Lepton Flavour Violation and neutrino masses

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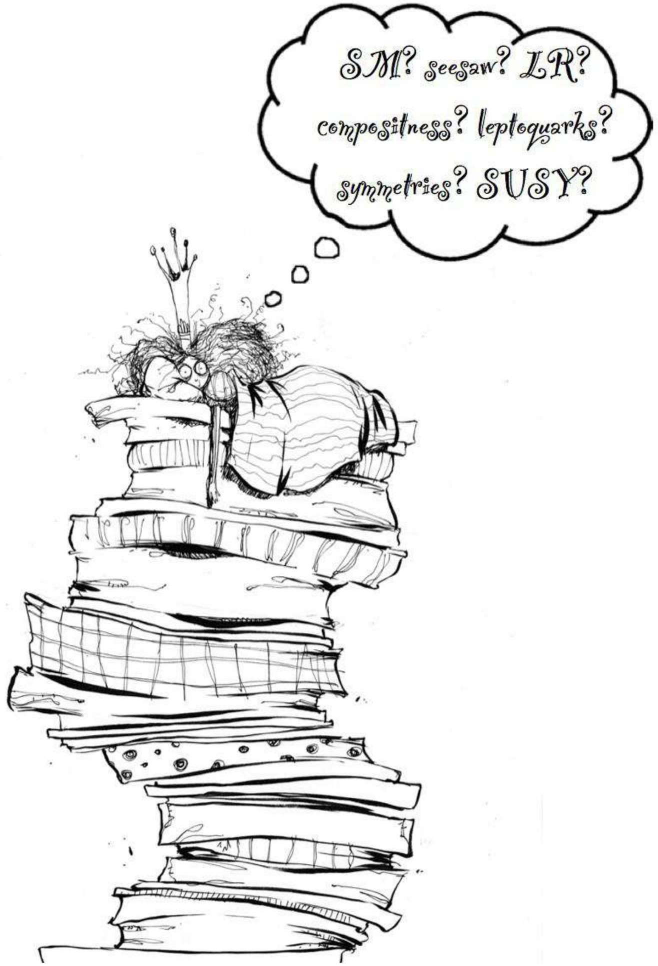
Beyond the Standard Model: New Physics

- **Strong arguments in favour of New Physics!**

Observations unaccounted for in the Standard Model: **neutrino oscillations,**

baryon asymmetry of the Universe, viable dark matter candidate

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



- **Neutrino oscillations: 1st laboratory evidence of NP**

  New mechanism of mass generation? New **(Majorana)** fields?

- **Extend the SM** (or embed in larger framework)! **But how?**

  Hundreths of (well motivated) theoretical constructions!!

  How to unveil the NP model at work?

- **Explore the full lepton sector!**

  A unique gateway to NP signals!

"Hints" on New Physics from neutrino masses

- What do we **know about the mechanism** of neutrino mass generation?

  ⇒ Should account for ν oscillation data!

  ⇒ **Address SM problems** (e.g. BAU from leptogenesis); not worsen TH caveats!

- **Numerous (appealing) mechanims of ν mass generation**

  Calling upon **distinct new states (singlets, triplets, ...)**, realised at **very different scales!**

- **Quick comparison** [SM + RH ν]: "standard" high-scale type I seesaw vs low-scale seesaw

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

Which observables? ▲

[High-scale seesaw in "UV complete" NP models (eg SUSY seesaw): very rich pheno!]

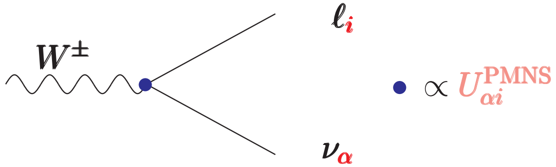
Leptonic observables: signs of New Physics

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

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

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

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

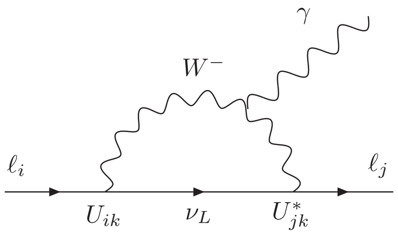


$m_\nu \neq 0$

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

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

- SM_{m_ν} - **cLFV possible??**



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

[Petcov, '77]

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

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

Lepton sector: gateway to new experimental signals

- Direct searches for New Physics states at high-energy colliders

  $\Rightarrow$ New resonances, SM-forbidden final states, ...

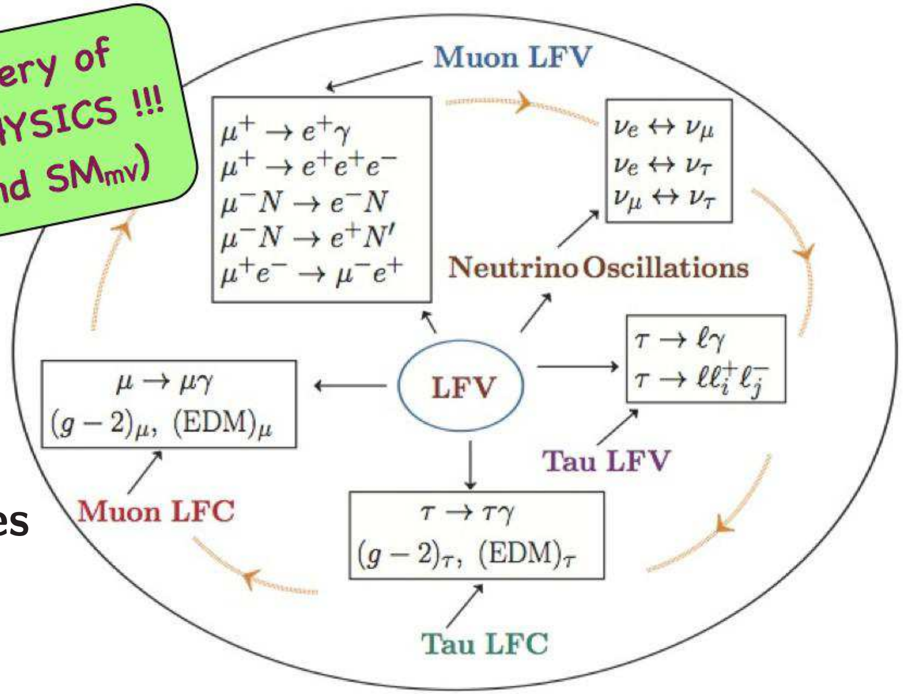
Discovery of NEW PHYSICS !!! (beyond $SM_{m\nu}$)

- "Leptonic" observables $\rightsquigarrow$ cLFV, LNV, ...

Rare processes searched for at high-intensities

  $\Rightarrow$ NP discovery (before LHC!)

  $\Rightarrow$ Complementary information to direct searches



cLFV, LNV, ... not necessarily related to ν masses!

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

$$\mathcal{C}^5_{m_\nu} \leftrightsquigarrow \mathcal{C}^6_{\text{cLFV}}\ ?$$

Multiple "NP" scales: $\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{\mathcal{C}^5\mathcal{O}^5}{\Lambda_{\text{LNV}}}\ (m_\nu) + \frac{\mathcal{C}^6\mathcal{O}^6}{\Lambda^2_{\text{LFV}}}\ (\ell_i \leftrightarrow \ell_j) + ... + \frac{\mathcal{C}^9\mathcal{O}^9}{\Lambda'^5_{\text{LNV}}}\ (0\nu2\beta) + ...$

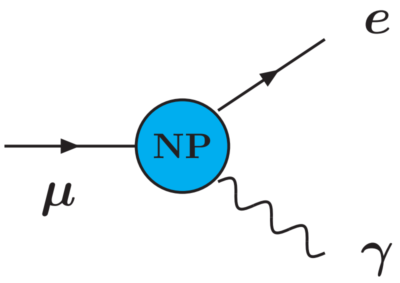
  $\Rightarrow$ Still - a possible **bridge to the mechanism** of ν mass generation

Brief summary

- **Leptonic high-intensity observables: signs of New Physics**
- **Observables and experimental status**
  - **Lepton number violation**
  - **Charged lepton flavour violation**
- **Models of New Physics (ν mass generation & more)**
  - **Ad-hoc extensions and seesaw realisations**
  - **Additional fields and symmetries**
  - **Larger frameworks**
- **Overview & discussion**

- **Leptonic observables (cLFV, LNV): current status**

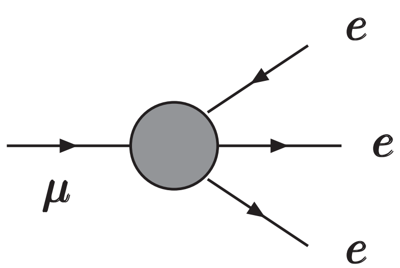
cLFV: radiative and 3-body muon channels



- 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

- **Current status:** BR($\mu \to e\gamma$)$\lesssim 4.2 \times 10^{-13}$ [MEG, '16]
- **Future prospects:** MEG II @ PSI $\rightsquigarrow$ sensitivity 4×10^{-14}



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

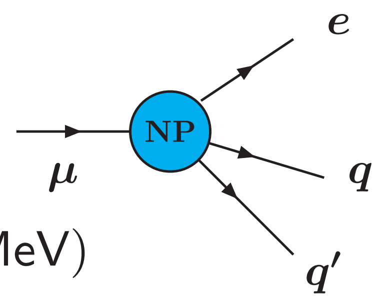
  common vertex; Time coincidence

- **Current status:** BR($\mu \to eee$)$\lesssim 1.0 \times 10^{-12}$ [SINDRUM, '88]
- **Future prospects:** Mu3e @ PSI

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

cLFV in muonic atoms

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



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

▶ **Event signature:** single mono-energetic electron, $E_{\mu e}^{\text{Al, Pb, Ti}} \approx \mathcal{O}(100\text{ MeV})$

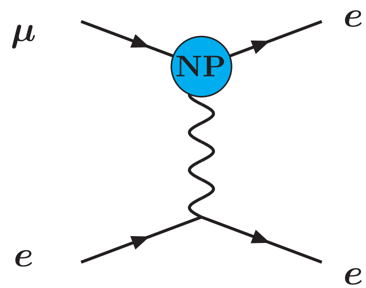
▶ **Current status:** **CR($\mu - e$, Au)$\lesssim 7 \times 10^{-13}$** [SINDRUM, '06]

▶ **Future prospects (Al):** **Mu2e @ FNAL $\sim 3 \times 10^{-17}$; COMET @ JPARC I (II)$\sim 10^{-15}(10^{-17})$**

▶ **Coulomb enhaced muonic atom decay:** $\mu^- e^- \to e^- e^-$

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

$\Rightarrow$ Consider large Z targets! Pb, U!?



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

▶ **Experimental status:** **New observable!**

Rare lepton processes: cLFV tau decays

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

  $$M_{\text{final}} = M_{\ell\gamma} \sim m_\tau$$

- **Current status:** BR$(\tau \to e\gamma) \lesssim 3.3 \times 10^{-8}$; BR$(\tau \to \mu\gamma) \lesssim 4.4 \times 10^{-8}$ [BaBar, '10]

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

  $$M_{3\ell} \sim m_\tau$$

- **Current status:**

3ℓ final state	BR (BaBar)	BR (Belle)
$e^- e^+ e^-$	2.9×10^{-8}	2.7×10^{-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}
$\mu^- \mu^+ \mu^-$	3.3×10^{-8}	2.1×10^{-8}

- **Future experimental prospects:**

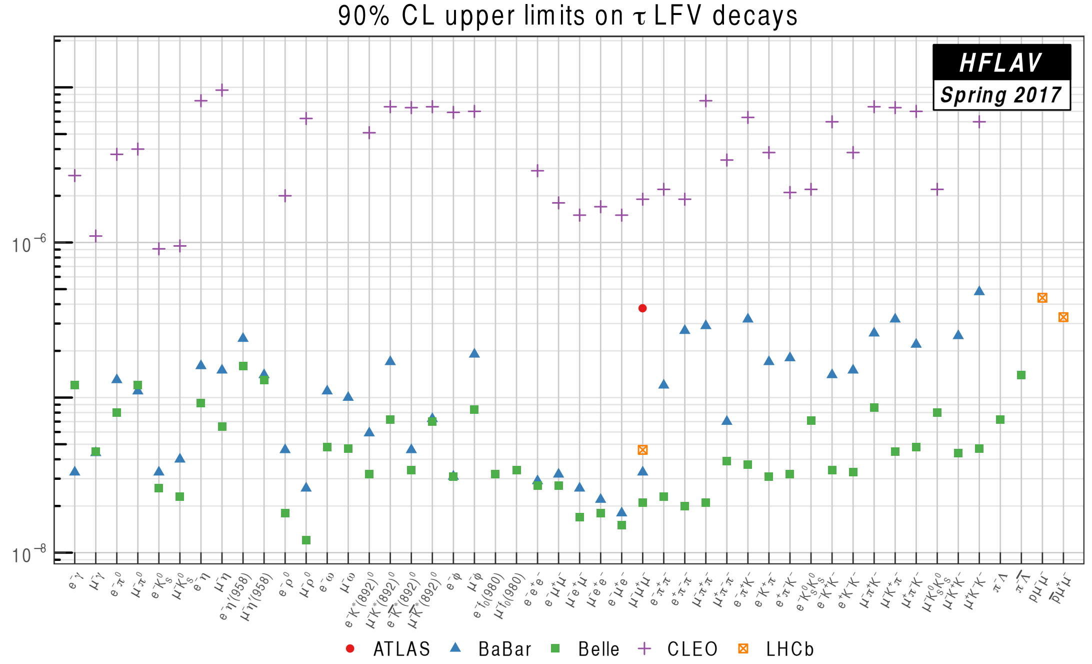
  SuperB (Belle II) and/or Tau-Charm factories

  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:** $\tau \to \ell h^0$; $\tau \to \ell h_i h_j$ ... and "exotic" modes...



