Synergy and complementarity between neutrino physics and high-intensity frontiers

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Neutrino oscillations: gateway to new physics

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

  ⇒ **SM must be clearly extended** (or embedded in a larger framework)!

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

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

  [⇝ presentations by A. De Gouvea, P. Hernandez, S. Antusch, A. Boyarski, ...]

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

Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

Neutrino oscillations: gateway to new physics

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  [⇝ presentations by A. De Gouvea, P. Hernandez, S. Antusch, A. Boyarski, P. Paradisi, ...]

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

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

  Lepton flavour universality violation - weak boson and meson decays.. **(e.g. R_K)**

  Electric dipole moments and **Anomalous magnetic moments**

  Charged lepton flavour violation

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

  ⇒ Learn about **neutrino mass models!** (At least **probe and disfavour...**)

Brief summary

- **Leptonic high-intensity observables: signs of New Physics**
- **Observables and experimental status**

  Lepton number violation (observables at high and low energies)

  Charged lepton flavour violation

  CP violation: Electric dipole moments

  Further observables
- **Model-independent approaches to New Physics**
- **Models of neutrino mass generation: signals at high-intensities**

  Ad-hoc extensions

  Seesaw realisations

  Larger frameworks
- **Overview & discussion**

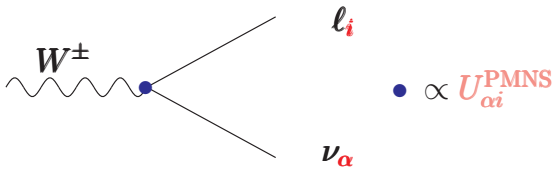
Leptonic observables: signs of New Physics

- 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 $\nu_\alpha \leftrightsquigarrow \nu_\beta$

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

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

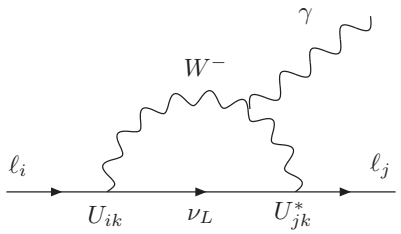


$m_\nu \neq 0$

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

- 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

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...)

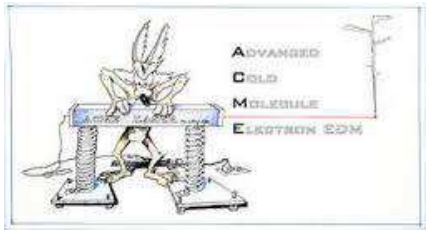
▶ Leptonic observables: current status

[$\rightsquigarrow$ WG4 presentations and reviews, Monday-Friday!]

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
$\lvert d_e \rvert$	8.7×10^{-29} [ACME]	$\mathcal{O}(10^{-30})$ [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** $\vec{\mu} = g_\ell \frac{e}{2\, m_\ell} \vec{S} \Rightarrow a_\ell = \frac{1}{2}(g_\ell - 2)$

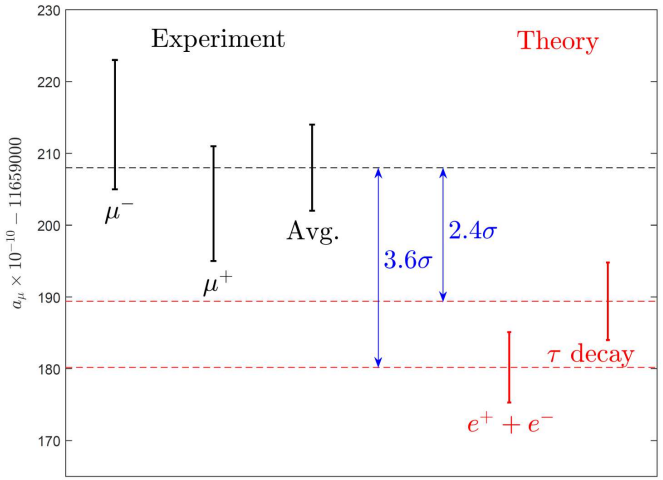
a_e : Best **determination of α...**

$$a_e^{\text{the}} = 0.00115965218164 3(764) \leftrightsquigarrow 5^{\text{th}} \text{ order in QED (12,672 diags)!}$$
$$a_e^{\text{exp}} = 0.00115965218073(28)$$

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!



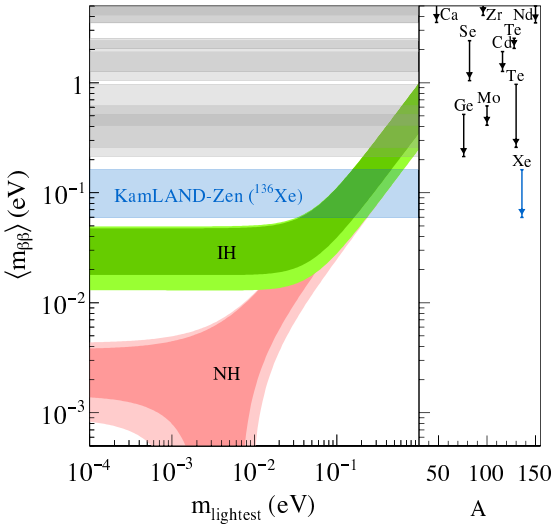
a_τ : Short **tau lifetime...**

$$a_\tau^{\text{the}} = 0.00117721(5) \text{ [0701260]}$$
$$-0.007 < a_\tau^{\text{exp}} < 0.005 \text{ [1601.07987]}$$

[0801.1134]

Lepton number violation: $\Delta L = 2$ observables and searches

▶ Neutrinoless double beta decays



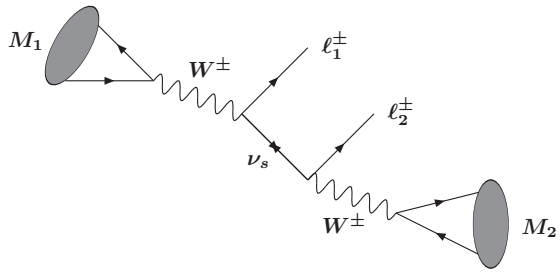
[KamLAND-Zen, '15]

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}

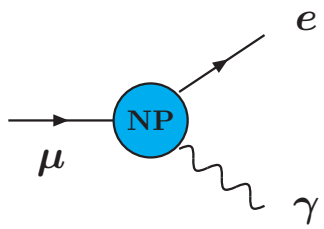
LNV decay	Current Bound	
	$\ell = e$	$\ell = \mu$
$\tau^- \to \ell^+ \pi^- \pi^-$	2.0×10^{-8}	3.9×10^{-8}
$\tau^- \to \ell^+ \pi^- K^-$	3.2×10^{-8}	4.8×10^{-8}
$\tau^- \to \ell^+ K^- K^-$	3.3×10^{-8}	4.7×10^{-8}



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 (also LNV!), Muonium channels...

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

  cLFV & Lepton Number violating decays - $B \to D e^- \mu^-, \ldots$

  violation of lepton flavour universality (e.g. R_K)

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

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

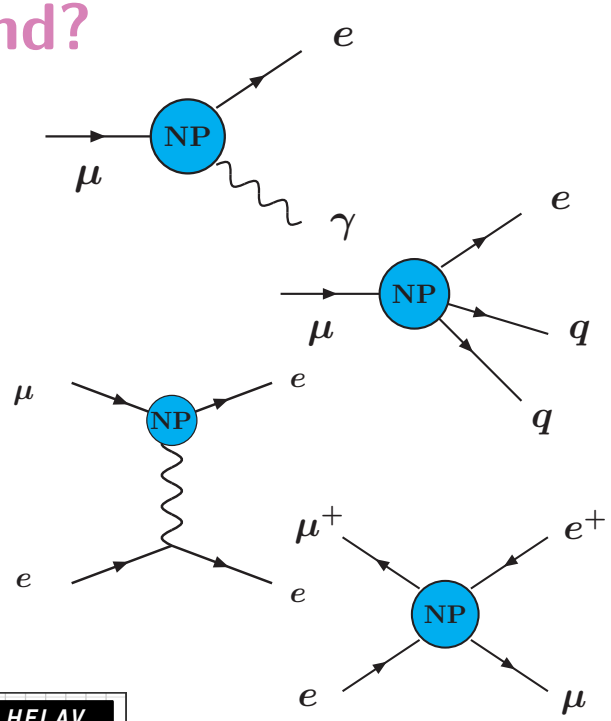
  SUSY $\tilde{\ell}_i \to \ell_j \chi^0$; FV KK-excitation decays; ...

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

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

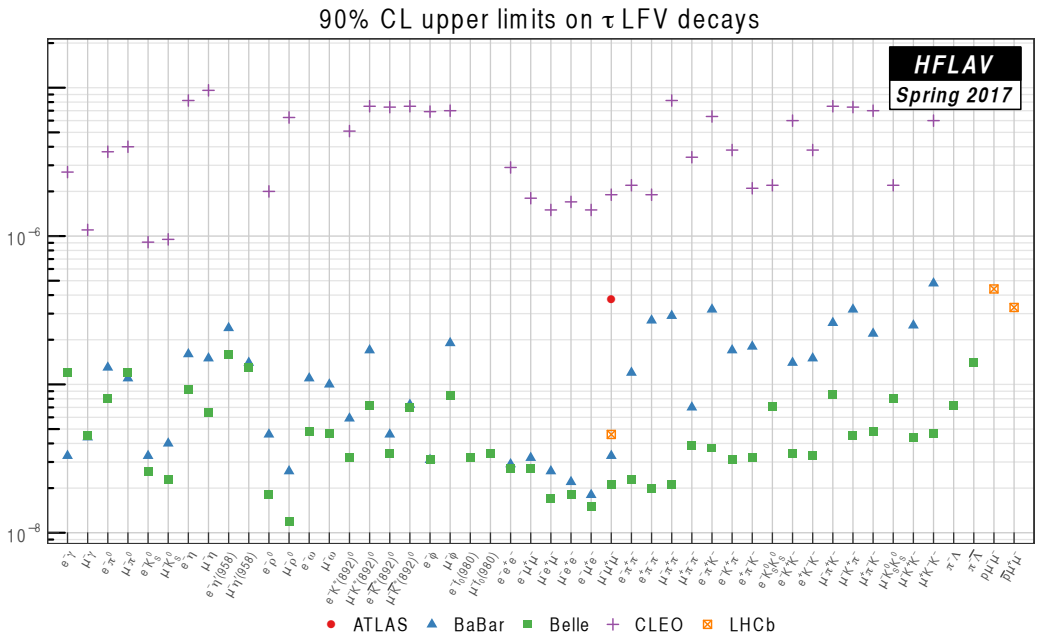
Searches for cLFV: where do we stand?

