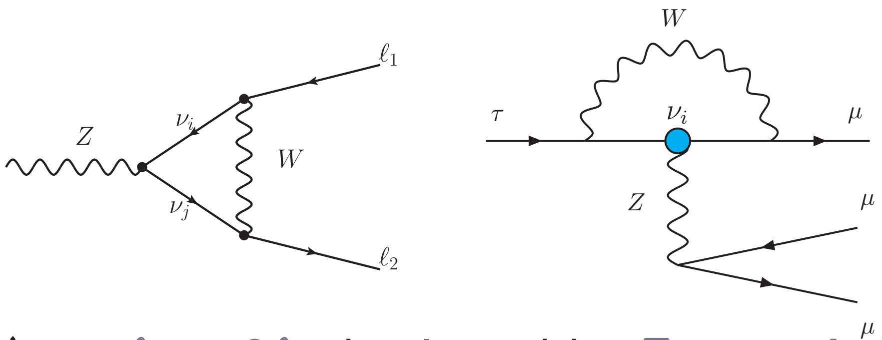


Sterile neutrinos and cLFV at higher energies

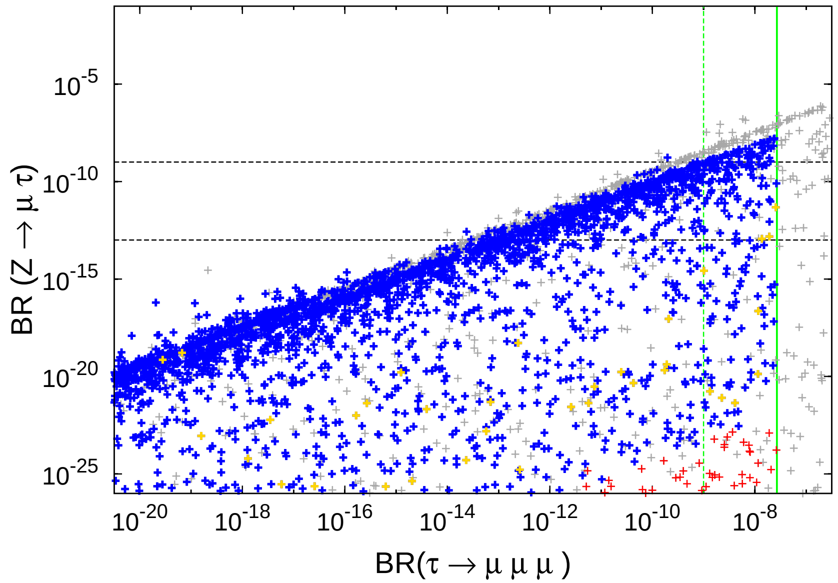
▶ **cLFV Z decays at FCC-ee vs 3 body decays $\ell_i \to 3\ell_j$**



▶ Potentially **observable** at **Future Circular Collider**



▶ $m_4 \gtrsim \Lambda_{\text{EW}}$: $\ell_i \to 3\ell_j$ dominated by **Z penguins**



▶ Strong correlation between $Z \to \mu\tau$ and $\tau \to 3\,\mu$

▶ **Probe $\mu - \tau$ cLFV** beyond **Belle II reach**

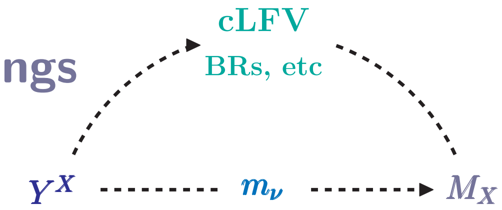
▶ **Complementarity probes** of **ν_s cLFV**

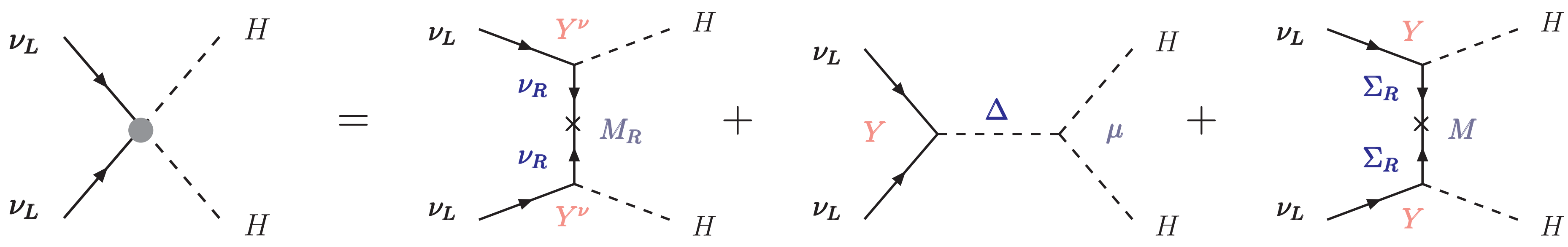
at **low- and high energies!**

- **Models of neutrino mass generation**

The seesaw mechanism

★ **Seesaw mechanism:** explain **small ν masses** with **"natural" couplings** via **new dynamics** at **"heavy" scale**





$\frac{1}{\Lambda} L\, L\, H\, H$ — "Seesaw mechanism"

ν_R (fermion singlet) — **Type I**

Δ (scalar triplet) — **Type II**

Σ_R (fermion triplet) — **Type III**

- **Observables:** depend on **powers of Y^ν** $\rightsquigarrow$ large rates $\Rightarrow$ sizable Y^ν and on the **mass of** the (virtual) **NP propagators**

- **Fermionic seesaws:** $Y^\nu \sim \mathcal{O}(1) \Rightarrow M_{\text{new}} \approx 10^{13-15}$ **GeV!**