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

▶ 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 "higher" 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**

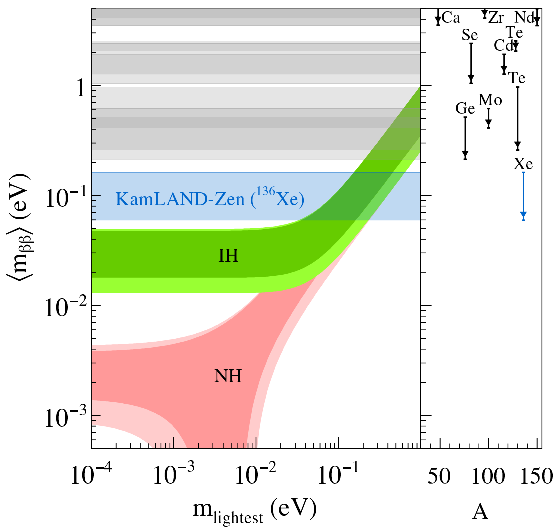
  Multiplicity, composition, E_{miss}, ...: properties of final state strongly model-dependent...

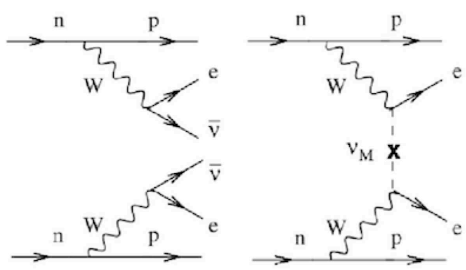
- **Future experimental prospects:** **LHC Run 2 !!** **... and Linear Collider / FCC-ee**

Lepton Number Violation observables

★ **LNV suggests the presence of Majorana states; opens the door for leptogenesis...**

▶ **Neutrinoless double beta decays:** $(A, Z) \to (A, Z+2) + 2e^-$





[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 ($\Delta L = 2$) $\mu^- - e^+$ conversion:** $\mu^- + (A, Z) \to e^+ + (A, Z-2)^*$

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

▶ **Event signature:** single positron - but *complex* E-spectrum

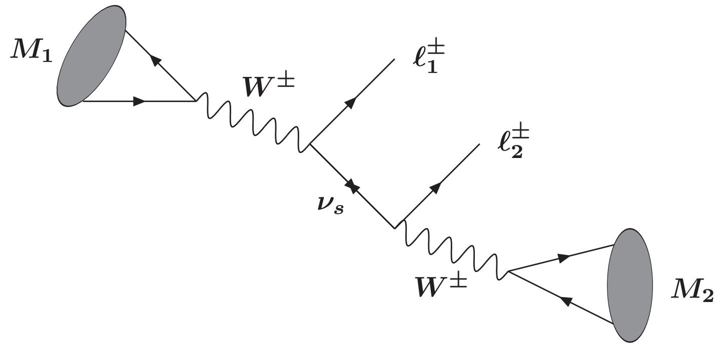
▶ **Experimental status:** **CR($\mu^- +$ Ti $\to e^+ +$ Ca$^{(*)}$)** $\lesssim 3.6 \times 10^{-11}$ (1.7×10^{-12}) [SINDRUM, '98]

▶ **Future prospects: Mu2e, COMET** $\rightsquigarrow \mathcal{O}(10^{-16})$**??**

Lepton Number Violation observables

- **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}



◀ ▼ **Experimental status: BaBar, Belle**

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}

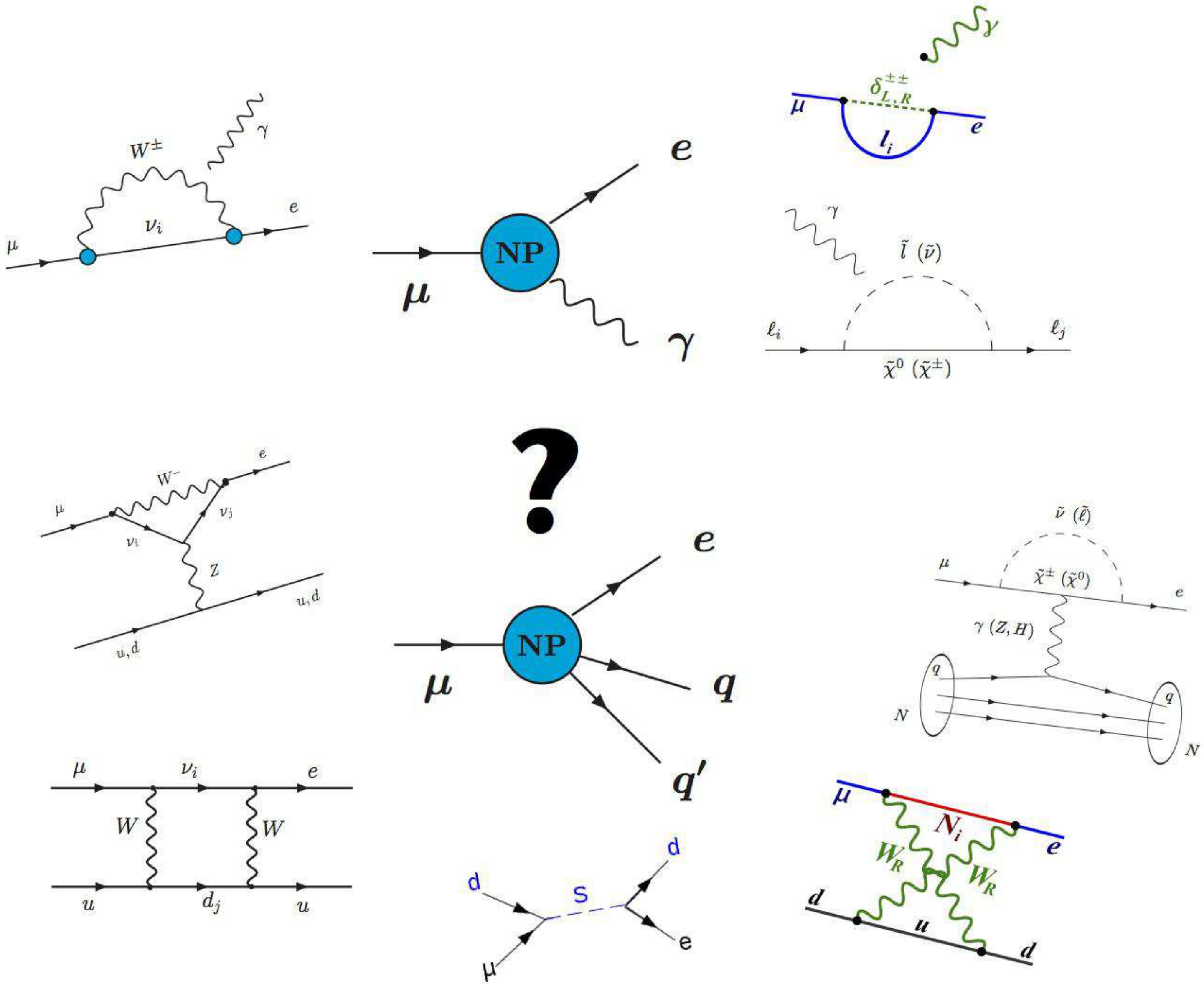
- **Future prospects: LHCb, Belle II, ...**

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

cLFV (and LNV) might be - or not! -

associated with NP responsible for ν mass generation...

Many models to one observable?



Interpreting data - how??

- **Pheno approaches:**

  Effective approach

  (model-independent)

  [Presentation by A. Signer]

  Model dependent

  (specific NP scenario)

- **Different from quark FV!**

  No SM "TH background"...

Theoretical frameworks

▶ **SM extensions (aiming at accounting for ν masses and mixings...)**

- **Standard seesaws** [type I, type II, type III] & **variants**
  Inverse Seesaw (ISS), ...
- **Additional states (and symmetries): leptoquarks,**
  Left-Right symmetric, ...
- **Extended frameworks: supersymmetric seesaws,**
  GUTs, ...

▶ **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!...]**

▶ 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)]

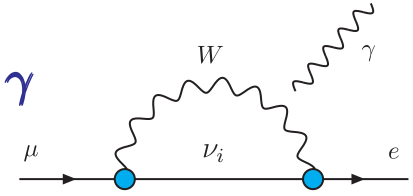
- **Modified charged ($W^\pm$) and neutral (Z^0) current interactions:**

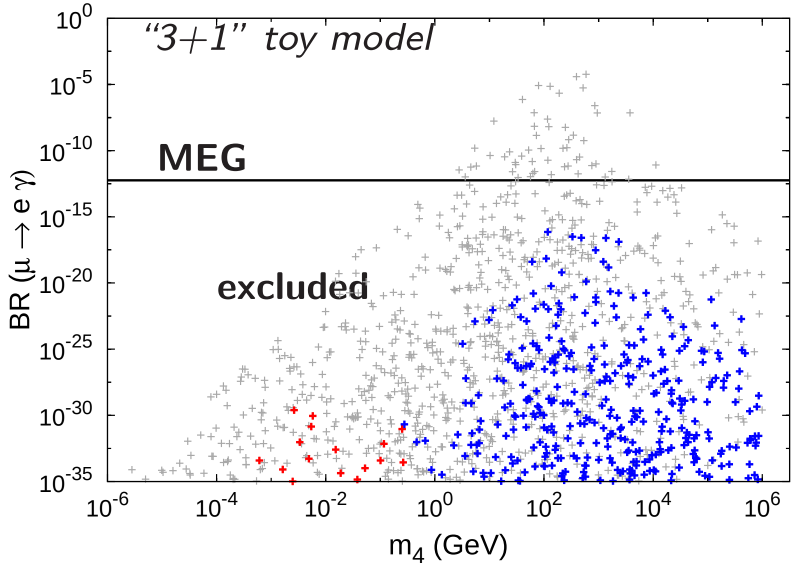
$$\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+n_S} \mathbf{U}_{\alpha i}\, \bar{\ell}_\alpha\, \gamma^\mu\, P_L\, \nu_i$$

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

ν_s and cLFV: radiative and 3 body decays

- **Radiative decays: $\ell_i \to \ell_j \gamma$**



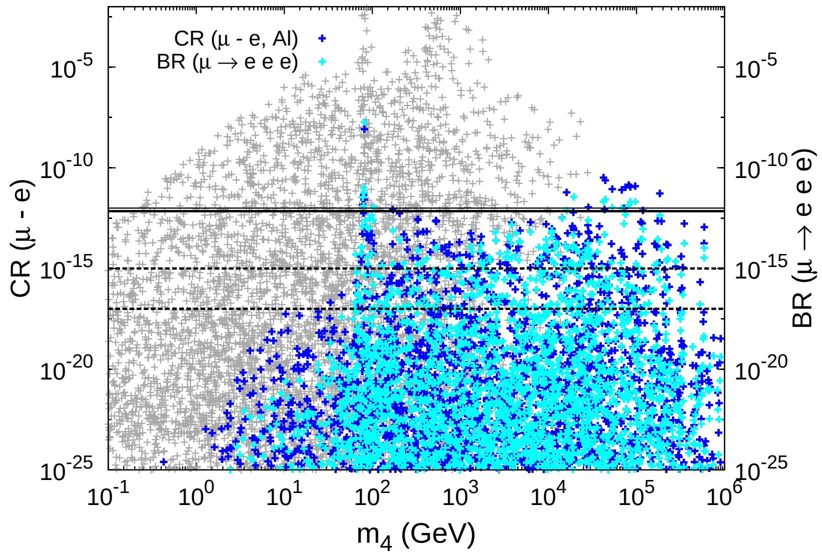


  - Consider $\mu \to e\gamma$
  - For $m_4 \gtrsim 10$ GeV sizable ν_s contributions