Observable	Bound (90% C.L.)	future sensitivity
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13}	4×10^{-14} [MEG II]
$\mathrm{BR}(\mu \to 3e)$	1.0×10^{-12}	10^{-15} [Mu3e Phase I]
$\mathrm{BR}(\mu - e,\mathrm{N})$	7×10^{-13} (Au)	10^{-14} [SiC, DeeMe] 10^{-17} [Al, Mu2e/COMET]
$\mathrm{BR}(\mu^- e^- \to e^- e^-)$	—	10^{-17} [Al, COMET ?]
$\mathrm{P}(\mathrm{Mu} - \overline{\mathrm{Mu}})$	8.3×10^{-11}	10^{-14} [FNAL ?]



[⇝ Y. Ulrich (NLO!)]

[⇝ See WG4 contributions Monday-Friday!]



Further bounds: $\mathrm{BR}(Z \to \ell_i \ell_j)$, ..., $\mathrm{BR}(K, D, B \to (h)\, \ell_i \ell_j)$, ... [⇝ **presentation by R. Bernstein!]**

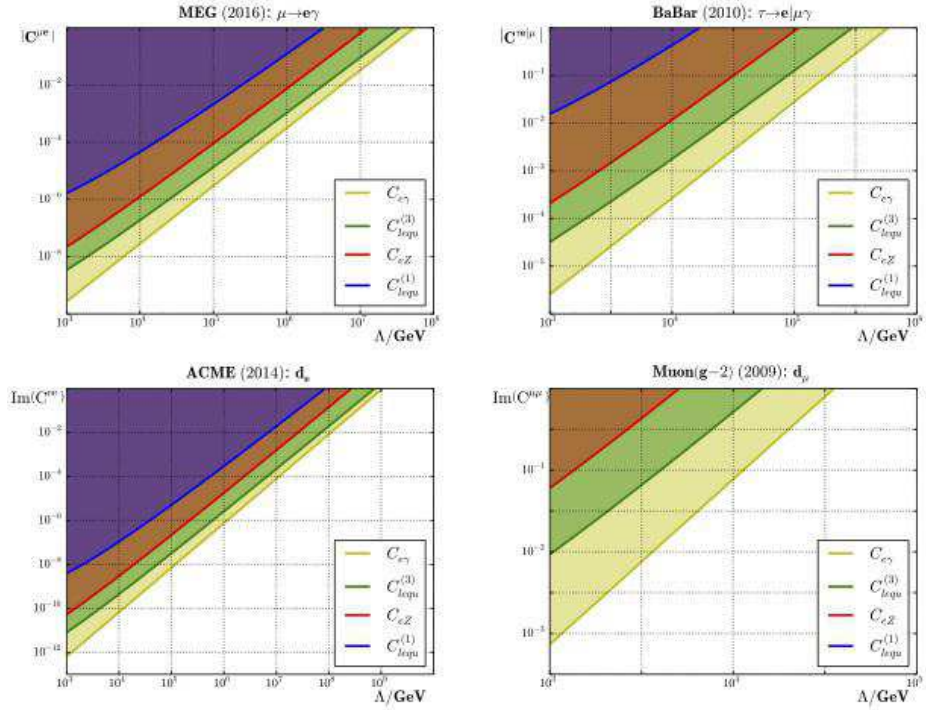
▶ Model independent approach

Neutrinoless radiative decay

$$\mathrm{Br}\,(\mu \to e\gamma) = \frac{\alpha_e m_\mu^5}{\Lambda^4 \Gamma_\mu} \left(\left| C_L^D \right|^2 + \left| C_R^D \right|^2 \right) .$$

Neutrinoless three-body decay

$$\begin{aligned} \mathrm{Br}(\mu \to 3e) &= \frac{\alpha_e^2 m_\mu^5}{12\pi \Lambda^4 \Gamma_\mu} \left(\left| C_L^D \right|^2 + \left| C_R^D \right|^2 \right) \left(8 \log \left[\frac{m_\mu}{m_e} \right] - 11 \right) \\ &+ \frac{m_\mu^5}{3(16\pi)^3 \Lambda^4 \Gamma_\mu} \Big(\left| C_{ee}^{S\,LL} \right|^2 + 16 \left| C_{ee}^{V\,LL} \right|^2 + 8 \left| C_{ee}^{V\,LR} \right|^2 \\ &\qquad + \left| C_{ee}^{S\,RR} \right|^2 + 16 \left| C_{ee}^{V\,RR} \right|^2 + 8 \left| C_{ee}^{V\,RL} \right|^2 \Big) . \end{aligned}$$



[⇝ presentation by G. M. Pruna]

- **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**

  Models of ν-mass generation - **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 $\quad n_L = U_{4\times4}\, \nu_i$

  $U_{4\times4}^T\, M\, U_{4\times4} = \text{diag}(m_{\nu_1}, ..., m_{\nu_4})$ $\quad$ "**Majorana** mass": $\mathcal{L}_{\text{toy}} \sim n_L^T C M n_L$

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

  rectangular matrix $\leftarrow \mathbf{U} = U|_{3\times4}$

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

  3×3 sub-block, non-unitary!

$$U_{4\times4} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- **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)]

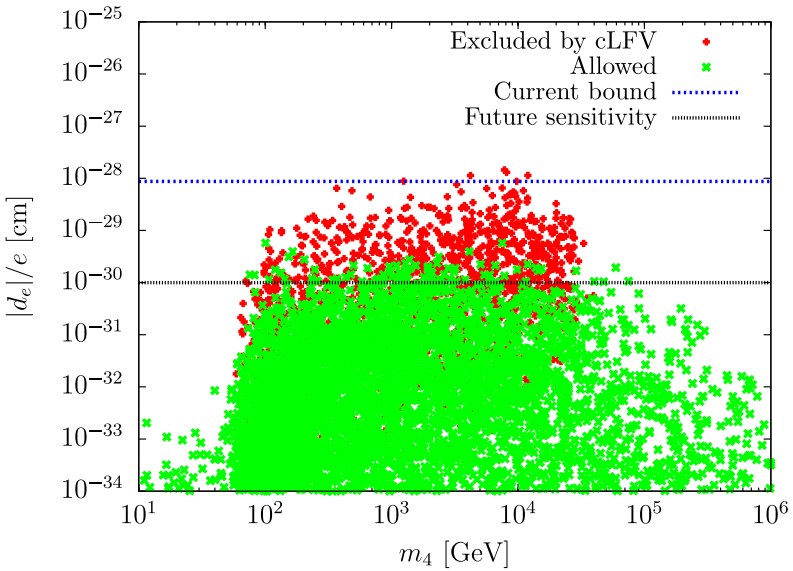
- **Modified charged ($W^\pm$) and neutral (Z^0) current interactions:**

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

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

Sterile neutrinos: impact for lepton properties

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



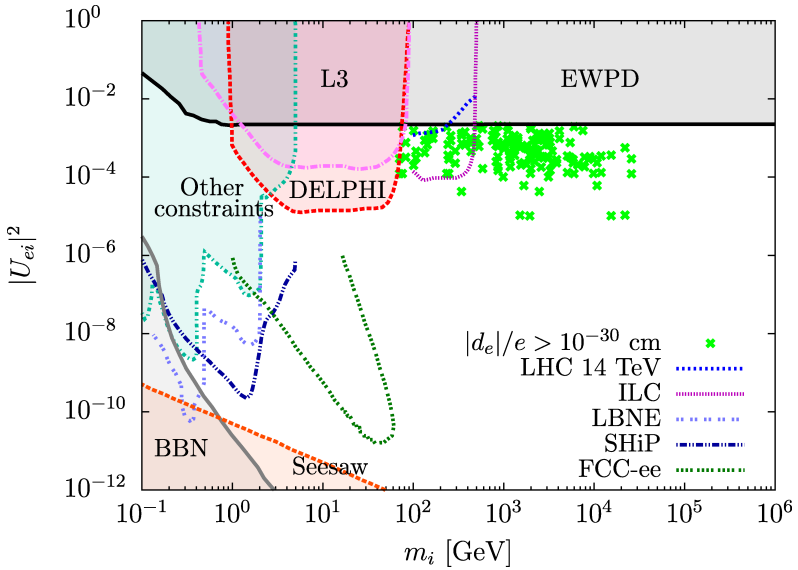
- **Majorana (and Dirac) phases** ⇒ **lepton EDMs**
- **Non-vanishing** contributions: at least **two sterile ν**
- $|d_e|/e \geq 10^{-30}$ **cm** for $m_{\nu_{4,5}} \sim$ [100 GeV, 100 TeV]

[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...



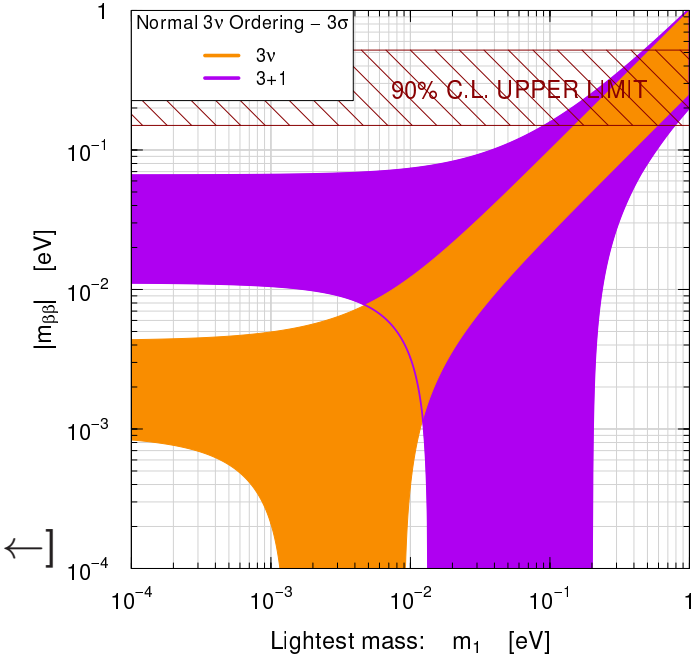
Sterile neutrinos: impact for LNV observables

- **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 $\leftarrow$]