  Suppression of rates due to the **large mass of the mediators!**

- **Low scale seesaws:** **rich phenomenology at high-intensities!** (and also at LHC)

Low scale: Inverse Seesaw (ISS)

$\rightsquigarrow$ **SM + Right-handed neutrinos + Extra steriles**

$$\mathcal{L}_{\text{ISS}} = -Y^\nu \overline{\nu_R} \tilde{H} L - M_R \overline{\nu_R} X - \frac{1}{2}\mu_X \bar{X}^c X + \frac{1}{2}\mu_R \overline{\nu_R} \nu_R^c$$

- Addition of **3 "heavy" RH** neutrinos and **3 extra "sterile" fermions X** to SM $\rightsquigarrow$ ISS$_{(3,3)}$
- **Spectrum and mixings:** **9 physical states**

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

Theoretically appealing: "naturally" small LNV parameter $\mu_X \sim \mathcal{O}(0.01\text{ eV} - \text{ MeV})$

$\Rightarrow$ accommodate m_ν^{light} with **sizeable Y^ν** for comparatively **low M_R !**

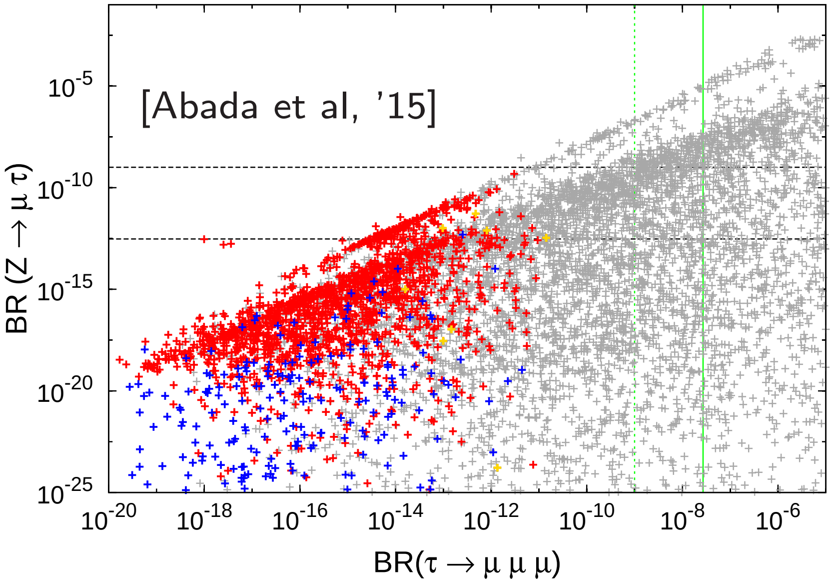
- **Non-unitarity $\tilde{U}_{\text{PMNS}} \Rightarrow$ modified neutral and charged leptonic currents**
- **New (virtual) states & modified couplings:** many new "observable" phenomena

cLFV, non-universality, signals at colliders!

and (warm) DM candidates, contributions to BAU, states within (direct) collider reach...

Low scale: Inverse Seesaw (ISS)

- **cLFV Z decays at FCC-ee vs 3 body decays $\ell_i \to 3\ell_j$**



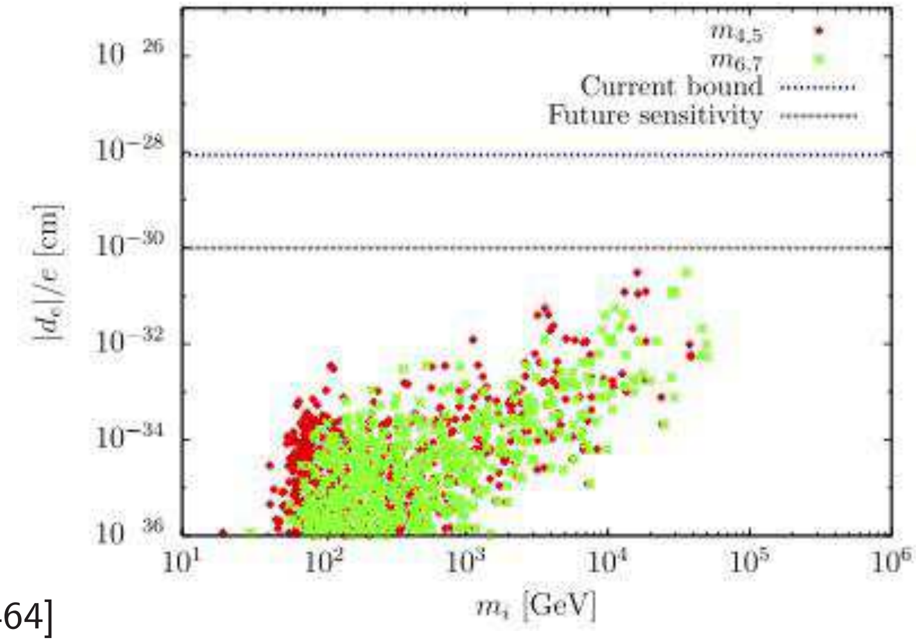
- Still dominated by Z **penguin** contributions
- Other **cLFV bounds** **preclude large BR($\tau \to 3\mu$)...**

  Contrary to "3+1 toy model", **flavour textures**

  & **parameters** constrained by ν **data...**
- Allows to **probe $\mu - \tau$ cLFV** beyond **Belle II reach**

- **Leptonic CP violation: EDMs**
  - **ISS contains additional sources of CPV!**
  - **Majorana contributions nearly negligible**

    heavy steriles form pseudo-Dirac pairs
  - **Electron EDM** beyond **future sensitivity...**