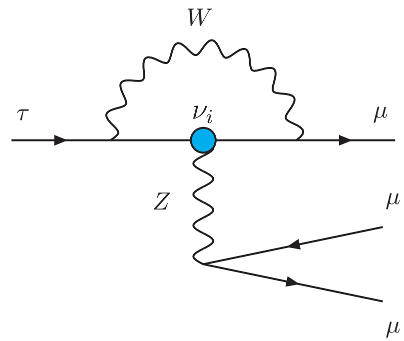
.. **but precluded by other cLFV observables**

as 3-body decays and nuclear conversion

- **Three-body decays $\ell_i \to 3\ell_j$ (■) and conversion in Nuclei $\mu - e$ (■)**

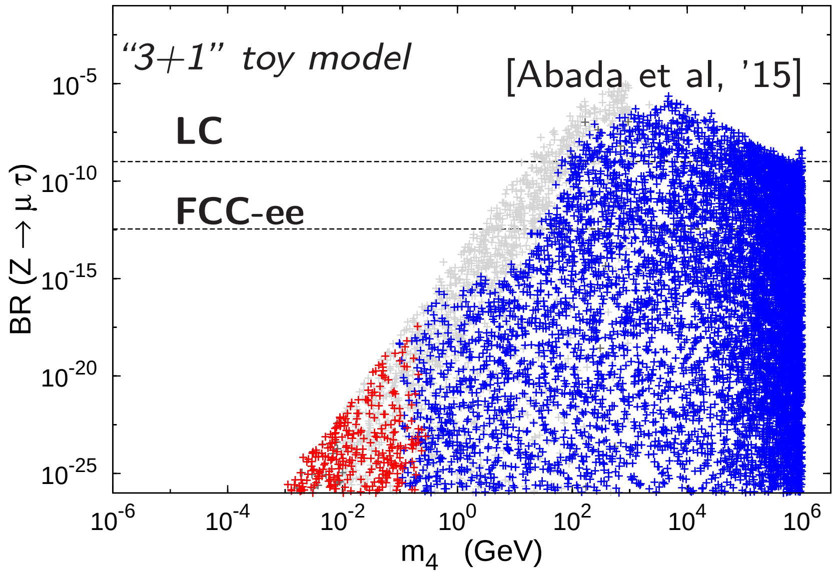


- For sterile states above EW scale, strongly dominated by Z **penguin** contributions

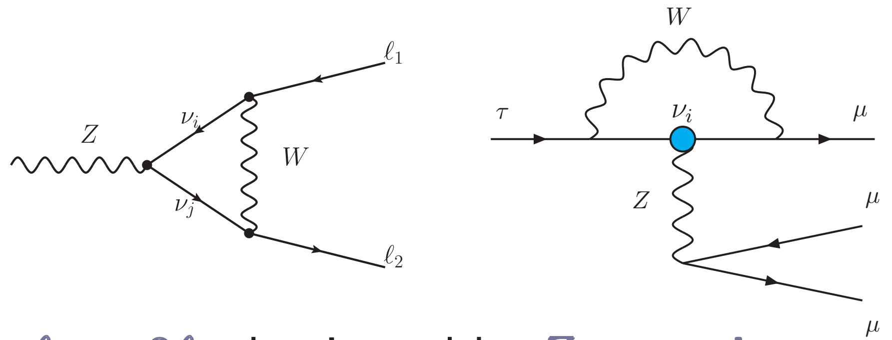


Sterile neutrinos and cLFV at higher energies

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



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



▶ Recall: $\ell_i \to 3\ell_j$ dominated by Z **penguins**

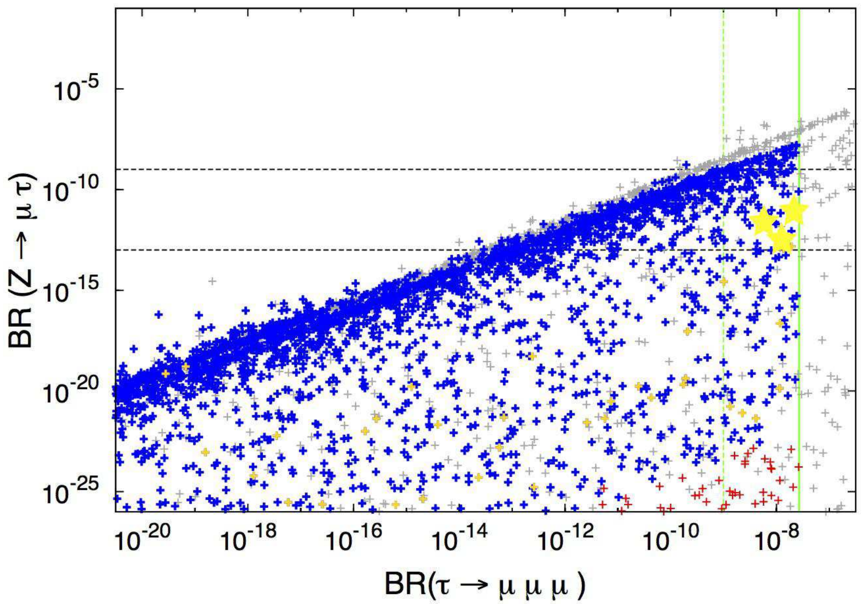
▶ Strong correlation between $Z \to \mu\tau$ and $\tau \to 3\,\mu$

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

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

at **low- and high energies!**

▶ **Testable LNV:** ★ ⇝ $0\nu2\beta$ within exp. sensitivity

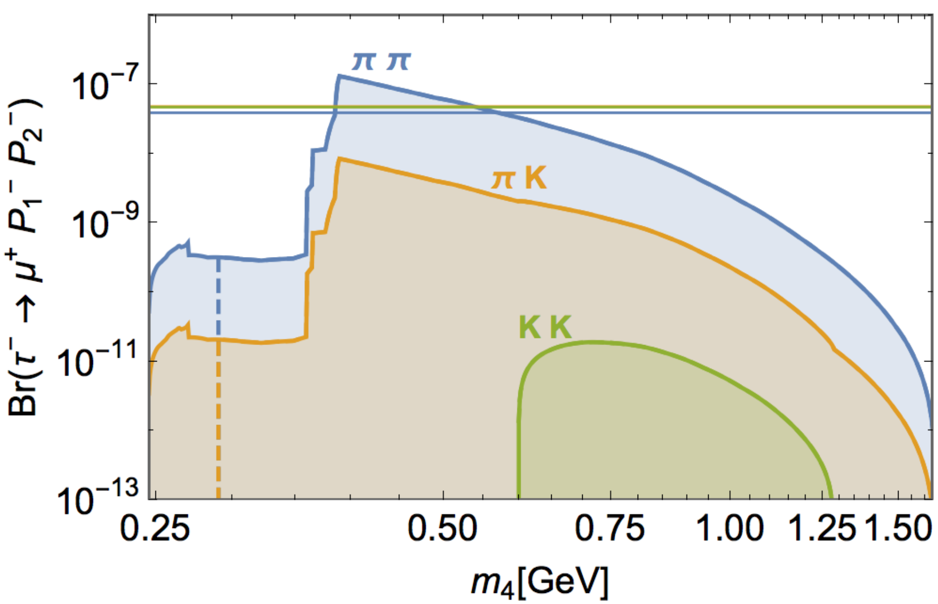


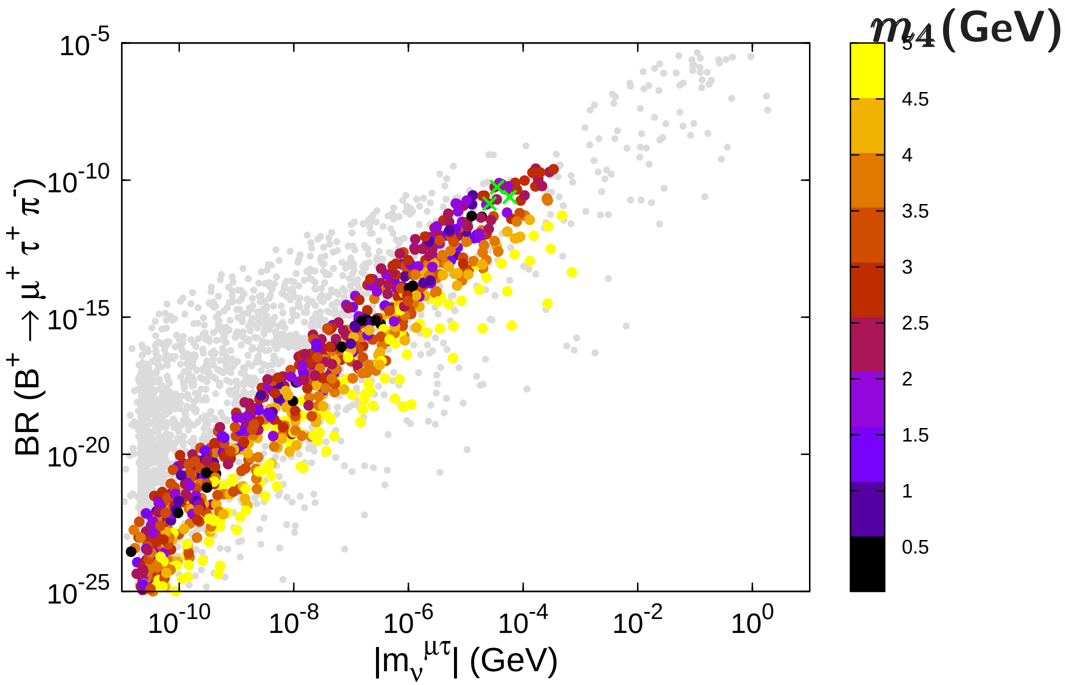
Sterile neutrinos: impact for LNV meson and tau decays

- **On-shell ν_s: "resonant-enhancement"** of $M_1 \to M_2 \ell^\pm_\alpha \ell^\pm_\beta$ and $\tau^\pm \to M_1 M_2 \ell^\mp$ decays
- Full update of **LNV constraints** on ν_s ($[0.1\ \mathrm{GeV}, 10\ \mathrm{GeV}]$) [1712.03984]
- **Several BRs close to experimental sensitivity!** Possibility to **infer information** on $m_\nu^{\ell_i \ell_j}$

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

(m_ν^{ee} best constraints from $0\nu 2\beta$)





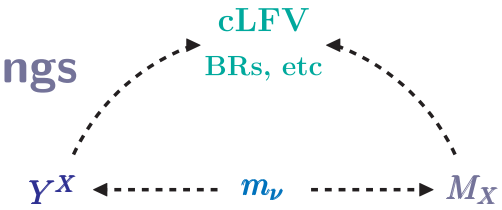
- **New bounds** on all $m_\nu^{\ell_i \ell_j}$ entries - $\lesssim \mathcal{O}(10^{-3}\mathrm{GeV})$ $[m_\nu^{\tau\tau} \lesssim \mathcal{O}(10^{-2}\mathrm{GeV})]$

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

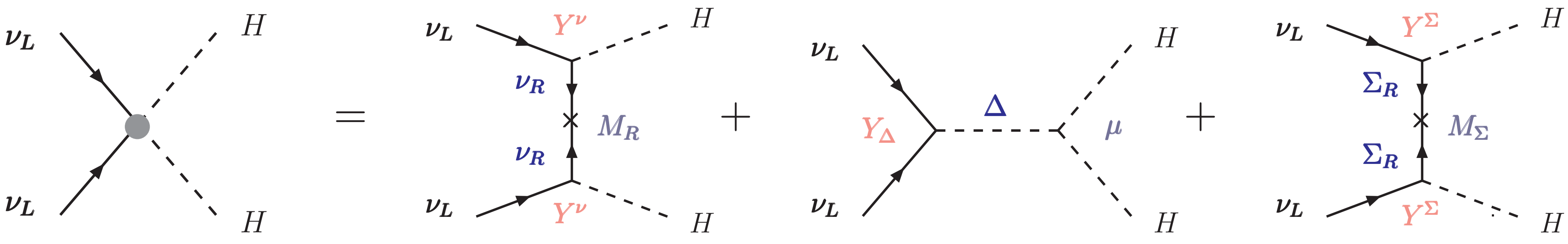
▶ **Models of neutrino mass generation**

(Illustrative) highlights...