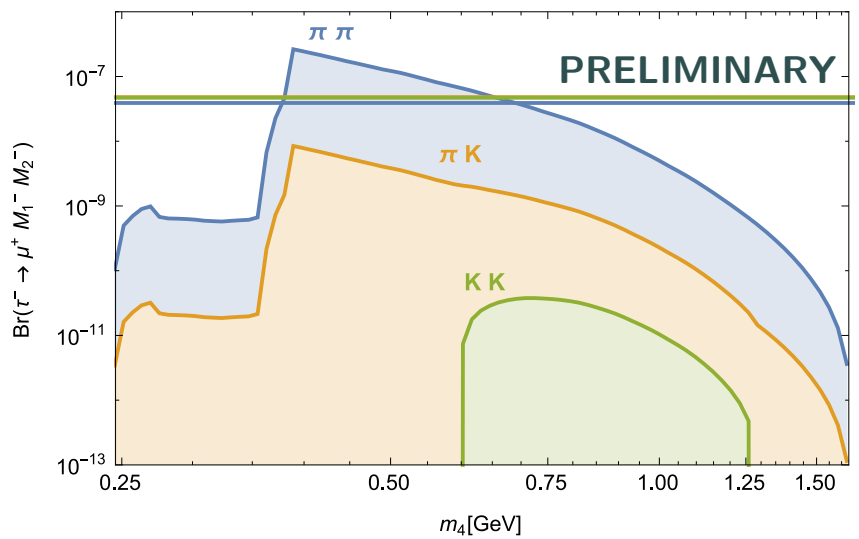


- **Lepton Number Violation in meson and τ decays**
  - **If ν_s produced on-shell,**

    resonant enhancement of **LNV decays**

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

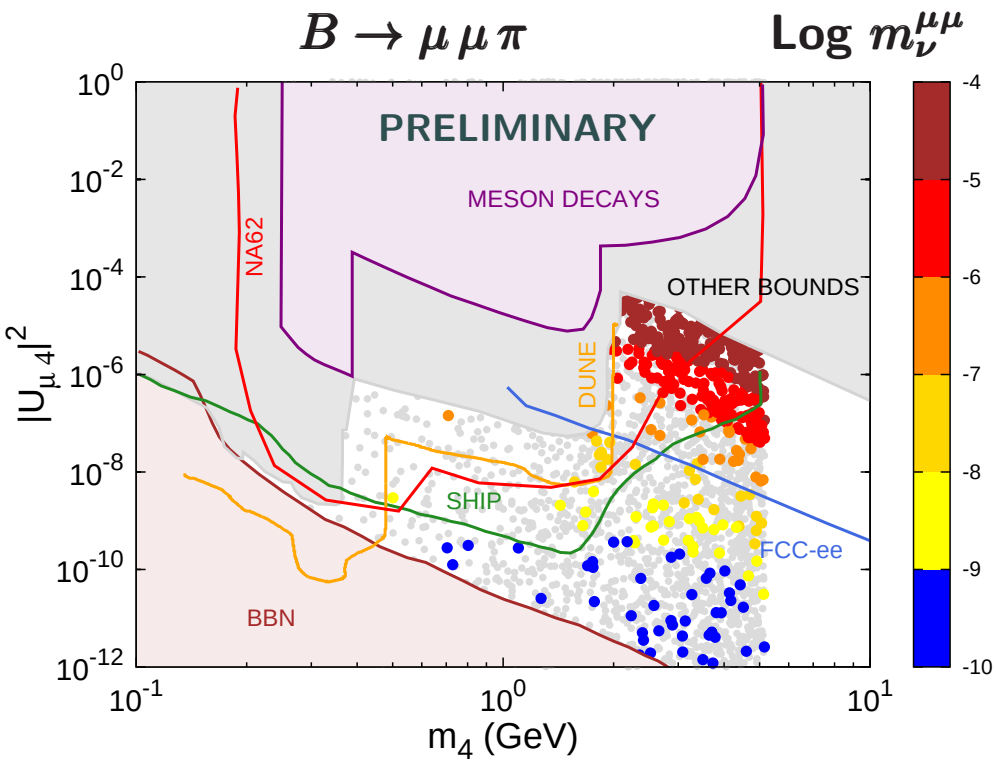
    [Abada, De Romeri, Lucente, Toma, AMT, to appear]

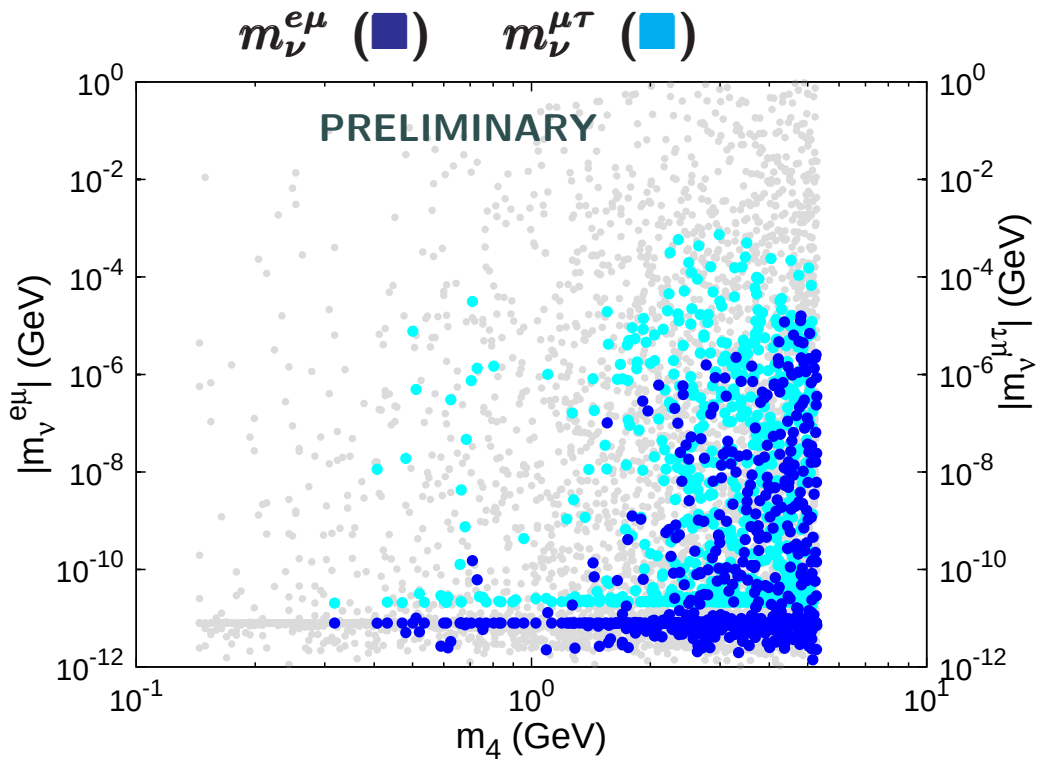


Sterile neutrinos: impact for LNV meson and tau decays

- In addition to **further constraining** the **active-sterile mixings** **[future sensitivities...]**
- **LNV meson and tau decays** offer possibility to **infer information** on $m_\nu^{\ell_i \ell_j}$

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

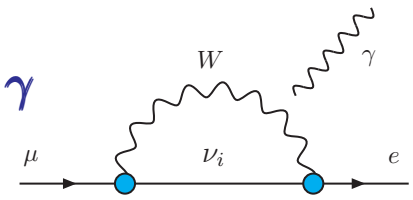




[Abada, De Romeri, Lucente, Toma, AMT, to appear]

ν_s and cLFV: radiative and 3 body decays

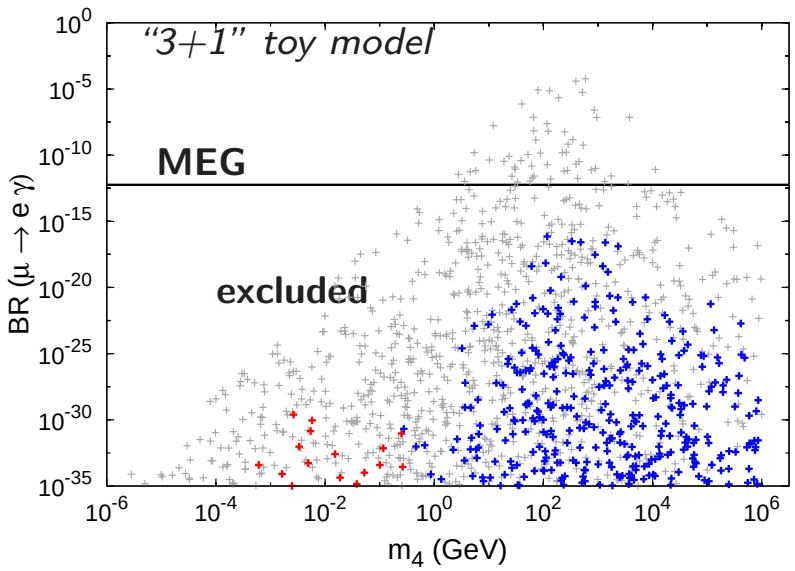
- **Radiative decays: $\ell_i \to \ell_j \gamma$**



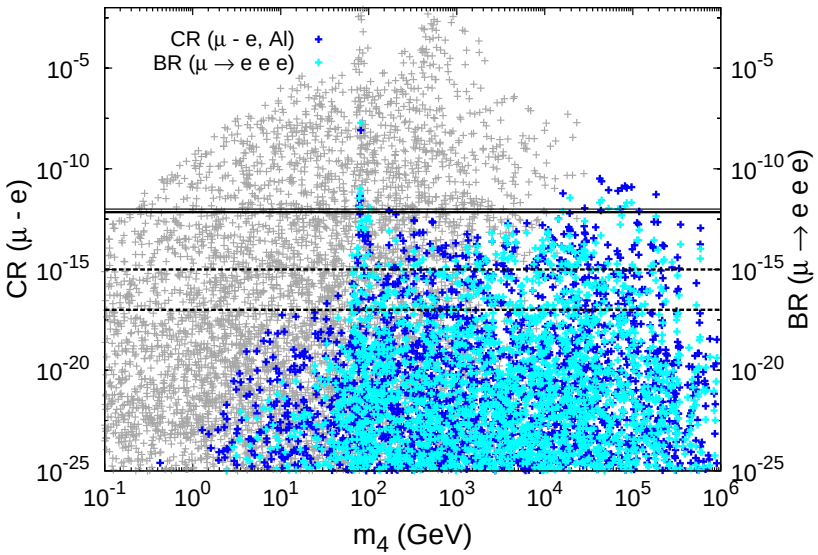
  - Consider $\mu \to e\gamma$
  - For $m_4 \gtrsim 10$ GeV sizable ν_s contributions