[Abada and Toma, 1611.03464]

The "triplet" seesaws

★ **Weinberg operator** realised via **triplet scalars Δ** (type II) or **fermions Σ (type III)**

- Very **distinctive signatures** for numerous **observables:** **cLFV example**

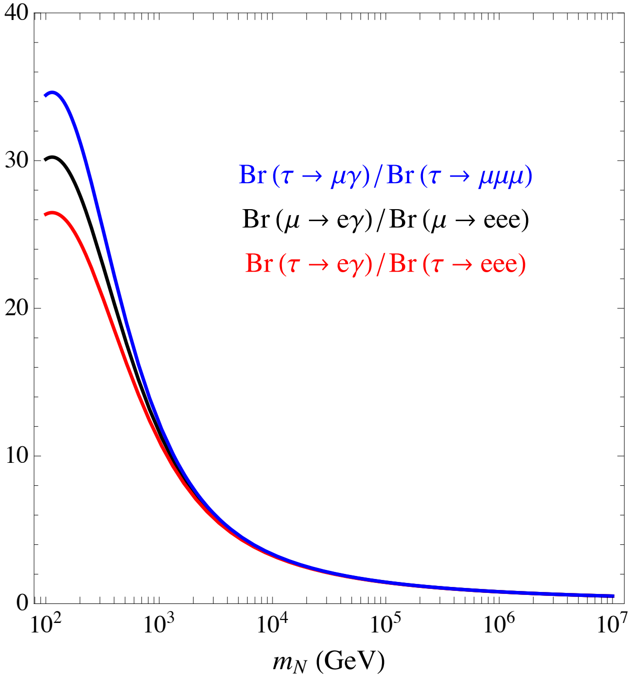
  Type I: cLFV transitions at **loop level** (radiative, 3-body, conversion in Nuclei)

  Type II: $\ell_i \to \ell_j \gamma$ & $\mu - e$, N at loop level; 3-body decays $\boldsymbol{\ell_i \to 3\ell_j}$ at **tree level!**

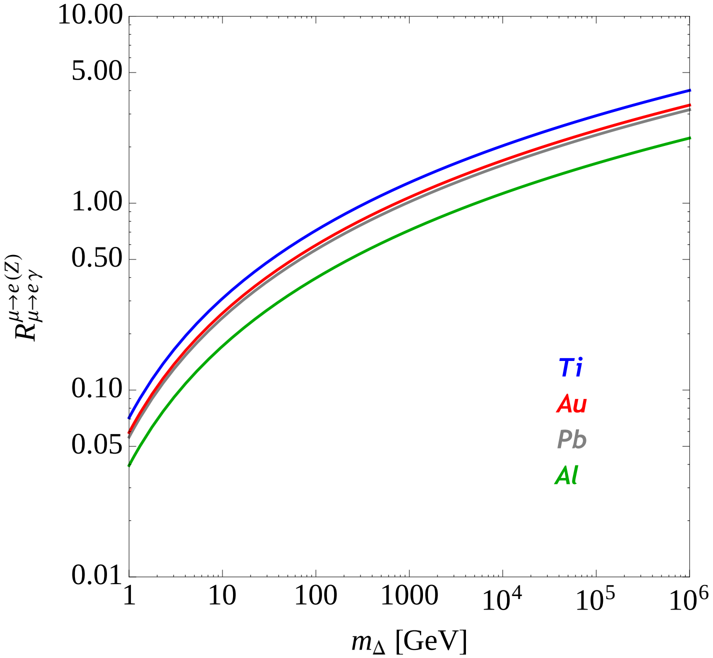
  Type III: 3-body decays and coherent conversion at tree-level! $\ell_i \to \ell_j \gamma$ @ loop...

- Use **ratios of observables to constrain and identify mediators!**

Type I



Type II



Type III

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

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

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

[Hambye, 2013]

- **Embedding the seesaw in larger frameworks**

Hints of an organising principle: SUSY seesaw and GUTs

★ Supersymmetric Grand Unified Theories

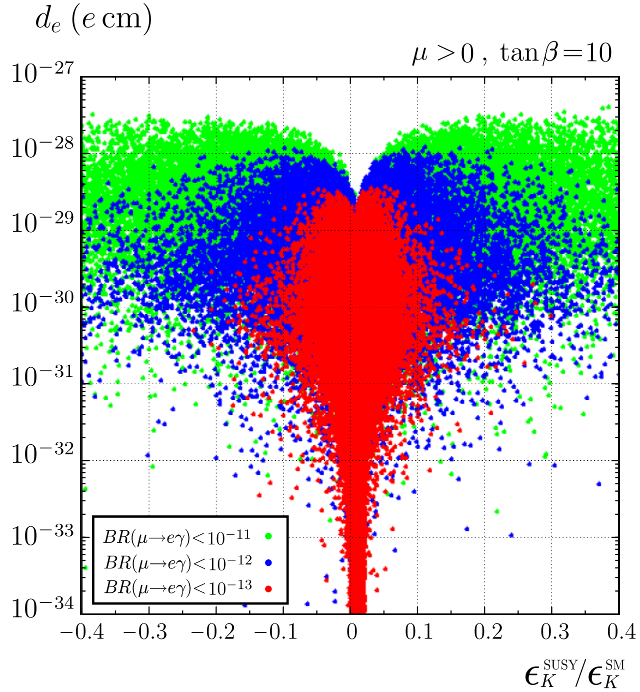
- **Reduce arbitrariness of Y^q, Y^ℓ, Y^ν, ...:** $\Rightarrow$ increase predictivity and testability!