The seesaw mechanism



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



$\frac{1}{\Lambda} L\,L\,H\,H$	ν_R (fermion singlet)	Δ (scalar triplet)	Σ_R (fermion triplet)
"Seesaw mechanism"	**Type I**	**Type II**	**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)

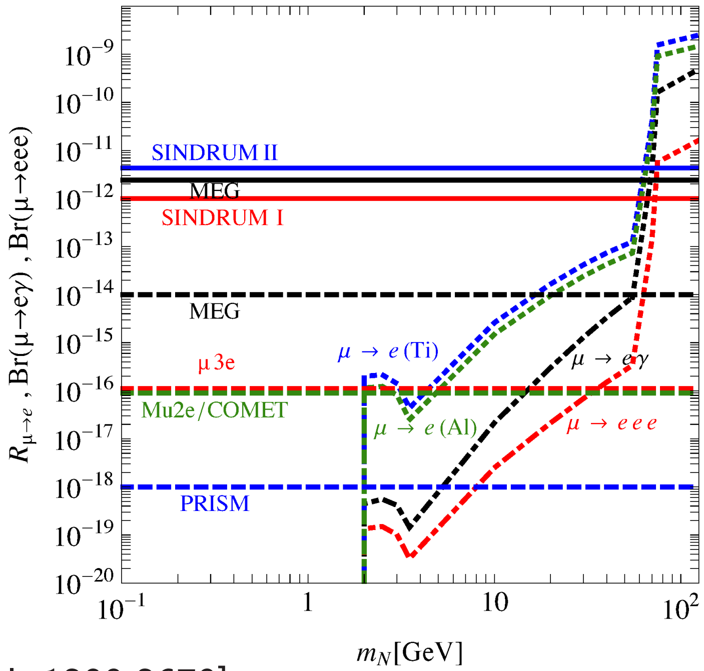
Low scale type I seesaw

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

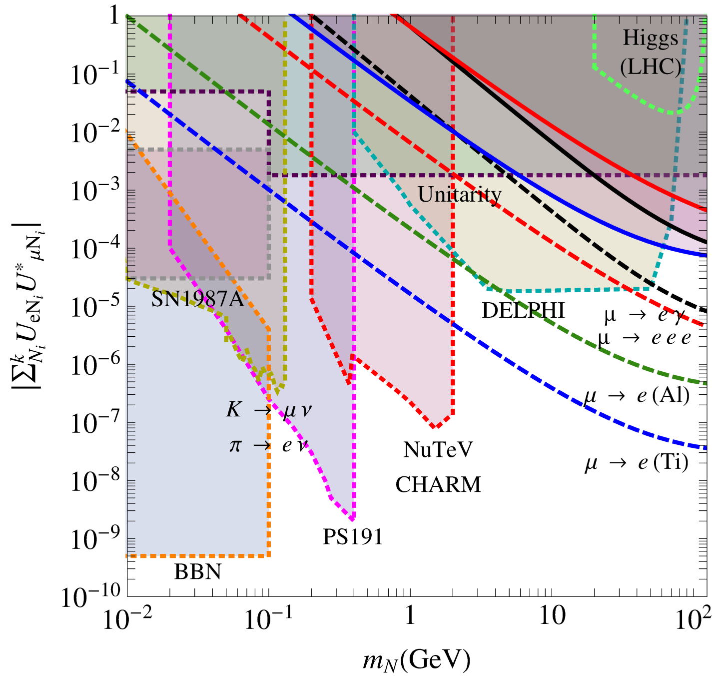
$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \quad U_{\nu\nu} \approx (1-\varepsilon)\, U_{\text{PMNS}}$$

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]



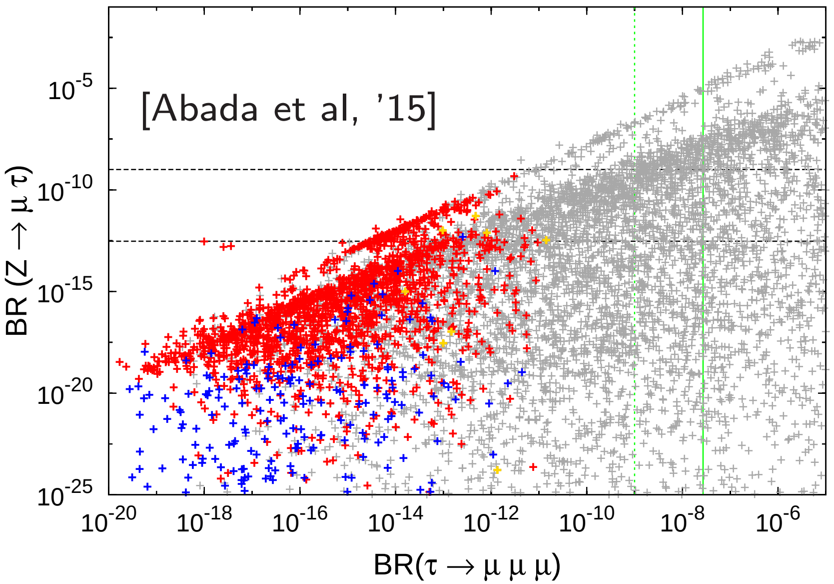
(see also Dinh et al, '12-'14)

Low scale: Inverse Seesaw (ISS)

- Addition of **3 "heavy" RH** neutrinos and **3 extra "sterile" fermions X** to the SM
- $\mathcal{M}^{9\times9}_{\text{ISS}} = \begin{pmatrix} 0 & Y_\nu v & 0 \\ Y_\nu^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix} \Rightarrow \begin{cases} \text{3 light } \nu : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2}\mu_X \\ \text{3 pseudo-Dirac pairs} : m_{N^\pm} \approx M_R \pm \mu_X \end{cases}$

- **Non-unitarity $\tilde{U}_{\text{PMNS}}$ $\Rightarrow$ modified neutral and charged leptonic currents**
- **Abundant signals at colliders, cLFV** (poor LNV - and EDM - prospects...)

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



- 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**
- **$\tau \to 3\mu$ at Belle II: $\rightsquigarrow$ disfavour ISS$_{(3,3)}$**

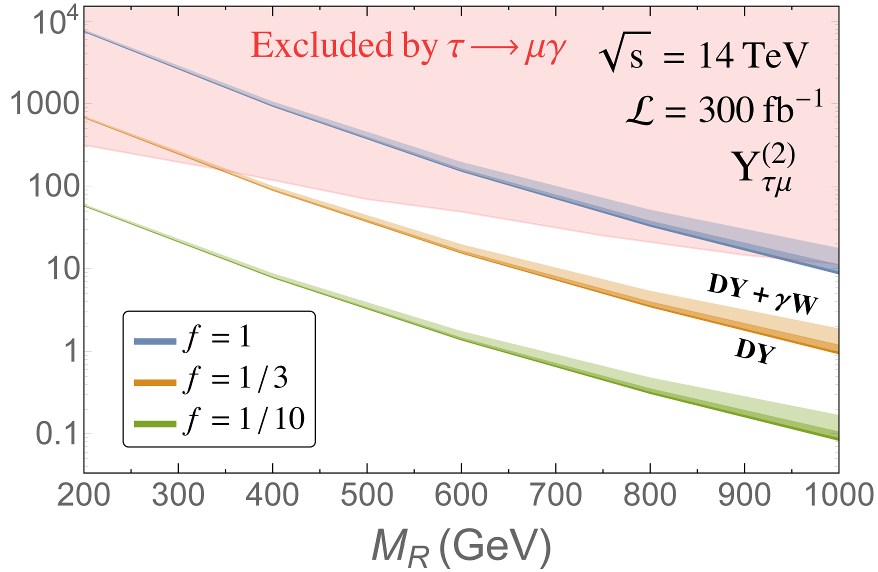
cLFV: (3,3) ISS realisation at colliders

- **cLFV exotic events at the LHC**
  - Searches for **heavy** N at the LHC

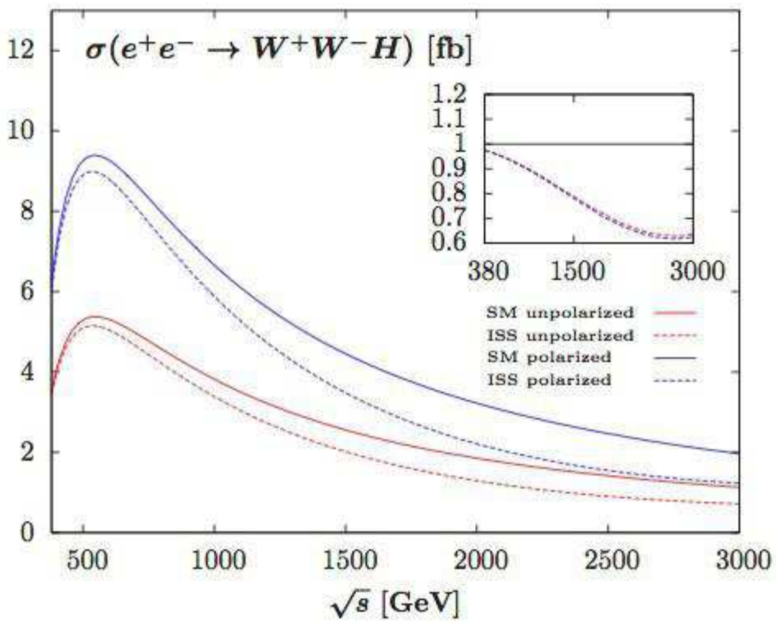
    $$q\,q' \to \tau\,\mu + 2\ \textbf{jets} \qquad \text{(no missing } E^T!)$$

  - After cuts, **significant number of events!**

[Arganda et al, 1508.05074]



- **Impact of heavy ν_s on WWH production at Lepton Colliders**



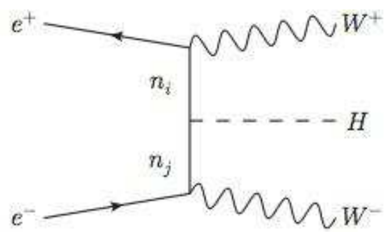
- **Sizeable deviations from SM expectations**

  $$\sigma(e^+e^- \to WWH) \quad \Rightarrow \quad \Delta^{\text{BSM}} \sim -38\%$$

- **Maximal effects** for $\sqrt{s} \sim 3$ **TeV** (CLIC)

  $$m_{\nu_s} \approx \text{few TeV}, \quad |Y^\nu| \sim 1$$

[Baglio et al, 1712.07621]



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**

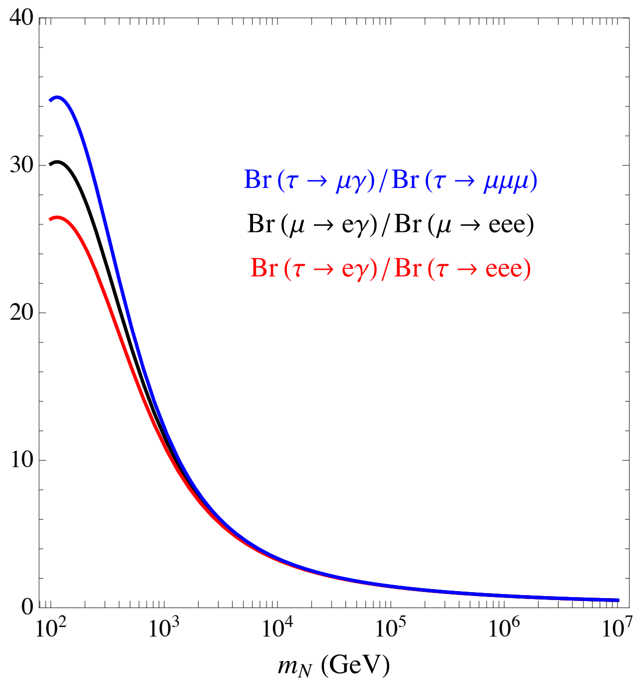
  Type I: cLFV transitions at **loop level** (radiative, 3-body, conversion in Nuclei)

  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!**

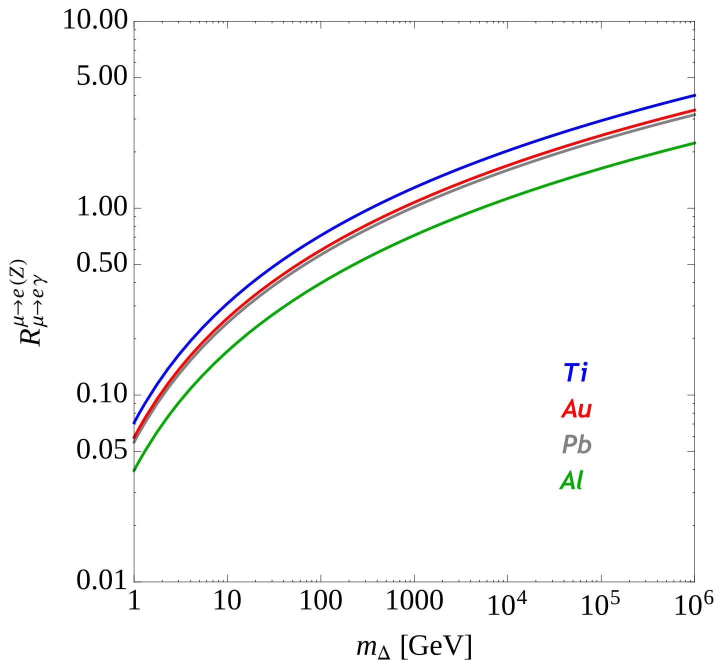
  Type III: 3-body decays and coherent conversion at tree-level! $\ell_i \to \ell_j \gamma$ @ loop...