    .. but precluded by other cLFV observables

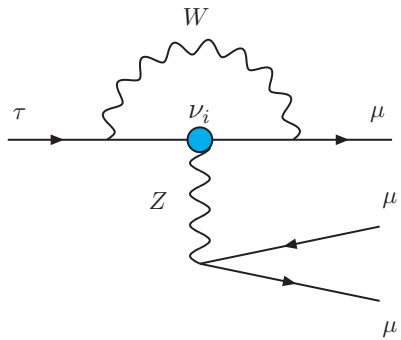
    as 3-body decays and nuclear conversion



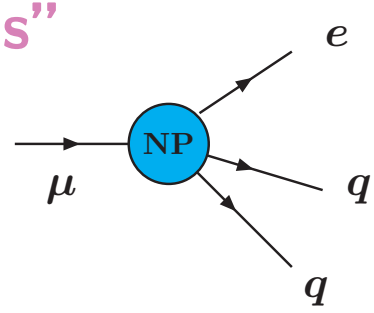
- **Three-body decays $\ell_i \to 3\ell_j$ (■) and conversion in Nuclei $\mu - e$ (■)**



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



Sterile neutrinos: cLFV in "muonic atoms"

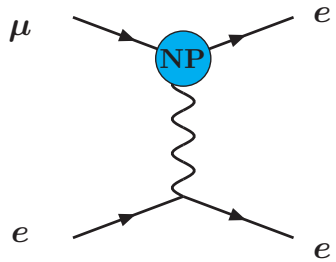


- **cLFV $\mu^- - e^-$ conversion:** $\mu^- + (A, Z) \to e^- + (A, Z)$

- **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]



[⇝ presentation by J. Sato]

- **cLFV in muonic atoms from ν_s:**

  $\mu^- e^- \to e^- e^-$ (■) vs

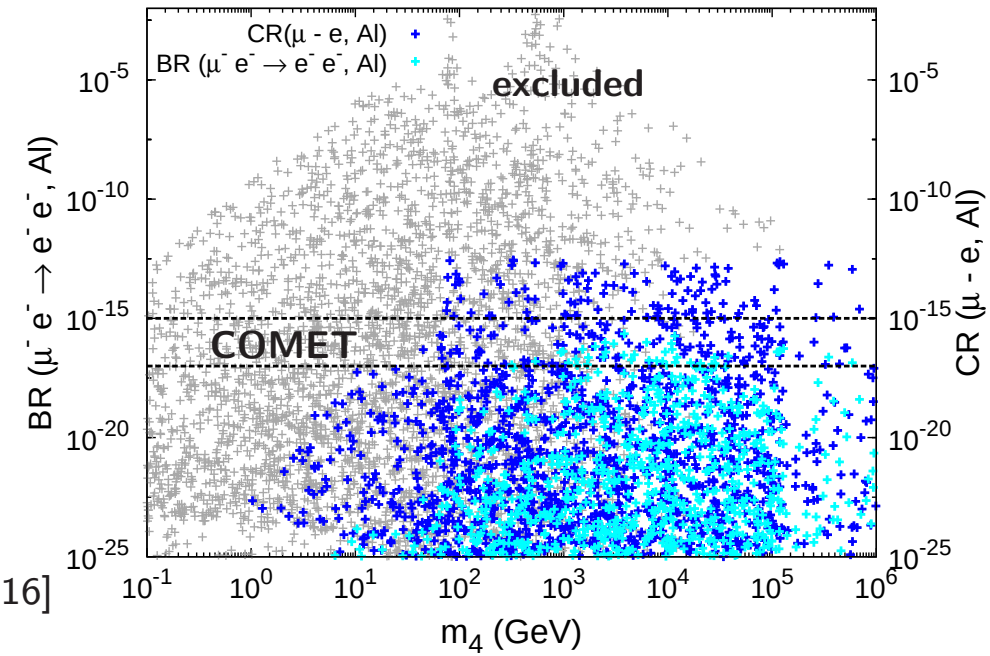
  $\mu - e$ **conversion** (■) in Aluminium

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

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

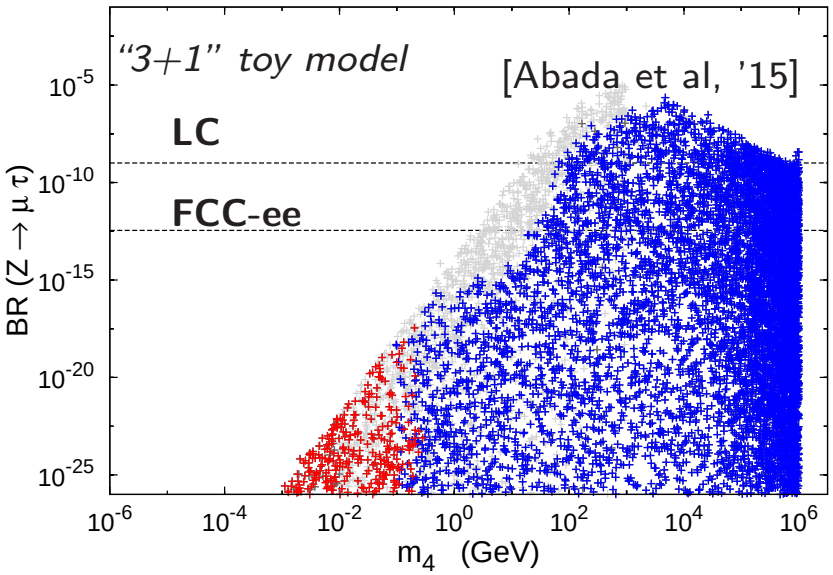
  BR($\mu^- e^- \to e^- e^-$)

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

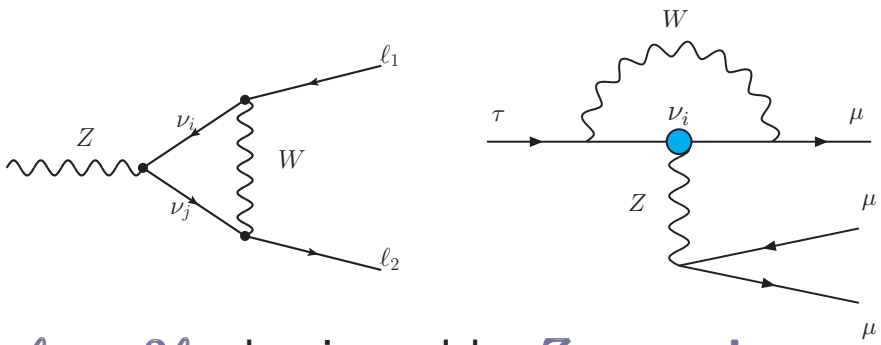


Sterile neutrinos and cLFV at higher energies

- **cLFV Z decays at FCC-ee vs 3 body decays $\ell_i \to 3\ell_j$** [⇝ presentation by S. Antusch]

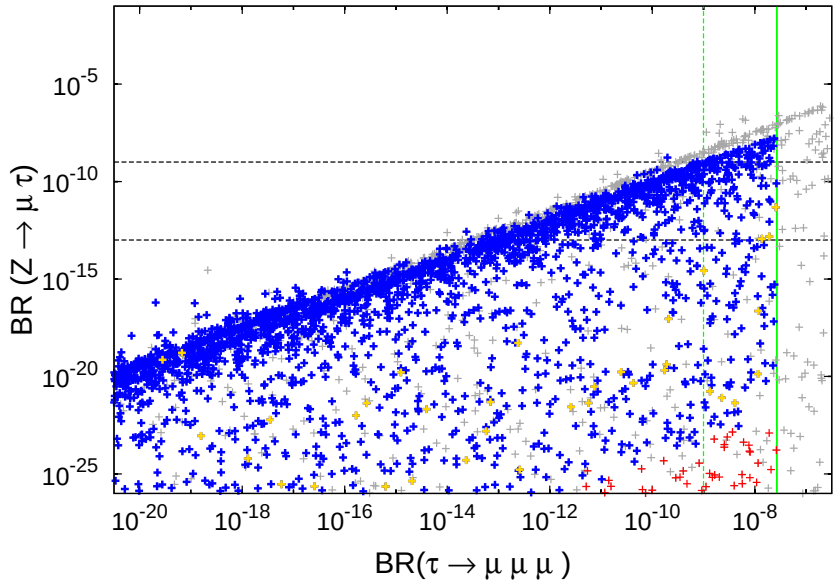


- Potentially **observable** at **Future Circular Collider**



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

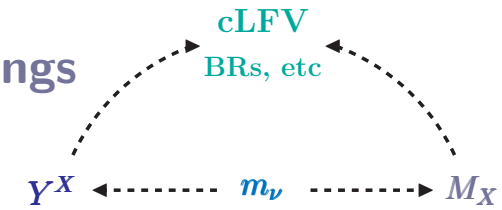
- Strong correlation between $Z \to \mu\tau$ and $\tau \to 3\,\mu$
- **Probe $\mu - \tau$ cLFV** beyond **SuperB reach**
- **Complementarity probes** of ν_s **cLFV** at **low- and high energies!**

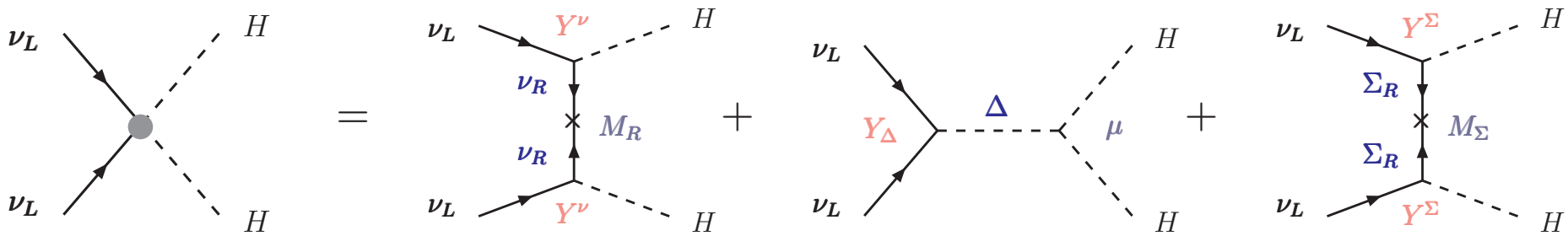


- **Models of neutrino mass generation**

The seesaw mechanism

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





$\frac{1}{\Lambda} L\,L\,H\,H$	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)