- **SU(5) + RH neutrinos SUSY GUTs**

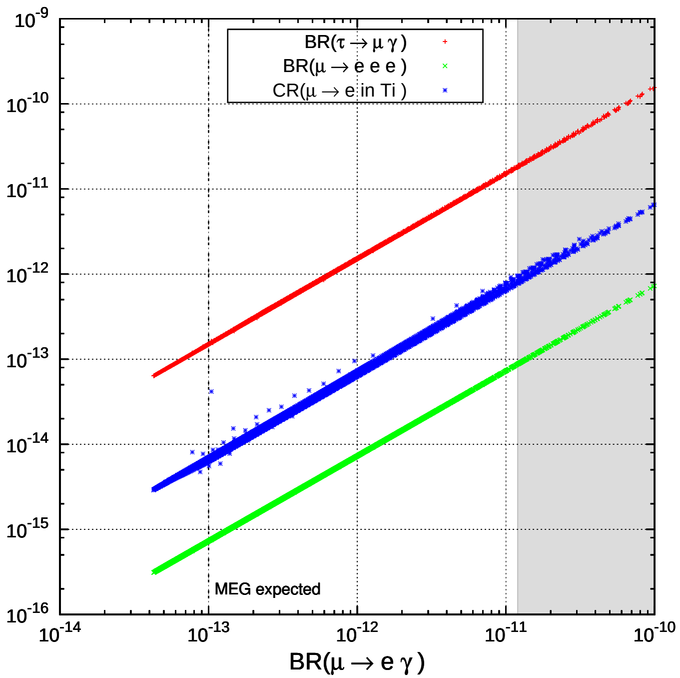
  Correlated CP violation and flavour observables

  in lepton and hadron sectors

  [Buras et al, 1011.4853]



- **SO(10) type II SUSY seesaw**



Leptogenesis motivated

highly correlated cLFV observables!

[Calibbi et al, 0910.0337]

- **Further possibilities**

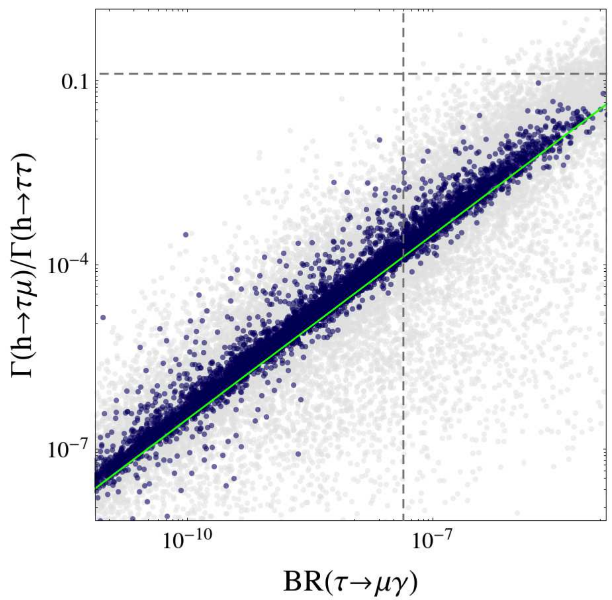
Vector-like leptons: an example

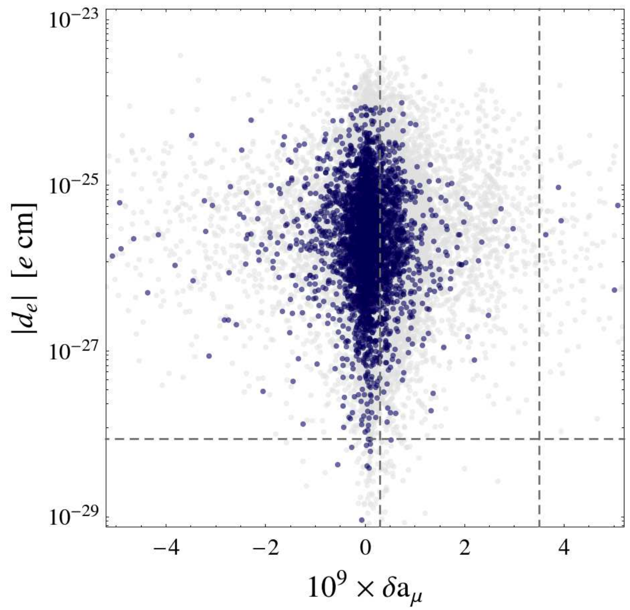
- **Massive vector-like fermions** present in **well-motivated SM extensions:**
  composite Higgs models, warped extra dimensions, ...

- **Global view:** generic set-up (composite Higgs inspired), 3 generations of L_i^V **and** E_i^V
  massive neutrinos from additional ν_R and vector-like partners

- **cLFV** parametrised by **small set of couplings**
  $\Rightarrow$ **correlated observables!**

$$\frac{\text{BR}(h \to \ell_i \ell_j)}{\text{BR}(\ell_i \to \ell_j \gamma)} \approx \frac{4\pi}{3\alpha} \frac{\text{BR}(h \to \ell_i \ell_i)|_{\text{SM}}}{\text{BR}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)}$$





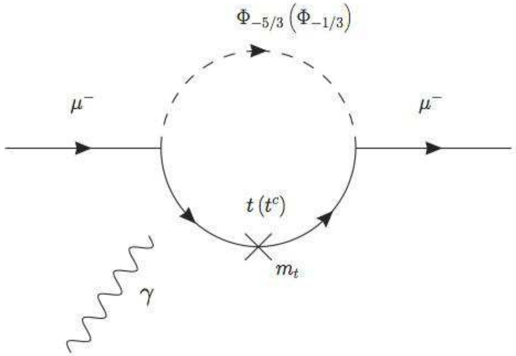
[Falkowski et al, '14]

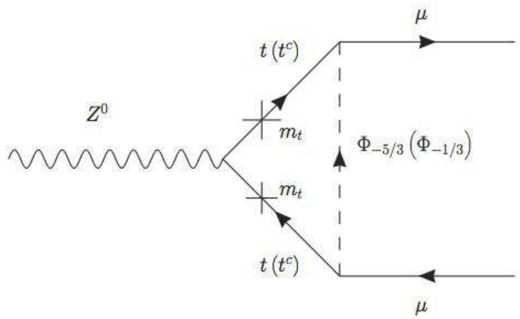
- **Synergy** between **FV Higgs decays and cLFV!** Flavour conserving **EDM and δa_μ as well!**

Leptoquarks - what about high-intensities?