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

Type I



Type II



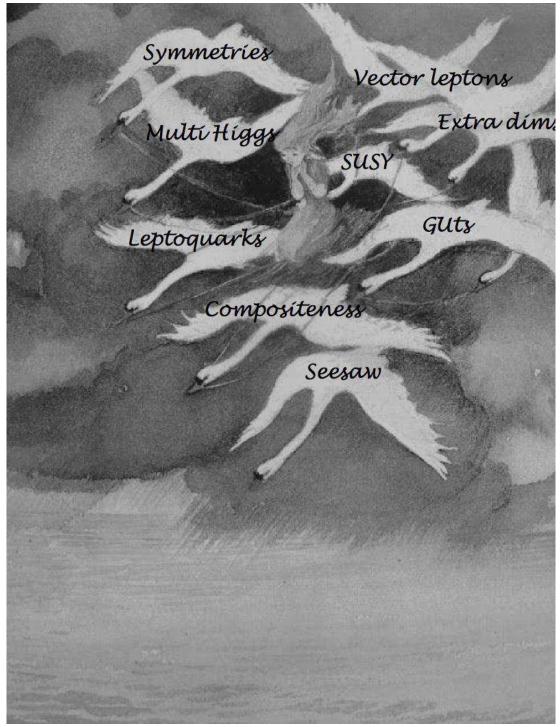
Type III

$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{BR}(\mu\to 3e)} = 1.3\times10^{-3}$$

$$\frac{\mathrm{BR}(\tau\to \mu\gamma)}{\mathrm{BR}(\tau\to 3\mu)} = 1.3\times10^{-3}$$

$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{CR}(e-\mu,\mathrm{Ti})} = 3.1\times10^{-4}$$

[Hambye, 2013]



- **Extensions of the SM: additional fields, symmetries and complete frameworks**

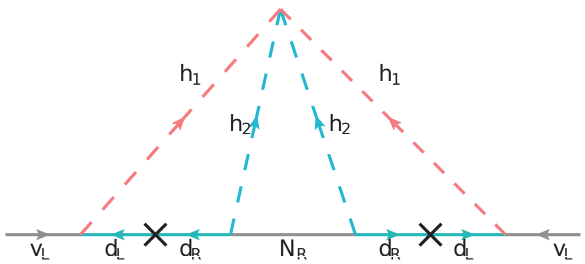
A few examples of a vast array of well motivated constructions...

Leptoquarks & massive neutrinos: cLFV constraints

Leptoquarks: well motivated solution to several tensions a_μ, R_K, R_D, anomalies, ...

- **Neutrino masses, DM and B anomalies:**

  SM + scalar leptoquarks ($h_{1,2}$) + RH lepton triplets Σ_R; SU(3)×SU(2)×U(1)×Z_2^{DM}



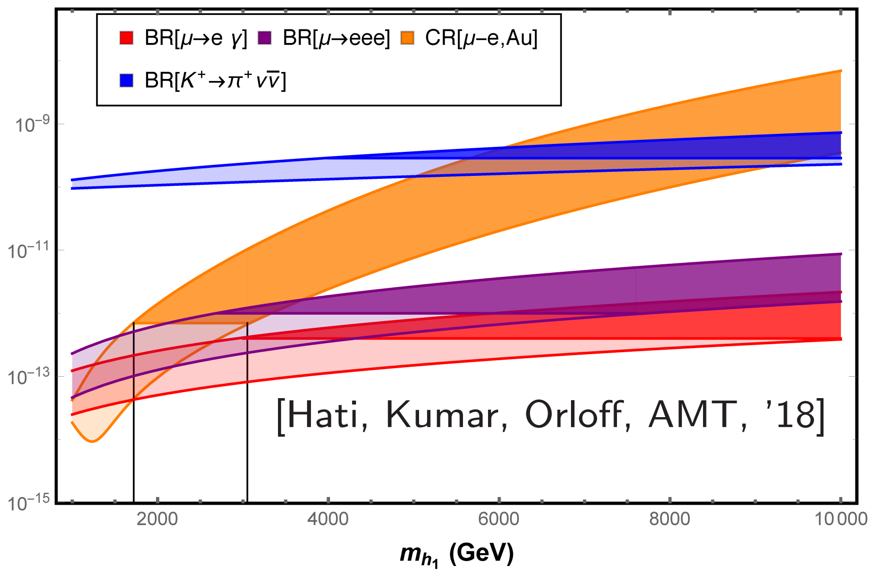
- Radiatively induced m_ν (3-loop); Σ^0 ⇝ **DM candidate**
- **Non-trival structure** in leptoquark Yukawa couplings y

  ⇒ **account for $R_K^{(*)}$ anomalies!**

$$y \sim \begin{pmatrix} \epsilon^4 & \epsilon^5 & \epsilon^2 \\ \epsilon^3 & \epsilon^3 & \epsilon^4 \\ \epsilon^4 & \epsilon & \epsilon \end{pmatrix}$$

- **Huge impact / constraints from cLFV and meson decays:**

  CR($\mu - e$,N), $K \to \pi\nu\bar{\nu}$ the most **stringent**



- **Oscillation data** (**perturbative** couplings)

  viable DM candidate

- **Explain $R_{K^{(*)}}$ anomalies** [no $R_{D^{(*)}}$, $(g-2)_\mu$]
- **Leptoquarks and triplets: within LHC reach!**

Adding symmetry: neutrino masses, LNV & cLFV

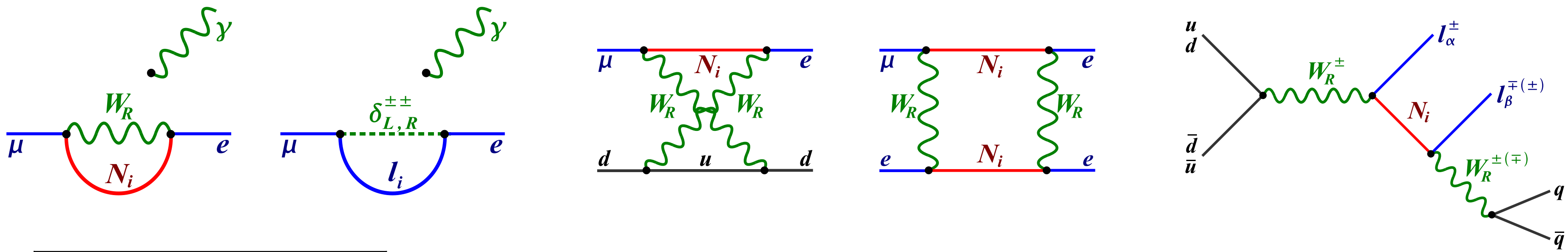
★ **Discrete and continuous flavour symmetries, extensions of the SM gauge group**

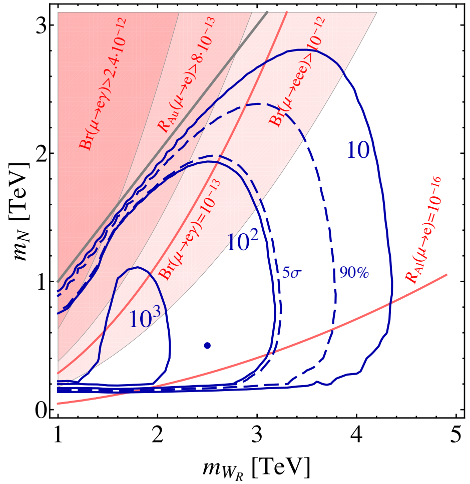
- Many appealing (predictive) models with interesting cLFV, LNV and CPV signatures

- **Minimal Left-Right extension of the SM:** $SU(2)_L \otimes U(1) \Rightarrow SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

  Spectrum includes RH neutrinos, bi-doublet and triplet Higgs, new Z_R, W_R bosons

- **New contributions to LNV & cLFV observables at low- and high-energies**





- **If LHC $\sqrt{s}$ above heavy neutrino threshold:**

  dilepton LFV/LNV signatures $pp \to W_R \to e^\pm \mu^{\mp,\pm} + 2$ jets

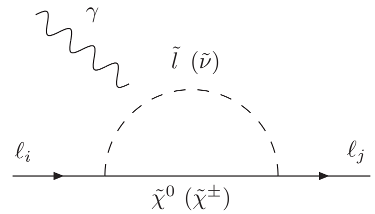
- **Complementarity studies of LHC signatures and low-energy rare decays**

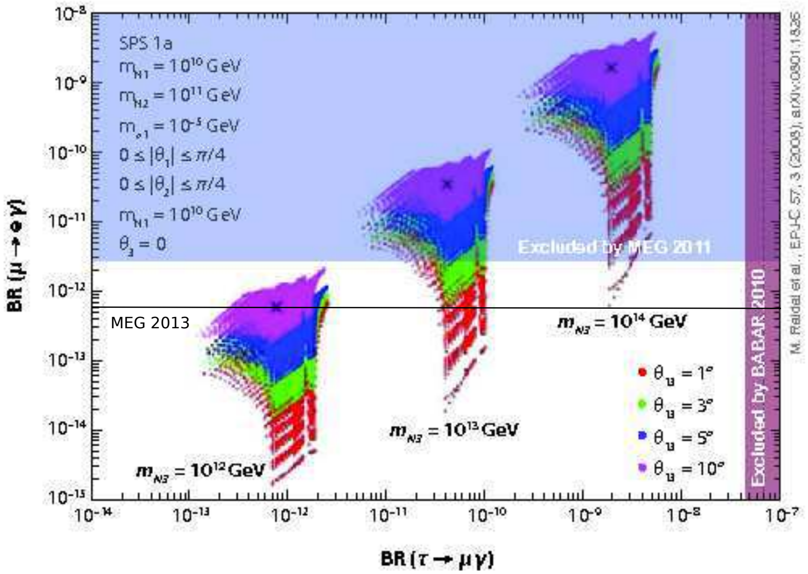
[Das et al, 1206.0656]

Supersymmetric type I seesaw

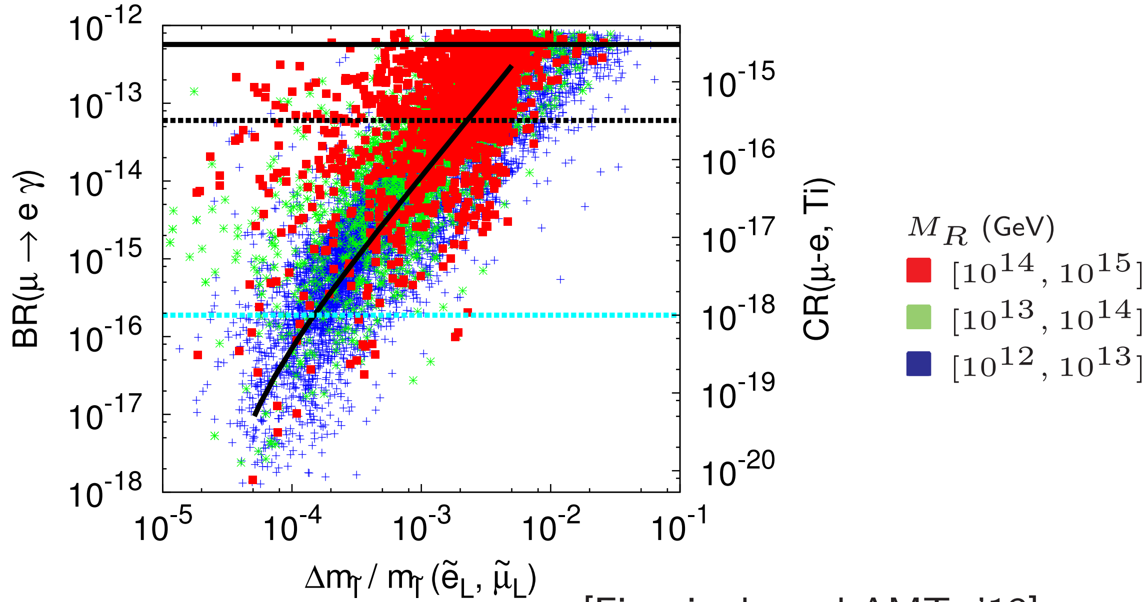
- **Large Y^{ν}: sizable contributions to cLFV observables**

  cLFV $\rightsquigarrow$ exchange of *virtual* **SUSY particles** $\quad \Lambda_{\text{cLFV}} \ll \Lambda_{\text{LNV}}^{m_\nu}$