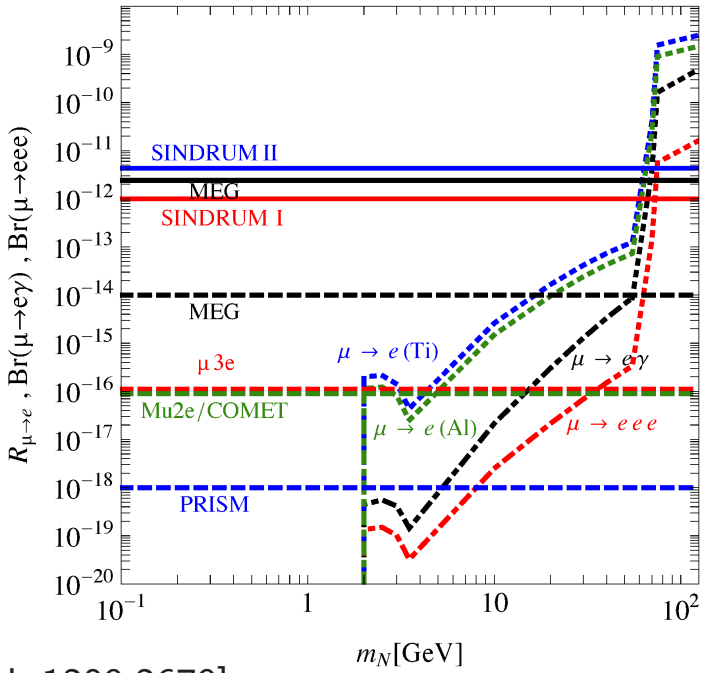
Low scale type I seesaw

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

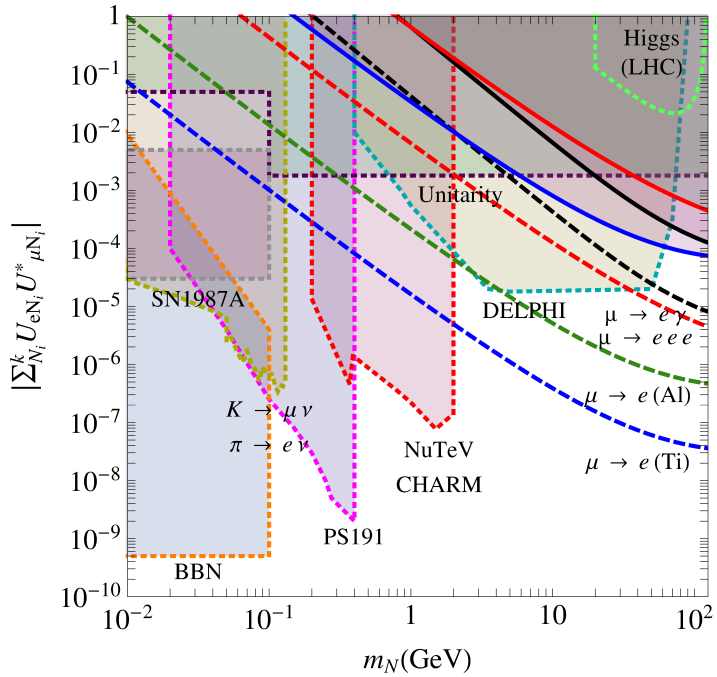
$$U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \qquad U_{\nu\nu} \approx (1-\varepsilon)\, U_{\text{PMNS}}$$

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!



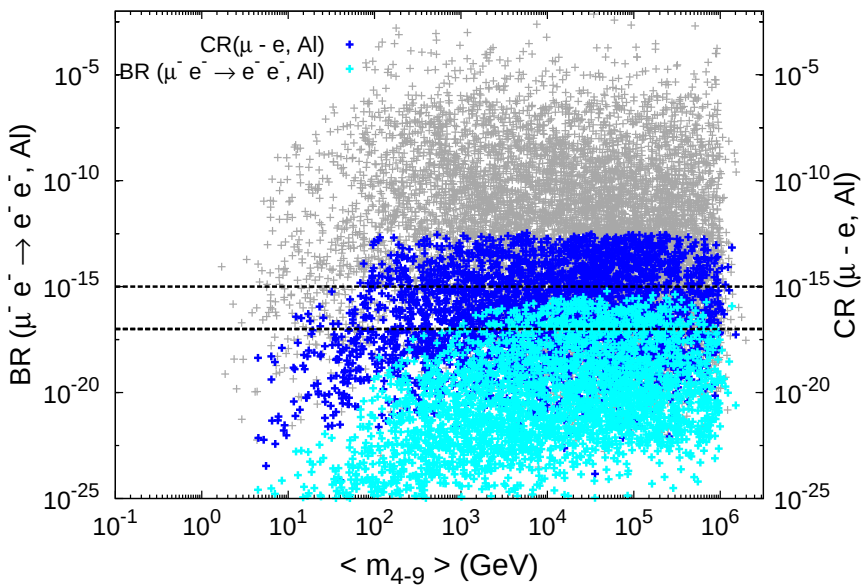
[Alonso et al, 1209.2679]

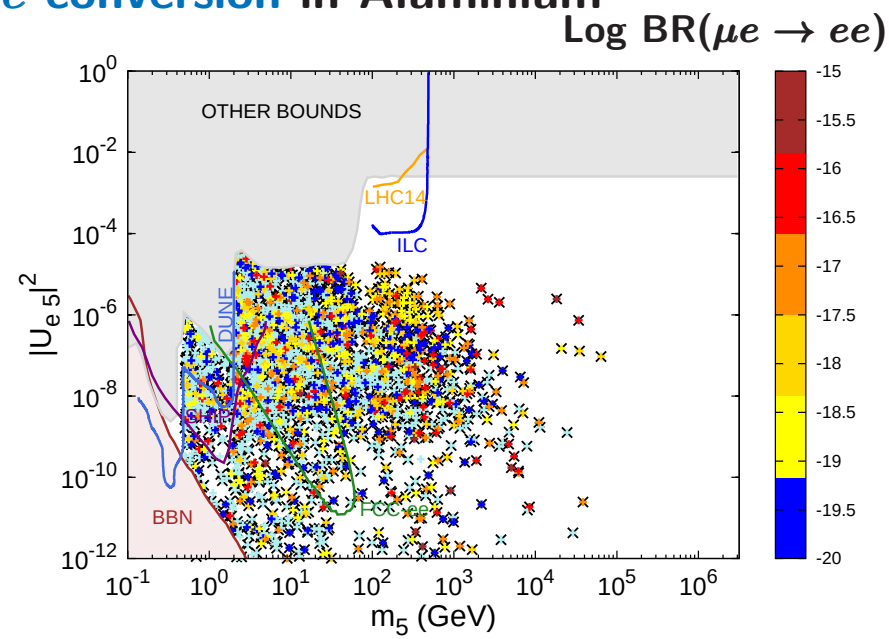


(see also Dinh et al, '12-'14)

Low scale: Inverse Seesaw (ISS)

- Addition of **3 "heavy" RH** neutrinos and **3 extra "sterile" fermions X** to the SM
- $\mathcal{M}_{\rm ISS}^{9\times 9} = \begin{pmatrix} 0 & Y_\nu v & 0 \\ Y_\nu^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix} \Rightarrow \begin{cases} \textbf{3 light } \nu : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2}\mu_X \\ \textbf{3 pseudo-Dirac pairs} : m_{N^\pm} \approx M_R \pm \mu_X \end{cases}$
- **Non-unitarity $\tilde{U}_{\rm PMNS}$ $\Rightarrow$ modified neutral and charged leptonic currents**
- **New (virtual) states & modified couplings: cLFV,** non-universality, signals at colliders!
- **cLFV in muonic atoms: $\mu^- e^- \to e^- e^-$ vs $\mu - e$ conversion in Aluminium**

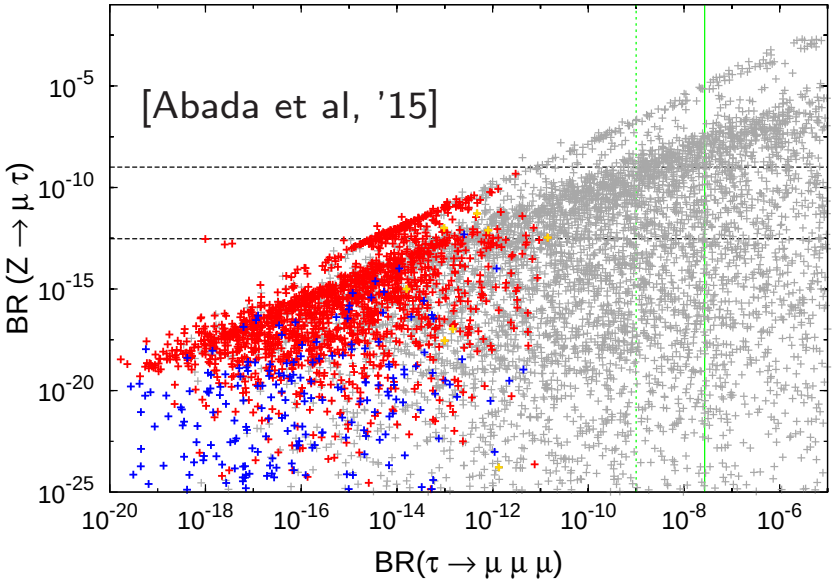




[Abada, DeRomeri, AMT, '15]

Low scale: Inverse Seesaw (ISS)