- **Leptoquarks** well motivated, natural solution to several experimental **"few-σ'itis"**
  a_μ, R_K, R_D, anomalies in $b \to s\,\mu^+\,\mu^-$, ...

- **LQ and a_μ: chiral enhancements!** $\Rightarrow$ **correlated** effects in a_μ, $\ell_i \to \ell_j \gamma$, $Z \to \ell_i \ell_j \ldots$





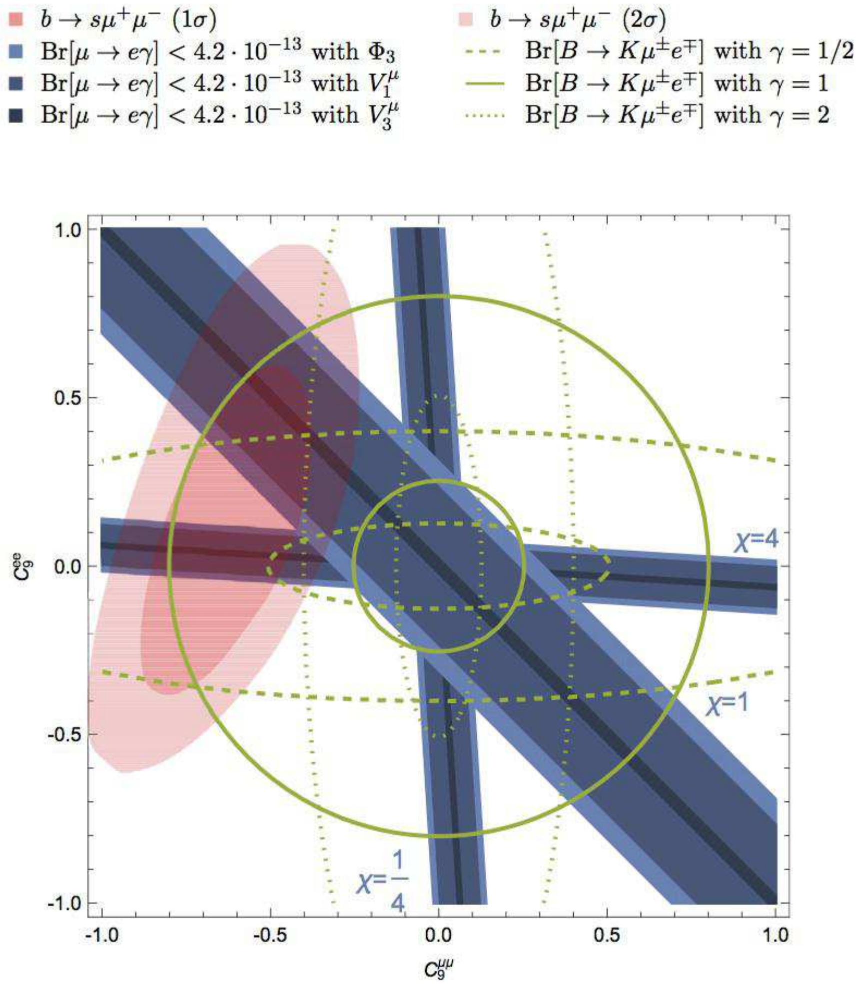
- If LQ account for a_μ $\Rightarrow$ **MEG bounds preclude effect** in $b \to s\,e^+\,e^-$ [Leskow et al, '16]
  ⇝ tiny LQ-electron couplings... still **sizeable LQ-τ (μ) couplings**
  FCC-ee should see deviations in $Z \to \mu\mu$; $Z \to \tau\mu$ possibly within future sensitivity

  Reconcile a_μ with B-anomalies: Pati-Salam inspired model (LQ & vector-like leptons)

- **cLFV** to **distinguish different LQ scenarios:** [Davidson et al, '17]
  Ratio of **spin-independent/spin-dependent** contributions to **$\mu - e$ conversion**
  Spin-independent contributions for **different targets** (other than Aluminium)

Leptoquarks - what about cLFV?

- **Correlation of R_K, R_D, and $b \to s\,\mu^+\,\mu^-$** to **cLFV $\mu \to e\gamma$ and $b \to s\,\mu^+\,e^-$**



[Crivellin et al, '17]

(No chiral enhancement; LQ couple only to Ψ_L...)

$$\mathrm{Br}[\mu \to e\gamma] = \tau_\mu \frac{\alpha^3 G_F^2 m_\mu^5}{512\pi^6} |V_{tb}V_{ts}^*|^2 N_c^2 \left(\chi C_9^{ee} + \frac{C_9^{\mu\mu}}{\chi}\right)^2 \begin{cases} 1/16 & \Phi_3 \\ 1/9 & V_1^\mu \\ 16 & V_3^\mu \end{cases}$$

$$\mathrm{Br}[B \to K\mu^\pm e^\mp] = 10^{-9}\,(a_K + b_K) \left[\left(\frac{C_9^{ee}}{\gamma}\right)^2 + (\gamma\, C_9^{\mu\mu})^2 \right]$$