[Antusch, Arganda, Herrero, AMT, '06 - '07]



[Figueiredo and AMT, '13]

- **Y^{ν} unique source of LFV: synergy of high- and low-energy observables**

- **Isolated cLFV** manifestations $\Rightarrow$ **disfavours SUSY seesaw hypothesis**

- **"Correlated" cLFV observations $\Rightarrow$ strengthen SUSY seesaw hypothesis !**

  $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \gtrsim \mathcal{O}(0.5\%)$ **and** $\mu \to e\gamma|_{\text{MEG}}$ ✔ !! **Hints on the seesaw scale: $M_R \sim 10^{14}$ GeV**

Hints of an organising principle: SUSY seesaw and GUTs

★ **Supersymmetric Grand Unified Theories**

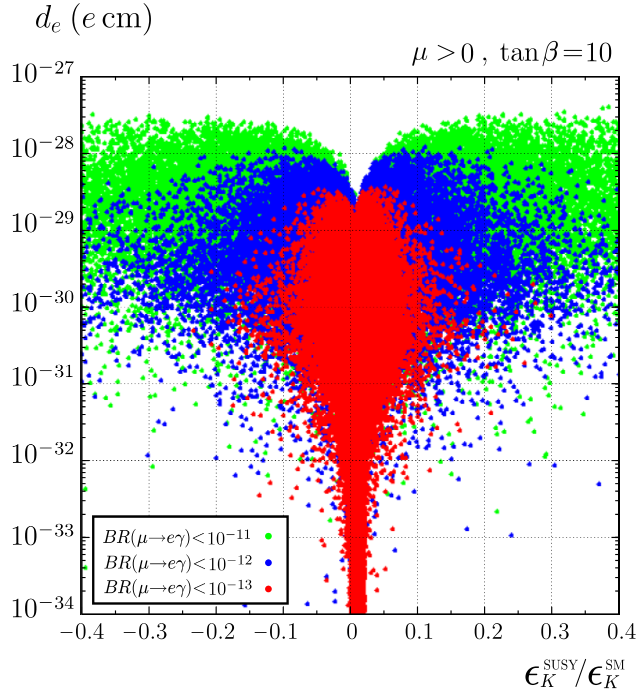
- **Reduce arbitrariness of Y^q, Y^ℓ, Y^ν, ...:** $\Rightarrow$ increase predictivity and testability!

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

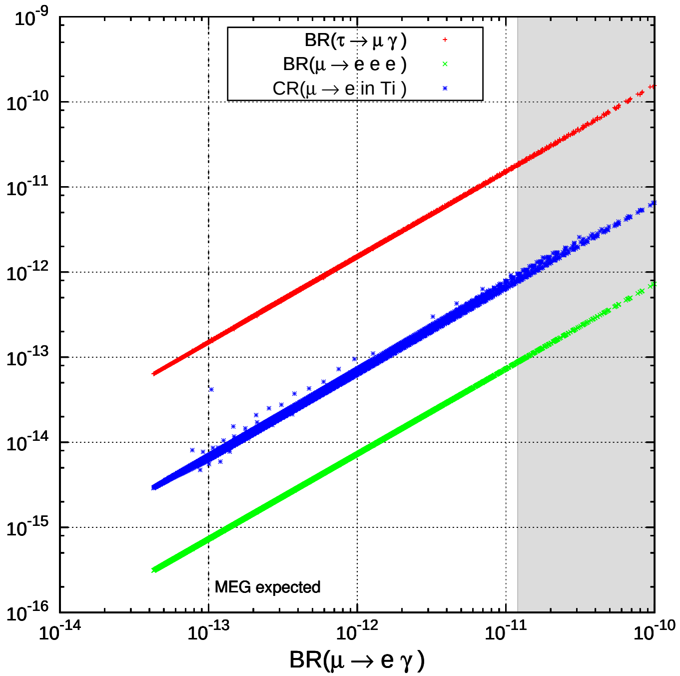
  Correlated CP violation and flavour observables

  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]

- **Concluding remarks**

New Physics and lepton observables

- **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**

- **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**

- **“Leptonic” observables (cLFV, LNV, CPV, ...)**

  might be induced by NP at the origin of ν masses...

  or from an “independent NP” source **(High scale type I + FV Multi-Higgs...)**

- **Experimentally exciting** near-future!

  Accompanied by **theoretical and phenomenological analyses and ideas!**

Leptonic observables: signs of New Physics

▶ Explore the underlying synergy between

ν physics and high-intensity observables

to constrain the New Physics model

at the origin of neutrino phenomena

▶ And keep an open eye on collider searches and new oscillation phenomena !

(not adressed here...)

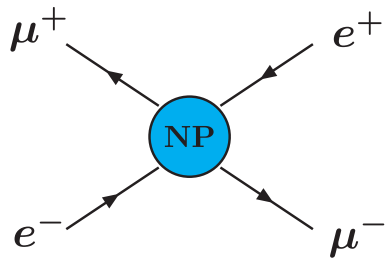
Backup

cLFV in muonic atoms: Muonium channels

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

▶ **Mu − $\overline{\text{Mu}}$** conversion

⇒ Oscillation between $(e^-\mu^+) \leftrightsquigarrow (e^+\mu^-)$



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

▶ **cLFV Mu decay:** Mu $\to e^+e^-$

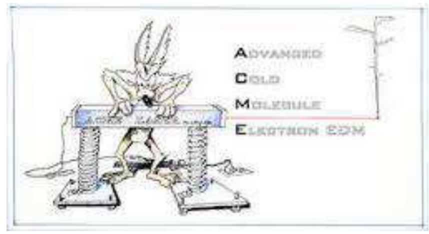
clear signal compared to SM decay Mu $\to e^+e^-\bar{\nu}_\mu\nu_e$ (no missing energy)

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

And many other... EDMs, magnetic moments...

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

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



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

$\boldsymbol{a_e}$: Best **determination of α...**

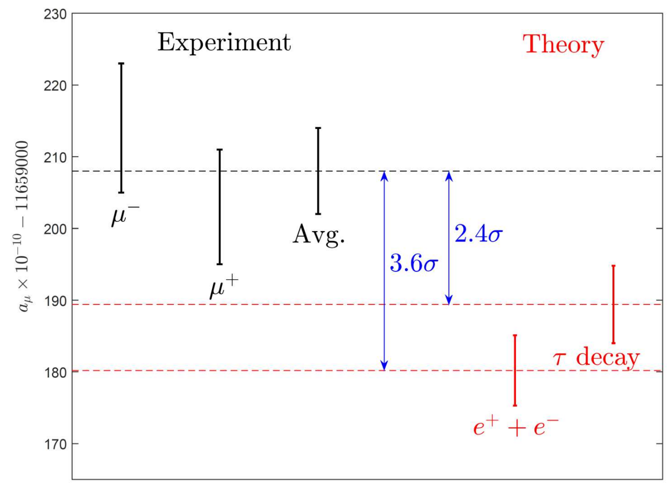
$a_e^{\text{the}} = 0.001159652181643(764)$ ⇝ 5^{th} order in QED (12,672 diags)!

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

$\boldsymbol{a_\mu}$: Current **tension** between **theory and experiment** $\longrightarrow$

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

If $\boldsymbol{\delta a_\mu}$ confirmed ⇝ **discrepancies** for $\boldsymbol{a_{e,\tau}}$ and $\boldsymbol{d_\ell}$!



$\boldsymbol{a_\tau}$: Short **tau lifetime...**

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

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

[0801.1134]

The effective approach to NP contributions

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

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

- **Dimension 5** - $\Delta\mathcal{L}^5$ **(Weinberg): neutrino masses** (LNV, $\Delta L = 2$) $\quad \mathcal{O}^5_{ij} \sim (L_i\, H)(H\, L_j)$

- **Dimension 6** - $\Delta\mathcal{L}^6$: kinetic corrections, **cLFV (dipole and 3-body)**, EWP tests, t physics...

  Dipole: $\mathcal{O}^6_{\ell_i \ell_j \gamma} \sim L_i \sigma^{\mu\nu} e_j H F_{\mu\nu}$ $\quad$ radiative decays $\ell_i \to \ell_j \gamma$

  4 fermion: $\mathcal{O}^6_{\ell_i \ell_j \ell_k \ell_l} \sim (\ell_i \gamma_\mu P_{L,R} \ell_j)(\ell_k \gamma^\mu P_{L,R} \ell_l)$ $\quad$ 3-body decays $\ell_i \to \ell_j \ell_k \ell_l$, ...

  $\mathcal{O}^6_{\ell_i \ell_j q_k q_l} \sim (\ell_i \gamma_\mu P_{L,R} \ell_j)(q_k \gamma^\mu P_{L,R} q_l)$ $\quad$ $\mu - e$ in Nuclei, meson decays, ...

  Vector/scalar: $\mathcal{O}^6_{H H \ell_i \ell_j} \sim (H^\dagger i \overleftrightarrow{D}_\mu H)(\ell_i \gamma_\mu \ell_j)$ $\quad$ 3-body decays $\ell_i \to \ell_j \ell_k \ell_l$, ...

- **Dimension 9** - $\Delta\mathcal{L}^9$: ... $0\nu 2\beta$ decays, ... $\quad \mathcal{O}^9_{ij} \sim (\ell_L q_L d^c_R)(\ell_L q_L d^c_R)$

- **Dimension 12, 14** - $\Delta\mathcal{L}^{12,14}$: ... **cLFV & LNV decays:** $\mu^- + (A, Z) \to e^+ + (A, Z-2)^*$

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"**

   $\Rightarrow$ **Natural couplings**

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

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

   $\Rightarrow$ **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]

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; ...]