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



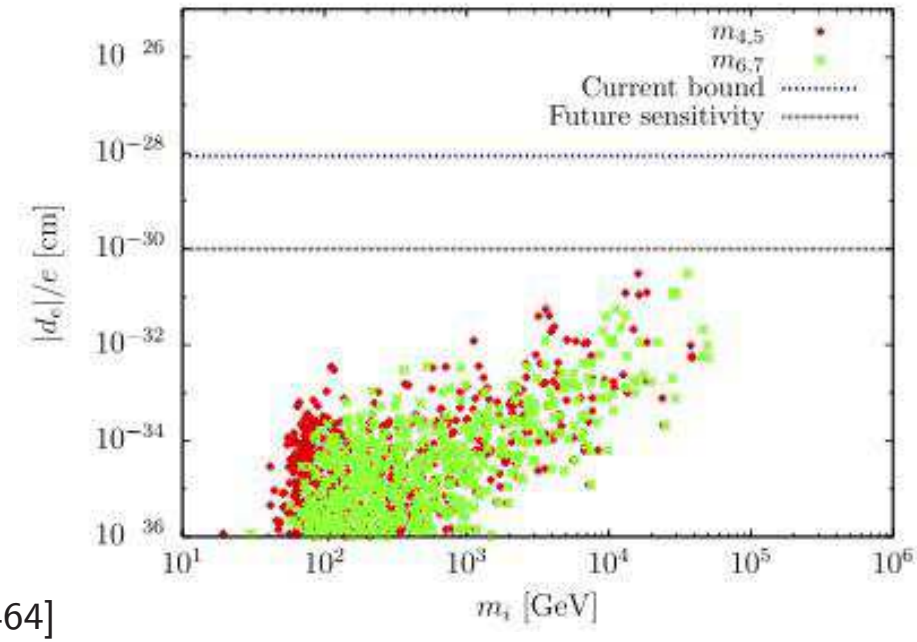
- Still dominated by Z **penguin** contributions
- Other **cLFV bounds preclude large BR($\tau \to 3\mu$)...**

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

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

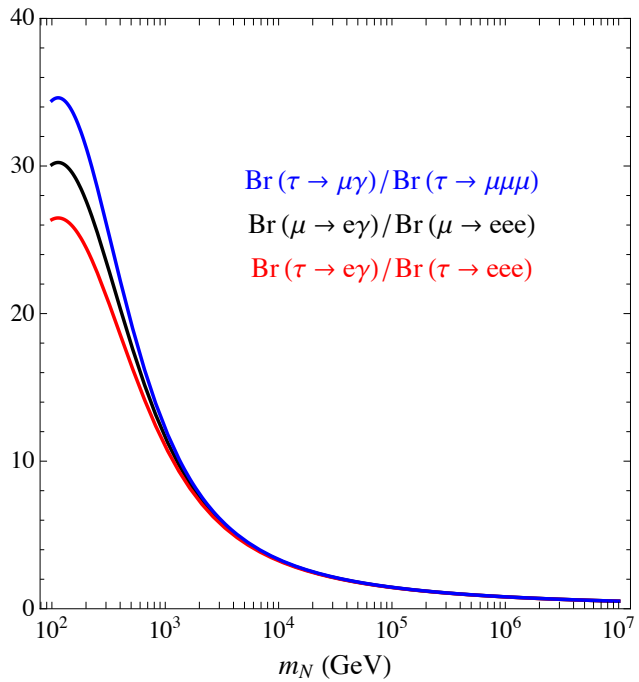
  Type I: cLFV transitions at **loop level** (radiative, 3-body, conversion in Nuclei)

  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!**

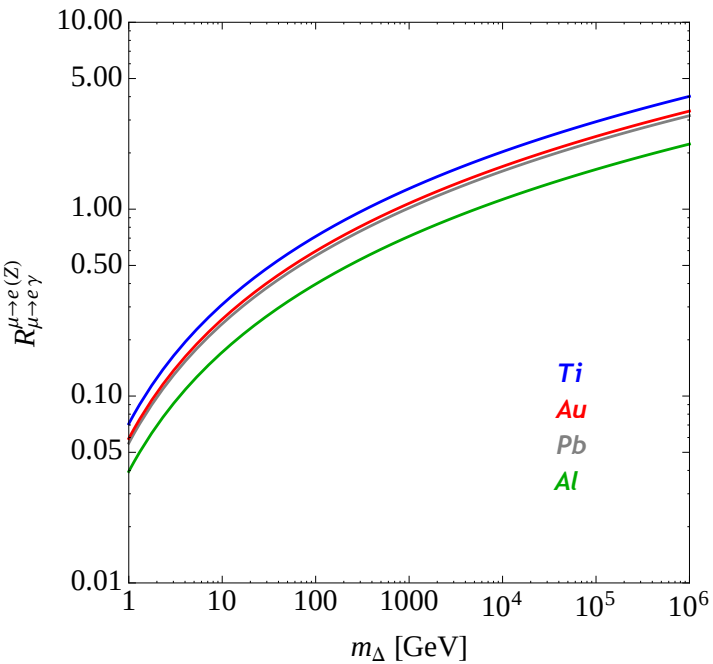
  Type III: 3-body decays and coherent conversion at tree-level! $\ell_i \to \ell_j \gamma$ @ loop...

- 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]

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):**

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

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

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

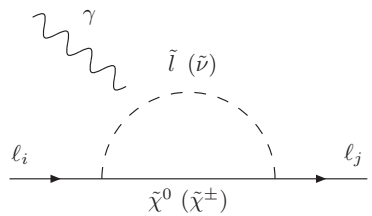
$f(Y_{\ell_i\ell_j}) \sim$ combination of $\sqrt{Y}\sqrt{Y}$

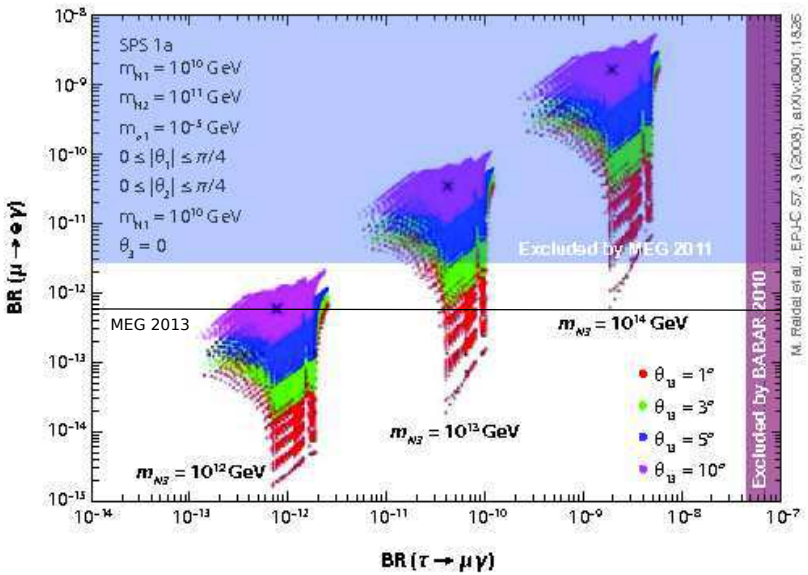
- **Embedding the seesaw in larger frameworks**

Supersymmetric type I seesaw

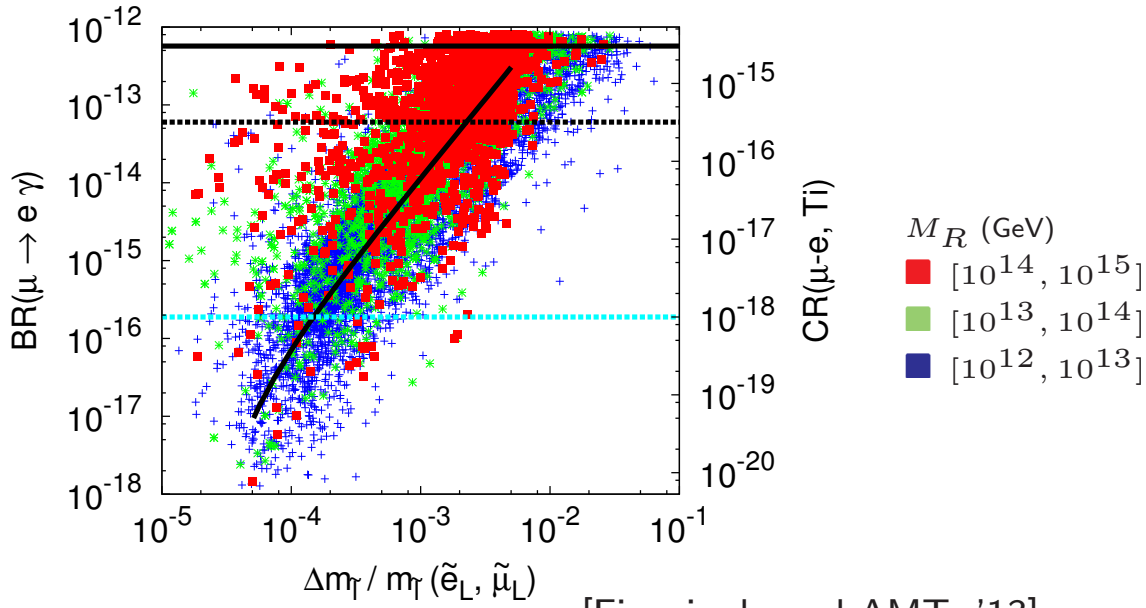
- **Large Y^ν: sizable contributions to cLFV observables**

  cLFV driven by the exchange of *virtual* **SUSY particles**





[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**

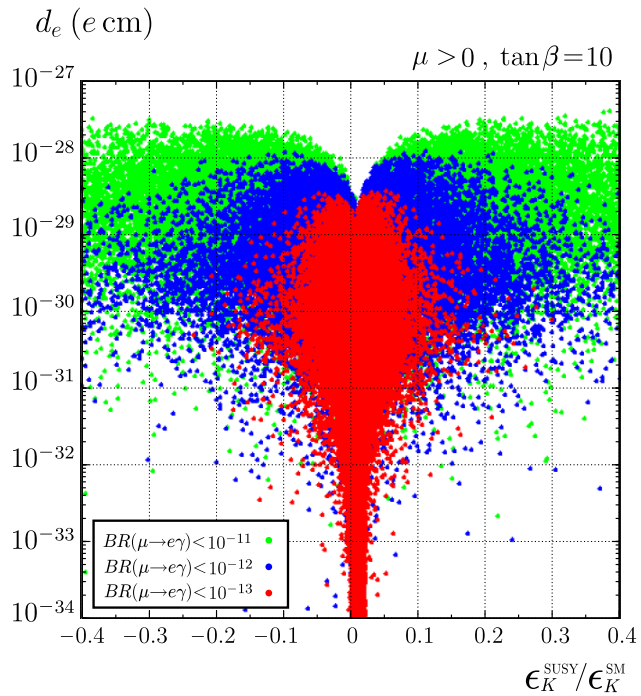
- **Reduce arbitrariness of Y^q, Y^ℓ, Y^ν, ...:** $\Rightarrow$ increase predictivity and testability!