- Three **LQ representations:** $\boldsymbol{\Phi_3}$, $\boldsymbol{V_1^\mu}$ and $\boldsymbol{V_3^\mu}$
- **Similar** impact of **constraints** from

  $b \to s\,\ell^+\,\ell^-$, $\mu \to e\gamma$ and $b \to s\,\mu^+\,e^-$
- **If anomalies persist**, **LQ hypothesis** suggests

  near-future **discovery** of $B_s \to \mu e$ and $\mu \to e\gamma$

Models of New Physics and cLFV: some examples

- **Generic cLFV extensions of the SM - supersymmetric (SUSY) extensions of the SM**

  cLFV observables at low- and high-energies (interplay) to constrain $\mathcal{L}_{\text{soft}}^{\text{SUSY}}$

  correlation of cLFV observables $\Rightarrow$ hint on the nature (dipole vs scalar) of NP operator

- **"Geometric" cLFV - extra dimensional Randall-Sundrum models**

  $e-\mu$ bounds constrain NP scale beyond LHC reach: $T_{\text{KK}} \gtrsim 4$ TeV ($\rightsquigarrow$ KK$^{(1\text{st})} \gtrsim 10$ TeV)

  future sensitivities: exclude (general) anarchic RS models up to 8 TeV ($\rightsquigarrow m_{\text{KK-g}} \gtrsim 20$ TeV)

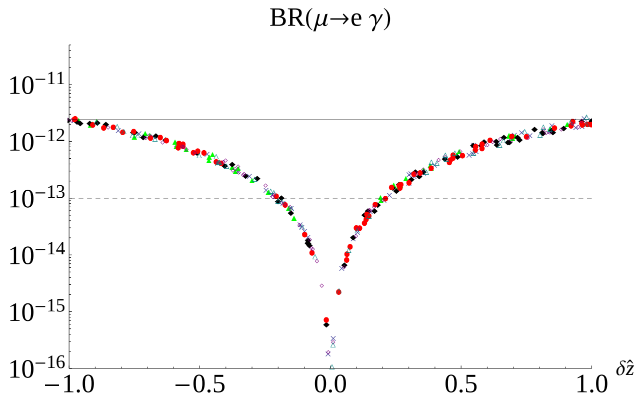
- **cLFV and compositness - Little(st) Higgs**

  distinctive patterns for ratios of observables (testability!)

  - Holographic composite Higgs

  $\text{BR}(\mu \to e\gamma)$ - constrain the size of boundary kinetic terms

  $\Rightarrow$ relevant information on fundamental parameters from cLFV!



[Hagedorn and Serone, '11-'12]

- **Concluding remarks**

Neutrino physics and high-intensity observables

- **Neutrinos** remain a very **open question** in **particle physics, astrophysics and cosmology**
- **Dedicated facilities** will **provide crucial data ... but many questions (likely) remain!**

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

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

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

- **Very brief overview** of a **subset of observables**

  [other observables: muonium, LFUV, in-flight conversion...]

  and **and prospects of a sub-sub set of New Physics models**

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

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

  High-intensity data can provide **information on the underlying NP model**

cLFV & friends: hunting for New Physics

- Explore the underlying synergy between high-energy and high-intensity observables to constrain the New Physics model at the origin of lepton phenomena

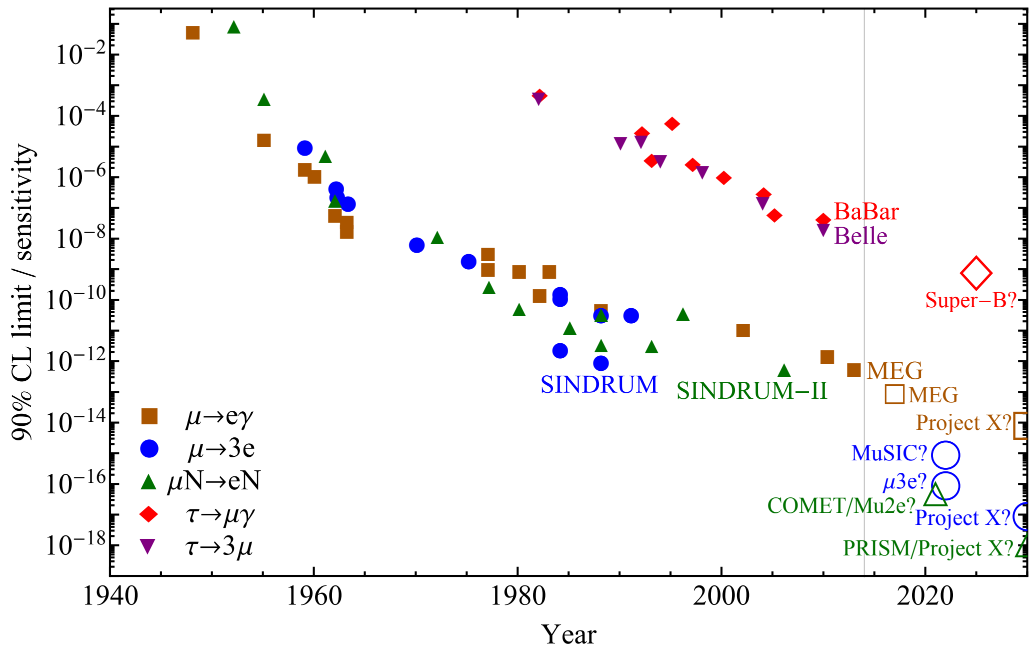
- And keep an open eye for other indirect searches and new oscillation phenomena !