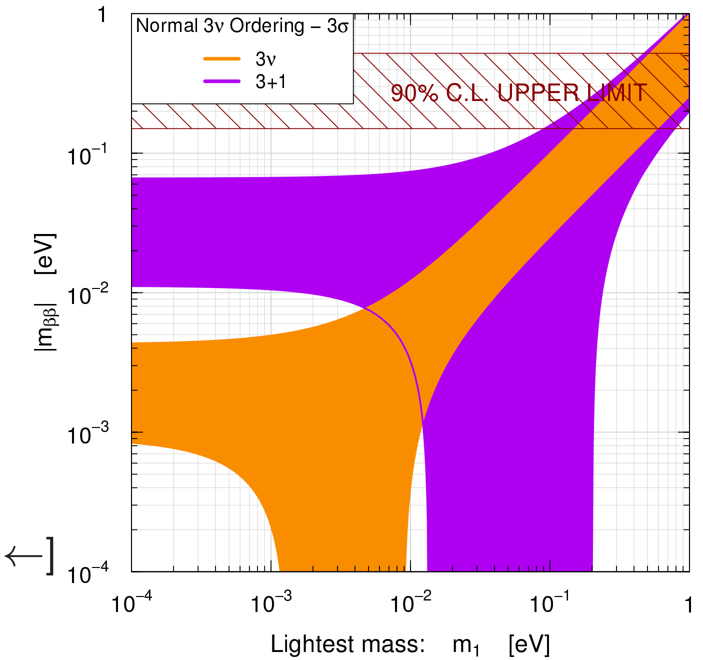
Sterile neutrinos: impact for LNV observables

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

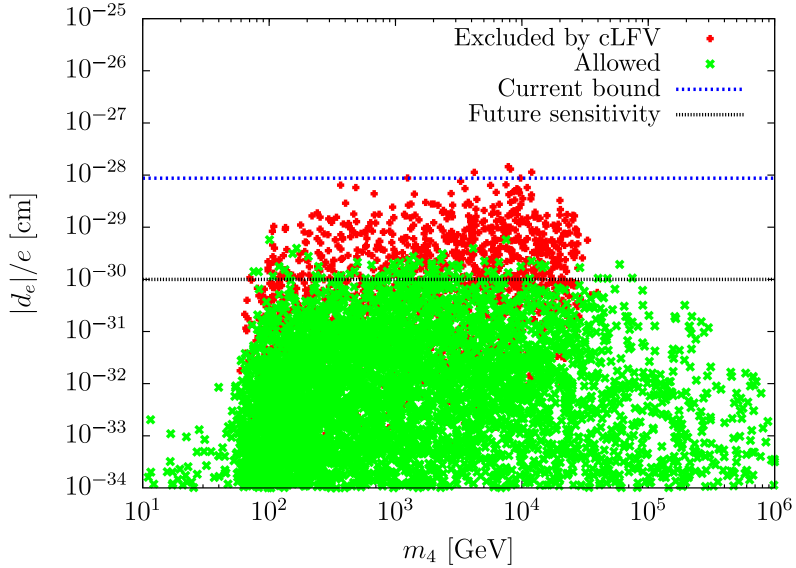
    $\Rightarrow$ **augmented ranges** for effective mass *(IO and NO)*
  - **Observation of $0\nu2\beta$ signal** in future experiments

    does not imply Inverted Ordering for light νs

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



- **LNV & Leptonic CPV: electric dipole moments**



- Majorana (and Dirac) phases $\Rightarrow$ **lepton EDMs**
- **Non-vanishing** contributions: at least **two sterile ν**

  Dominant **Majorana contribution!**
- $|d_e|/e \geq 10^{-30}$ **cm** for $m_{\nu_{4,5}} \sim$ **[100 GeV, 100 TeV]**
- **EDM observation:** Majorana CPV neutrinos?

[Abada and Toma, '15]

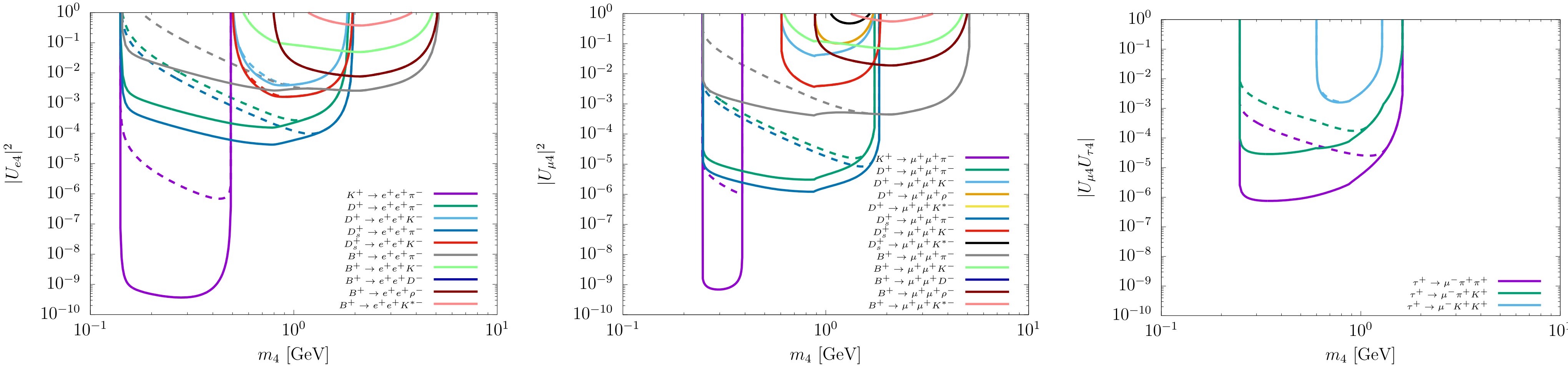
Sterile neutrinos: impact for LNV meson and tau decays

- **On-shell ν_s: “resonant-enhancement”** of $M_1 \to M_2 \ell_\alpha^\pm \ell_\beta^\pm$ and $\tau^\pm \to M_1 M_2 \ell^\mp$ decays

- **Experimental searches:** strong constraints on ν_s **parameter space!**

  Bounds from BaBar, Belle, LHCb; near future - LHCb, Belle II, BES-III, NA62...

- Full update of **LNV constraints** on ν_s ($[0.1\text{ GeV}, 10\text{ GeV}]$) [1712.03984]



- **Prospects for observation:**

  $\Rightarrow$ ν_s must **decay inside the detector** (sufficiently short-lived)

  $\Rightarrow$ **Sizeable $\#_{\text{events}}$: BRs $\sim \mathcal{O}(10^{-8,-10})$**

  } **Non-negligible mixings!**

$$N_{B\to\ell_\alpha\ell_\beta M} \approx \mathcal{L}^{\text{int}} \times \sigma^{\text{prod}}(pp \to B^+ + X) \times \text{BR}(B^+ \to \ell_\alpha^+ \ell_\beta^+ M^-) \times \mathcal{D}$$

Sterile neutrinos: impact for LNV meson and tau decays

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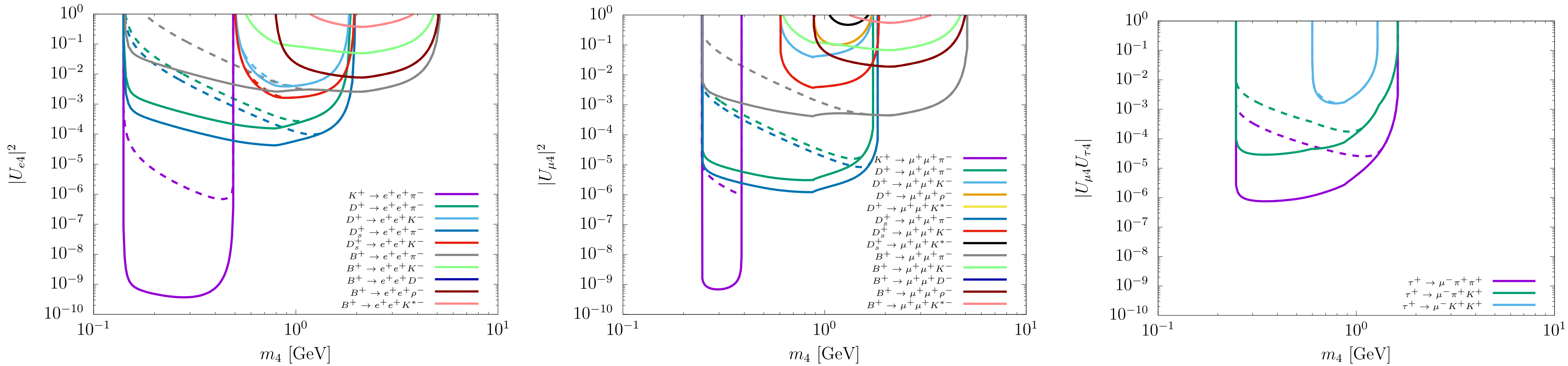


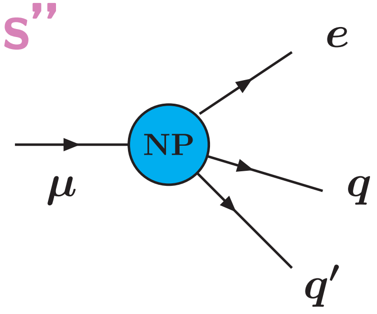
- **Prospects for observation:**

- BRs of **several LNV meson and tau decays** close to **current sensitivities**

  ⇒ Certain **τ and K LNV decay modes** already in **conflict with experimental data!**

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

Sterile neutrinos: cLFV in "muonic atoms"

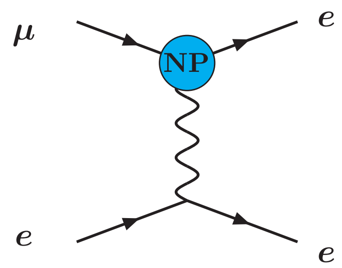


- **cLFV $\mu^- - e^-$ conversion:** $\mu^- + (A, Z) \to e^- + (A, Z)$

- **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

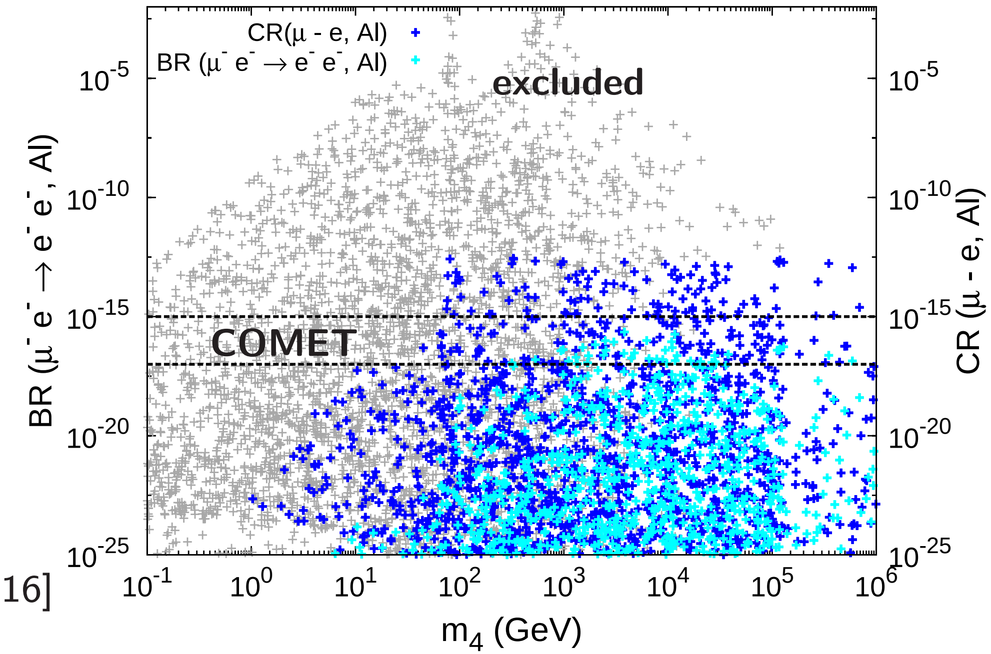
  $\mu - e$ conversion (■) in Aluminium

- 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]

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**

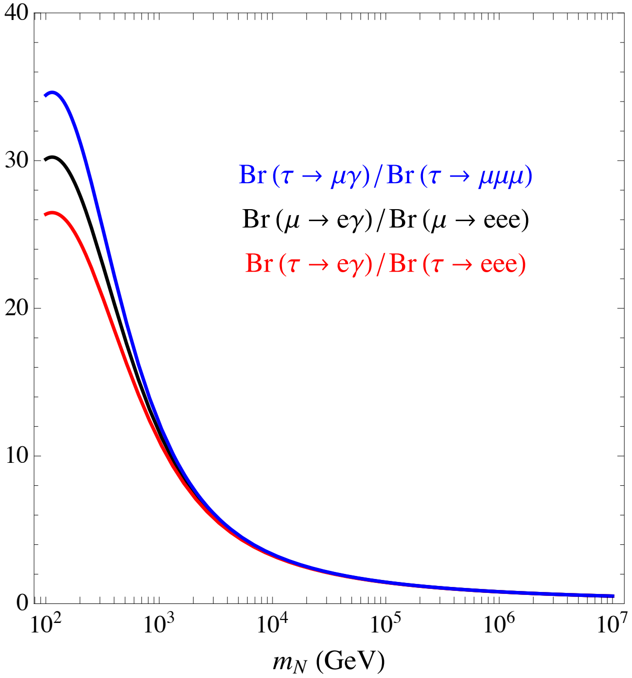
  Type I: cLFV transitions at **loop level** (radiative, 3-body, conversion in Nuclei)

  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!**

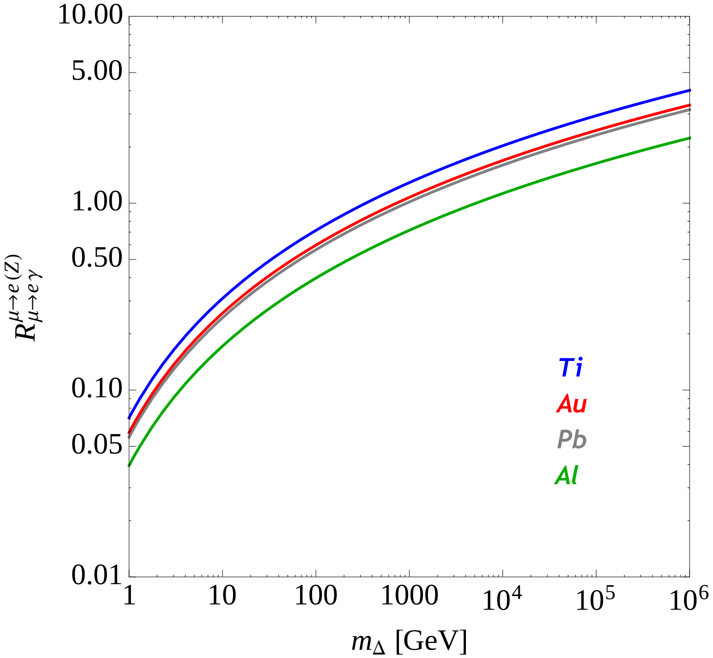
  Type III: 3-body decays and coherent conversion at tree-level! $\ell_i \to \ell_j \gamma$ @ loop...