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

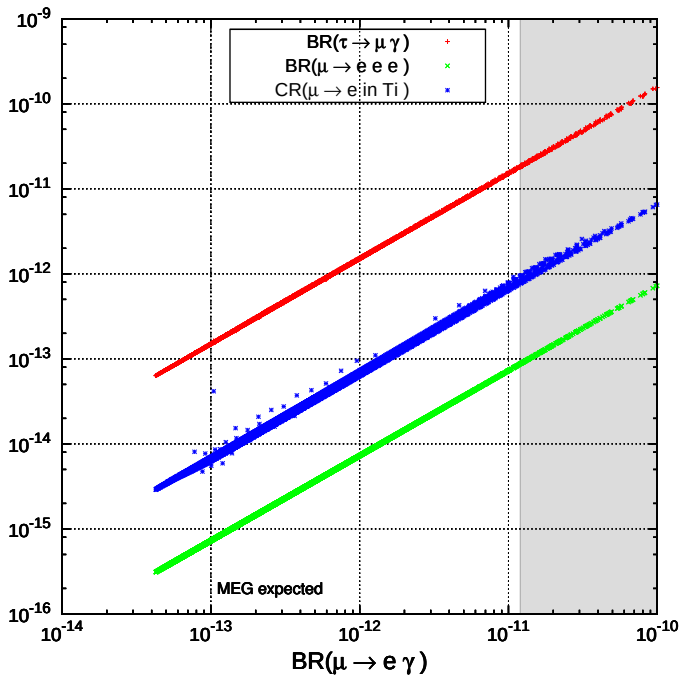
  Correlated CP violation and flavour observables

  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]

- **Further possibilities**

Vector-like leptons: an example

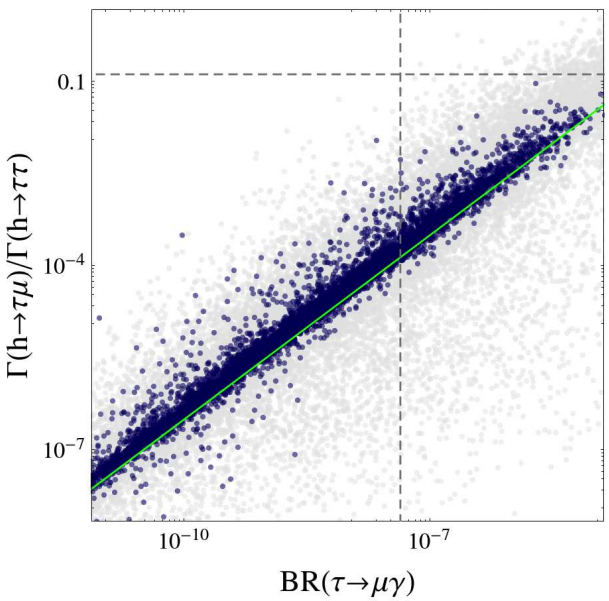
- **Massive vector-like fermions** present in **well-motivated SM extensions:**
  composite Higgs models, warped extra dimensions, ...

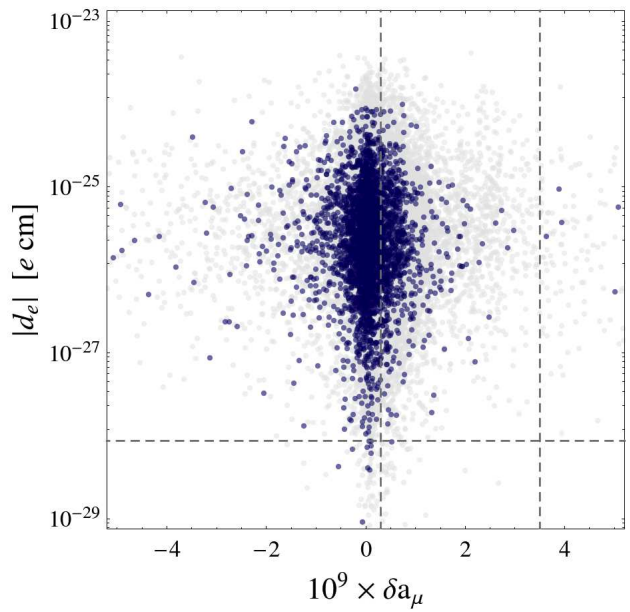
- **Global view:** generic set-up (composite Higgs inspired), 3 generations of L_i^V **and** E_i^V
  massive neutrinos from additional ν_R and vector-like partners

- **cLFV** parametrised by **small set of couplings**

  $\Rightarrow$ **correlated observables!**

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





[Falkowski et al, '14]

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

The flavour puzzle: neutrino masses from flavour symmetries

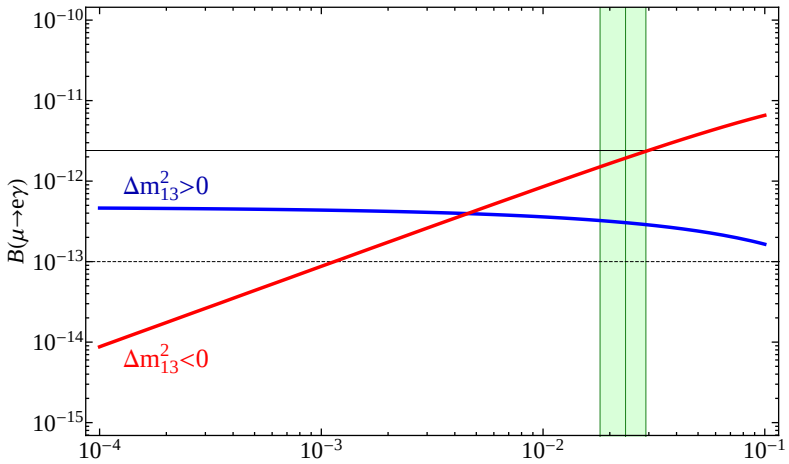
★ **Texture** of Y from spontaneous or explicit breaking of **flavour symmetry** G_f

▶ **Continuous flavour symmetries: minimal Abelian case** $\Rightarrow$ $G_f = \mathrm{U}(1)_{L_e+L_\mu} \times \mathrm{U}(1)_{L_\tau}$

$$Y^\nu = \begin{pmatrix} \epsilon_e & a e^{-i\pi/4} & a e^{i\pi/4} \\ \epsilon_\mu & b e^{-i\pi/4} & b e^{i\pi/4} \\ \epsilon_\tau & \kappa_1 & \kappa_2 \end{pmatrix}$$

$$\mathrm{BR}(\mu \to e\gamma) \approx 8.0 \times 10^{-4} \times a^2 b^2 \times \left(\frac{\Lambda_{\mathrm{EW}}}{M_R}\right)^4$$

[Deppisch and Pilaftsis, '10]



▶ **Discrete flavour symmetries:** $G_f \sim \Delta(3n^2)$ type

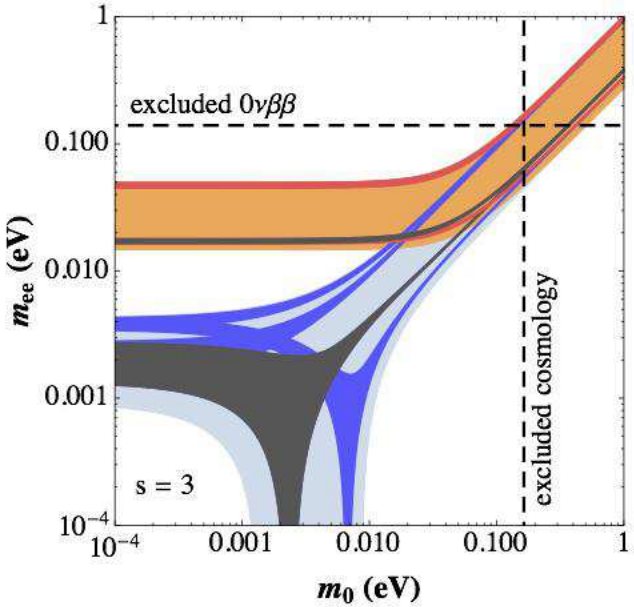
Flavour and CP symmetries $\Rightarrow$ **lepton mixings**

& low/high energy CP phases

Strong predictions for $0\nu 2\beta$ **decay** m_{ee}

Interplay of low-energy **CP phases and BAU**

[Hagedorn and Molinaro, '16]



▶ 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..., $\mu N\,(eN) \xrightarrow{H} \tau X$, ...]

  [$\rightsquigarrow$ M. Yamanaka]

  and **sub-sub set of New Physics models** aiming at **accounting for ν phenomena!**

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

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

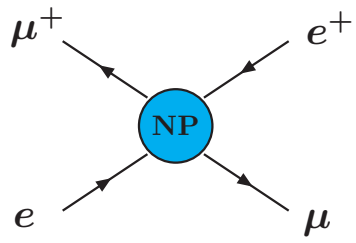
  High-intensity data can provide **information on the underlying NP model**

▶ **Backup**

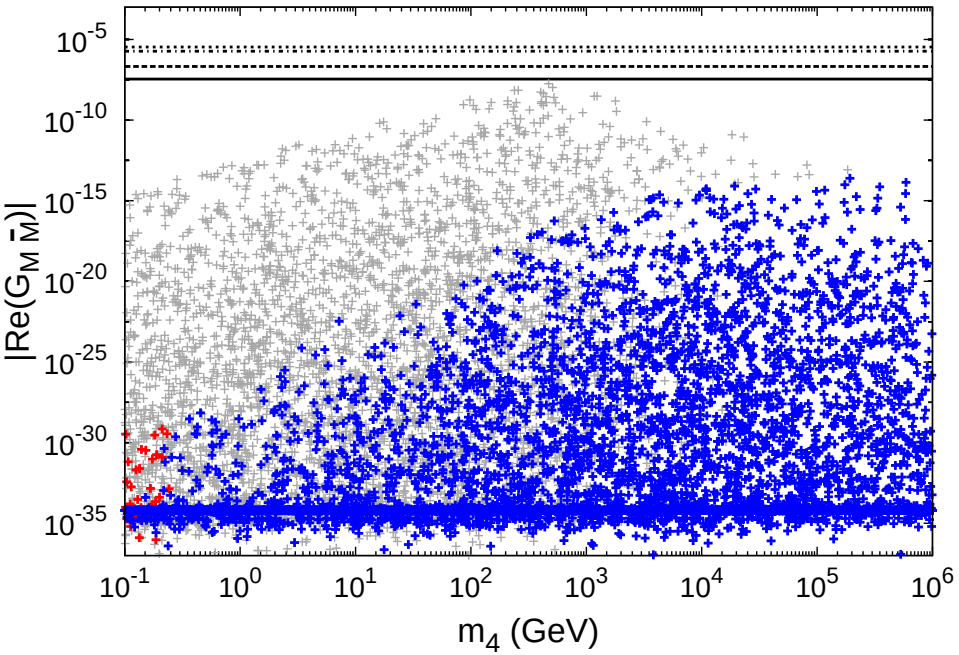
Sterile neutrinos: Muonium cLFV

- **Muonium:** hydrogen-like **Coulomb bound state** $(e^-\mu^+)$; free of hadronic interactions!
- **Mu – $\overline{\text{Mu}}$** conversion

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



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



- **Large values** of $G_{M\bar{M}}$ precluded due to conflict with **CR($\mu - e$, Au)** and **BR($\mu \to 3e$)**

  Within **FNAL experimental reach**??