Charged lepton flavour violation: outlook

▶ **Lepton sector** of **BSM remains comparatively unexplored...**

Numerous observables are being addressed: massive **experimental effort**

closely followed by **theoretical studies and phenomenological analyses**



⇒ **Unveil the underlying mechanism of flavour violation in the lepton sector!**

Backup

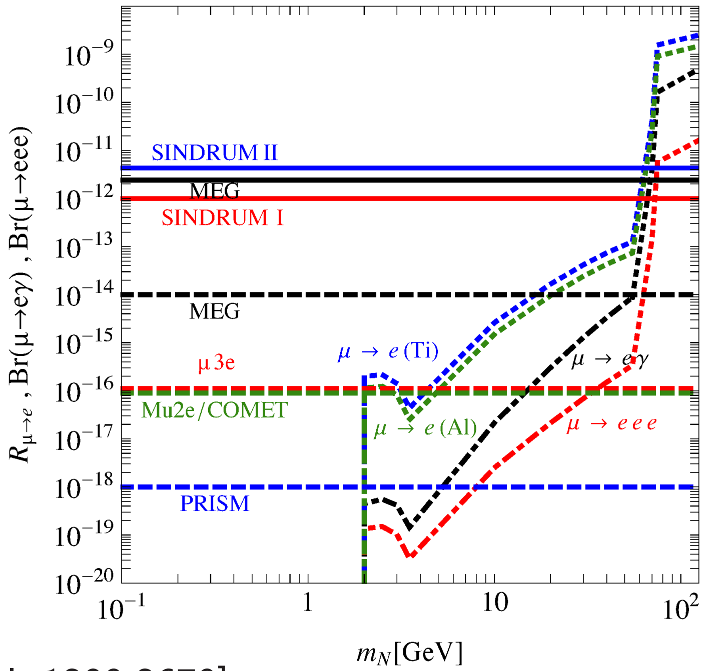
Low scale type I seesaw

- Addition of **3 "heavy" Majorana RH** neutrinos to SM; **MeV $\lesssim m_{N_i} \lesssim 10^{\text{few}}$TeV**
- **Spectrum and mixings:** $m_\nu \approx -v^2 Y_\nu^T M_N^{-1} Y_\nu$ $\quad U^T \mathcal{M}_\nu^{6\times6} U = \text{diag}(m_i)$

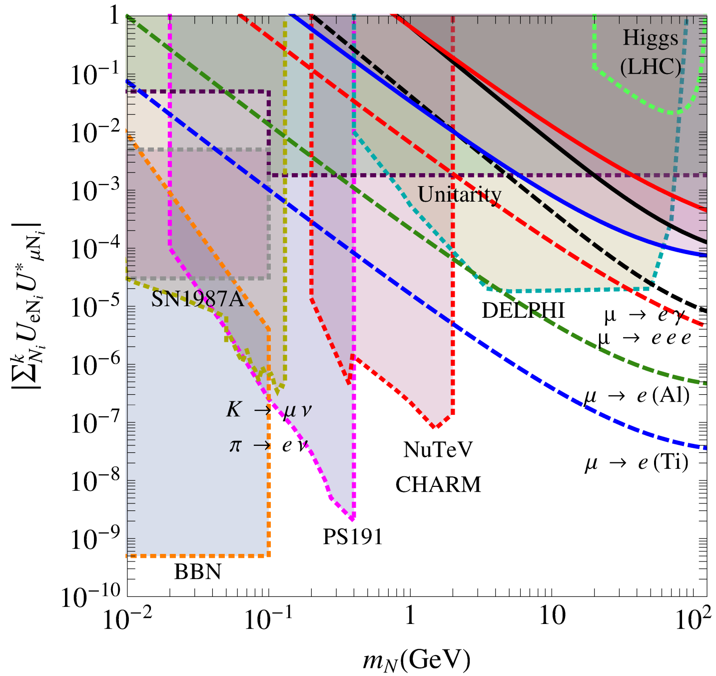
$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \qquad U_{\nu\nu} \approx (1-\varepsilon)\, U_{\text{PMNS}}$$

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

- **Heavy states do not decouple** $\Rightarrow$ **modified neutral and charged leptonic currents**
- Rich phenomenology at **high-intensity/low-energy** and at colliders!



[Alonso et al, 1209.2679]



(see also Dinh et al, '12-'14)

Hints of a geometric principle: RS warped extra dimensions

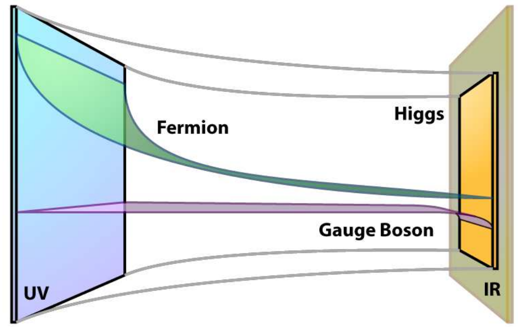
★ Embed **4dim space-time** into **5dim AdS space** (extra dim compactified on orbifold)

- **Two branes** (UV, IR) and **bulk** between; $M_{\text{TeV}} \simeq M_{\text{Planck}} e^{-\pi k L_5}$
- Localise fields: **Higgs** close to **IR brane**

  SM fermions and gauge bosons on **bulk**

  KK excitations of **SM fields** close to **IR brane**

  interactions ⇝ **overlap of wave functions**



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

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

- **Circumvent pheno issues:** enlarge **bulk symmetry** (prevent violation of custodial SU(2));