- 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]

The "triplet" seesaws

- **cLFV bounds** on the **seesaw mediators:** a comparative ("effective") view

Type I (singlet fermion):

$$\boldsymbol{m_N} \lesssim 100\text{ TeV} \times \left(\frac{10^{-14}}{\text{BR}(\mu\to e\gamma)}\right)^{\frac{1}{4}} \times f(Y^{\nu}_{\ell_i\ell_j})$$

$$\boldsymbol{m_N} \lesssim 300\text{ TeV} \times \left(\frac{10^{-16}}{\text{BR}(\mu\to 3e)}\right)^{\frac{1}{4}} \times f(Y^{\nu}_{\ell_i\ell_j})$$

$$\boldsymbol{m_N} \lesssim 2000\text{ TeV} \times \left(\frac{10^{-18}}{\text{CR}(\mu-e,\text{ Ti})}\right)^{\frac{1}{4}} \times f(Y^{\nu}_{\ell_i\ell_j})$$

Type II (scalar triplet):

$$\boldsymbol{m_\Delta} \lesssim 70\text{ TeV} \times \left(\frac{10^{-14}}{\text{BR}(\mu\to e\gamma)}\right)^{\frac{1}{4}} \times f(Y^{\Delta}_{\ell_i\ell_j})$$

$$\boldsymbol{m_\Delta} \lesssim 2200\text{ TeV} \times \left(\frac{10^{-16}}{\text{BR}(\mu\to 3e)}\right)^{\frac{1}{4}} \times f(Y^{\Delta}_{\ell_i\ell_j})$$

$$\boldsymbol{m_\Delta} \lesssim 600\text{ TeV} \times \left(\frac{10^{-18}}{\text{CR}(\mu-e,\text{ Ti})}\right)^{\frac{1}{4}} \times f(Y^{\Delta}_{\ell_i\ell_j})$$

Type III (fermion triplet):

$$\boldsymbol{m_\Sigma} \lesssim 100\text{ TeV} \times \left(\frac{10^{-14}}{\text{BR}(\mu\to e\gamma)}\right)^{\frac{1}{4}} \times f(Y^{\Sigma}_{\ell_i\ell_j})$$

$$\boldsymbol{m_\Sigma} \lesssim 1600\text{ TeV} \times \left(\frac{10^{-16}}{\text{BR}(\mu\to 3e)}\right)^{\frac{1}{4}} \times f(Y^{\Sigma}_{\ell_i\ell_j})$$

$$\boldsymbol{m_\Sigma} \lesssim 20000\text{ TeV} \times \left(\frac{10^{-18}}{\text{CR}(\mu-e,\text{ Ti})}\right)^{\frac{1}{4}} \times f(Y^{\Sigma}_{\ell_i\ell_j})$$

$f(Y_{\ell_i\ell_j}) \sim$ combination of $\sqrt{Y}\sqrt{Y}$

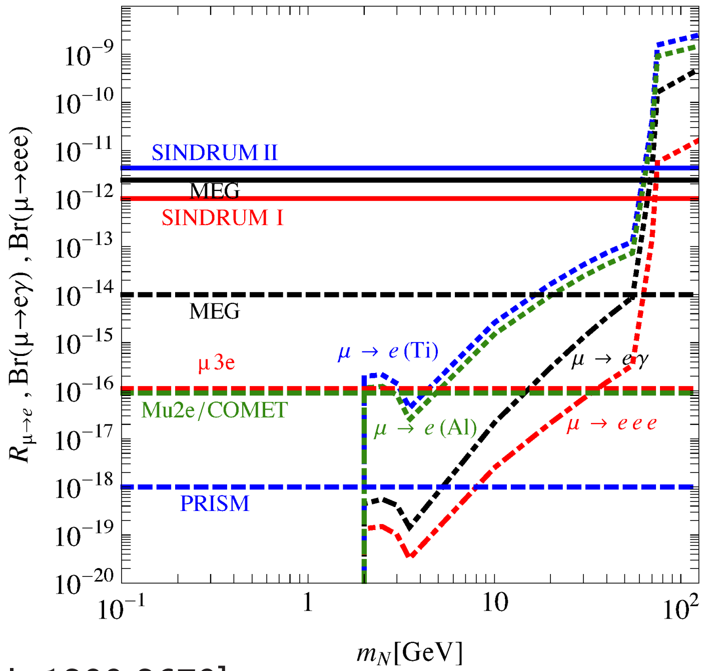
Low scale type I seesaw

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

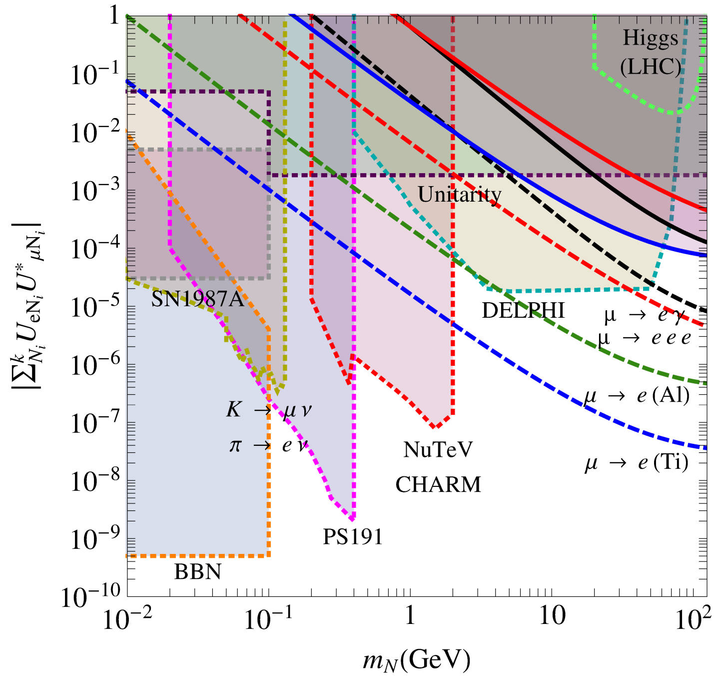
$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \quad U_{\nu\nu} \approx (1-\varepsilon)\, U_{\text{PMNS}}$$

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]



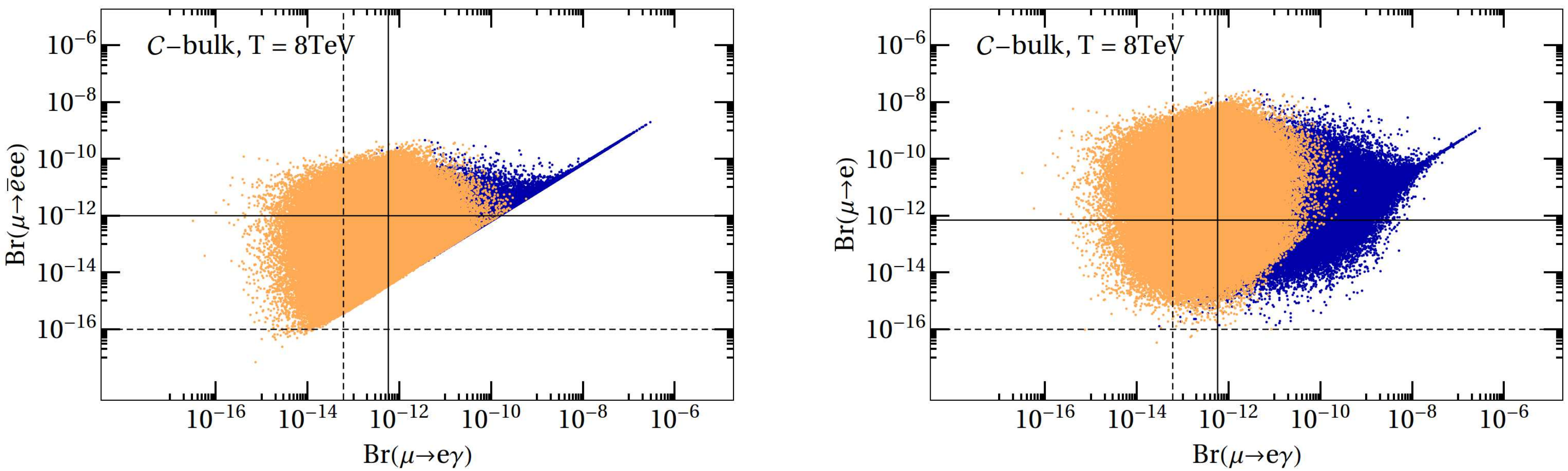
(see also Dinh et al, '12-'14)

Geometric cLFV: RS warped extra dimensions

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

Geometrical distribution in bulk: **Yukawa hierarchy** for **"anarchic" $\mathcal{O}(1)$ couplings!**

▶ **Custodially protected model**; **generic anarchic Yukawa couplings**



[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:** $T_{\mathsf{KK}} \gtrsim 4$ **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)

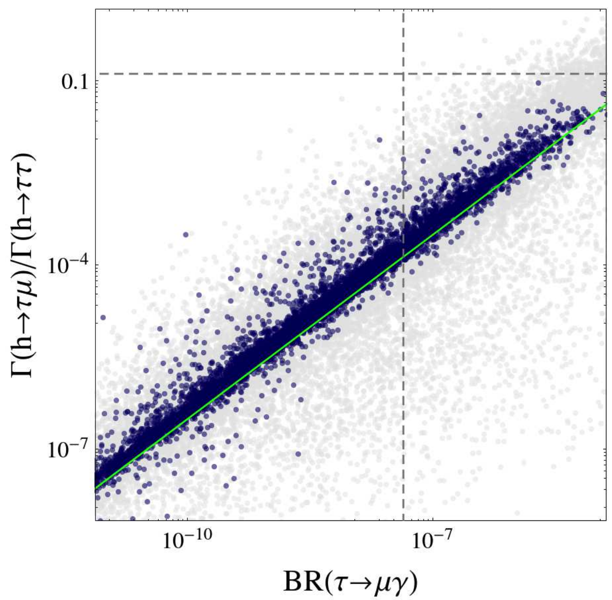
Vector-like leptons: an example

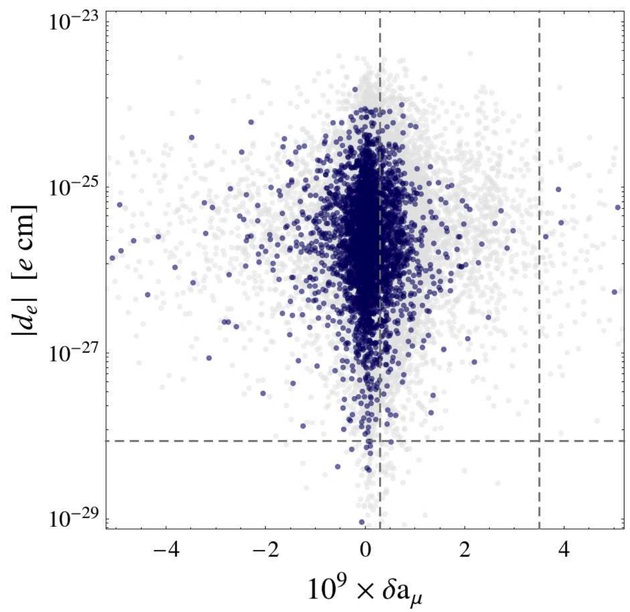
- **Massive vector-like fermions** present in **well-motivated SM extensions:**
  composite Higgs models, warped extra dimensions, ...

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

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

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





[Falkowski et al, '14]

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