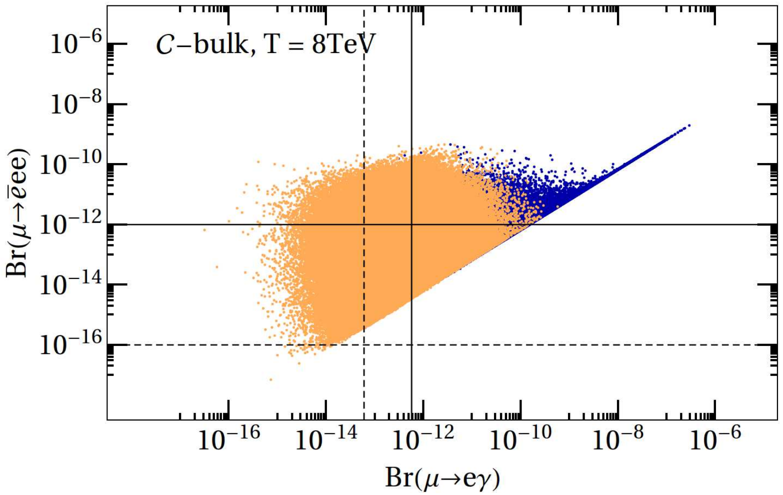
  additional **"rescue" ingredients** to **avoid excessive FCNCs,**

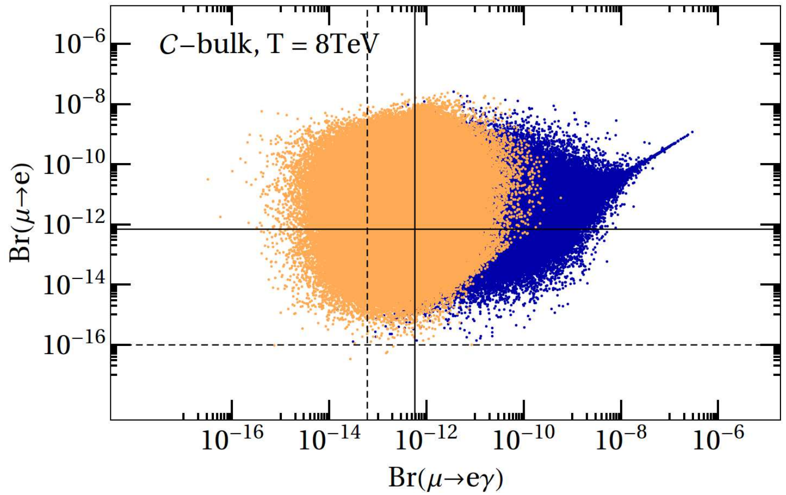
  protect **EW precision observables,** ...

[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]

Geometric cLFV: RS warped extra dimensions

- **Custodially protected model**; full inclusion of **all dim-6 operators**
- **Generic anarchic Yukawa couplings**
- cLFV processes mediated by **KK-lepton excitations, new gauge fields**





[Beneke et al, 1508.01705]

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

  τ **decays** comparatively less restrictive

- **Current** $\mu - e$ **bounds constrain NP scale beyond LHC reach:** $T_{\mathbf{KK}} \gtrsim 4$ **TeV**

  ($\rightsquigarrow$ 10 TeV for 1st KK-excitations)

- **Future cLFV sensitivities: exclude anarchic RS models** (without extra symmetries)

  up to **8 TeV** (KK gluon masses around 20 TeV)

Constraints on sterile fermions: masses and $\theta_{\alpha s}$

- **Neutrino oscillation parameters:** $\tilde{U}_{\text{PMNS}}$ comply with observed mixings

- **Electroweak precision tests:** invisible Z width; leptonic Z width; Weinberg angle...
  [Del Aguila et al, '08; Atre et al, '09; ...
  Antusch et al, '09-'14; Fernandez-Martinez et al, '16; ...]

- **Searches at the LHC:** invisible Higgs decays $H \to \nu_L \nu_R$; direct searches, ...
  [Dev et al, '12-'15; Bandyopadhyay et al, '12; Cely et al, '14;
  Arganda et al, '14-'15; Deppish et al, '15; ...]

- **Peak searches in meson decays:** monochromatic lines in $\ell^\pm$ spectrum from $X_M^\pm \to \ell^\pm \nu_s$
  [Shrock, '80-'81; Atre et al, '09; Kusenko et al, '09; Lello et al,'13]

- **Beam dump experiments:** ν_s decay products (light mesons, $\ell^\pm$) from $X_M^\pm$ decays
  [PS191, CHARM, NuTeV, ...]

Constraints on sterile fermions: masses and $\theta_{\alpha s}$

- **Neutrinoless double beta decays - $|m_{ee}|$:** [EXO-200, KamLAND-Zen, GERDA,...]
  [Blenow et al, '10; Lopez-Pavon et al, '13;
  Abada et al, '14, ..., Giunti et al]

- **Rare meson decays:** **Lepton Number Violating (LNV)** e.g. $K^+ \to \ell^+ \ell^+ \pi^-$

  Lepton Universality Violating (LUV) e.g. R_{X_M}, $R(D)$, R_τ
  [CLEO, Belle, BaBar, NA62, LHCb, BES III, ...]
  [Shrock, '81; Atre et al, '09; Abada et al, '13-'15, ...]

- **Lepton Flavour Violation:** **3 body decays among most stringent...**
  [Gronau et al, '85; Ilakovac & Pilaftsis, '95 - '14;
  Deppisch et al, '05; Dinh et al, '12; Alonso et al, '12; ...]

- **Cosmology:** large scale structures, Lyman-α, BBN, CMB, X-ray, SN1987a, ...
  [Smirnov et al, '06; Kusenko, '09; Gelmini, '10;
  Donini et al, '14; Hernández et al, '15-'16; ...]