- Maximal values **Mu** $\to e^+e^- \sim \mathcal{O}(10^{-25})$

  Within experimental reach ?

"3+1" toy model [Abada, De Romeri and AMT, '15]

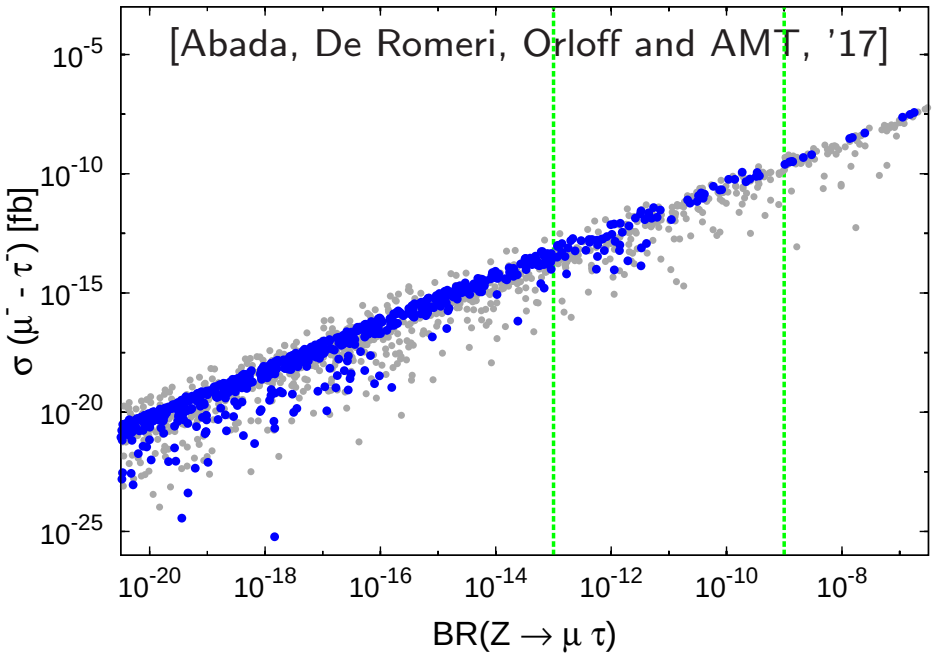
cLFV in-flight conversion

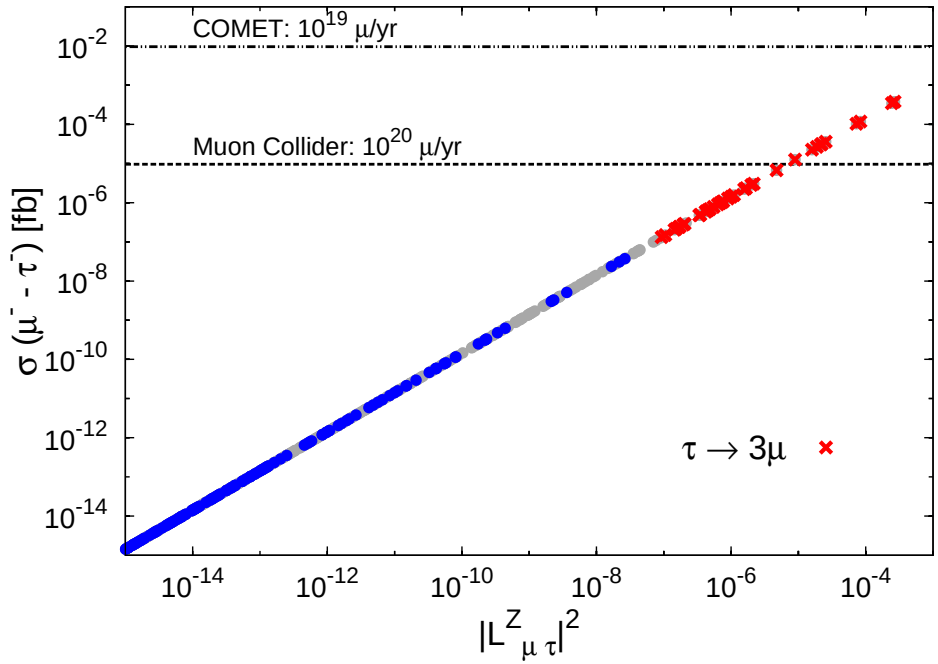
- **Energetic beam of leptons (e, μ) directed on fixed (dense) target**

$$e + N \to \mu + N,\ e + N \to \tau + N \text{ and } \mu + N \to \tau + N$$

$$N_{\text{signal}}(\ell_i \to \ell_j) = N_{\ell_i} \times \sigma(\ell_i \to \ell_j) \times T_m \times N_{p+n} \times \text{BR}(\tau \to \mu\nu\nu)$$

- $\sigma(\ell_i \to \ell_j)$: elastic interactions with nuclei, Z-penguin dominated cLFV





- **Large values** of $\ell_i \to \ell_j$ **precluded** due to conflict with $\text{CR}(\mu - e,\ \text{Au})$ and $\text{BR}(\ell_j \to 3\ell_i)$
- N_{signal} **beyond experimental sensitivity** - even for very intense lepton beams

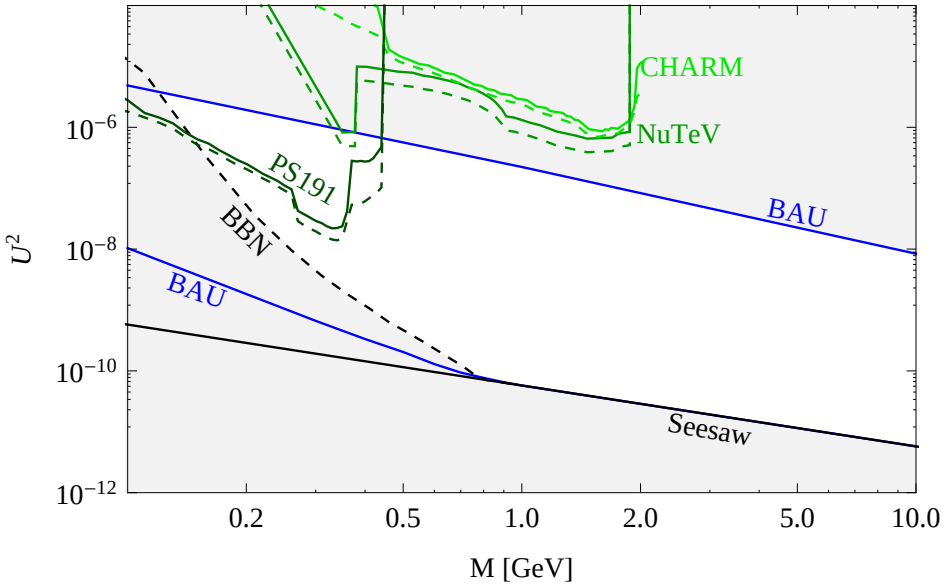
cLFV and ν_s: νMSM

- **Minimal "type I seesaw-like" extension: SM + 3 ν_R**

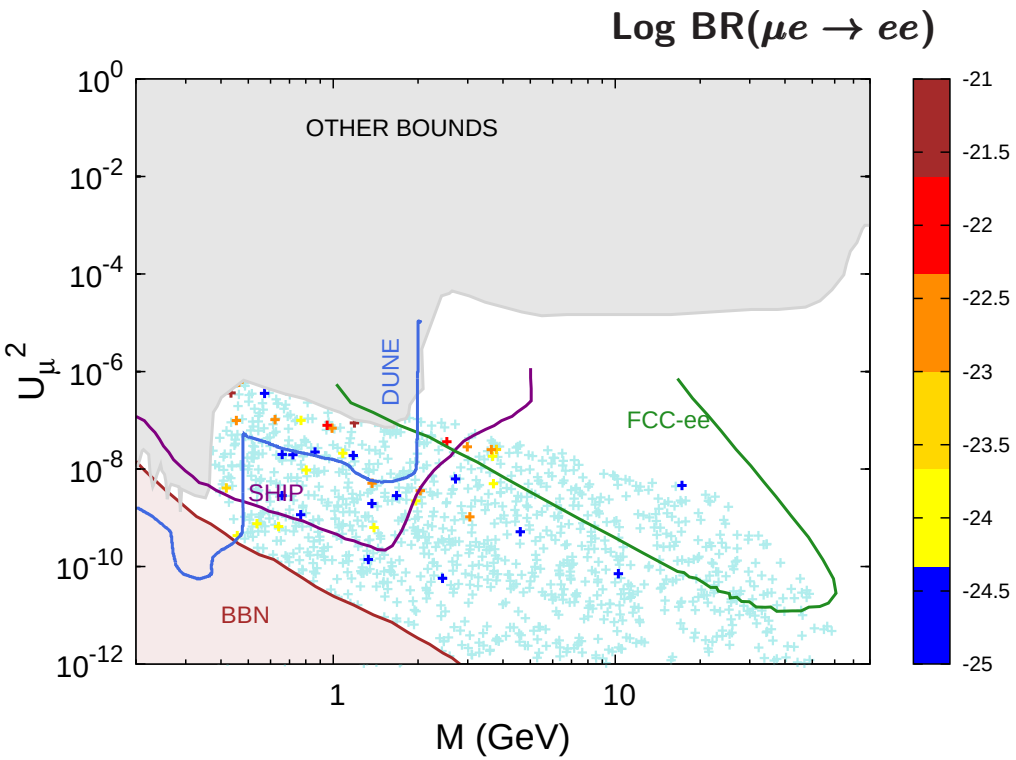
  New states account for m_ν^{light}, offer DM candidate, allow for BAU via leptogenesis

  $\Rightarrow$ tiny Yukawa couplings; heavily constrained parameter space (th, cosmo, exp..)

[Canetti et al, '13]



[Abada et al, '15]



- **νMSM: very difficult prospects for cLFV**

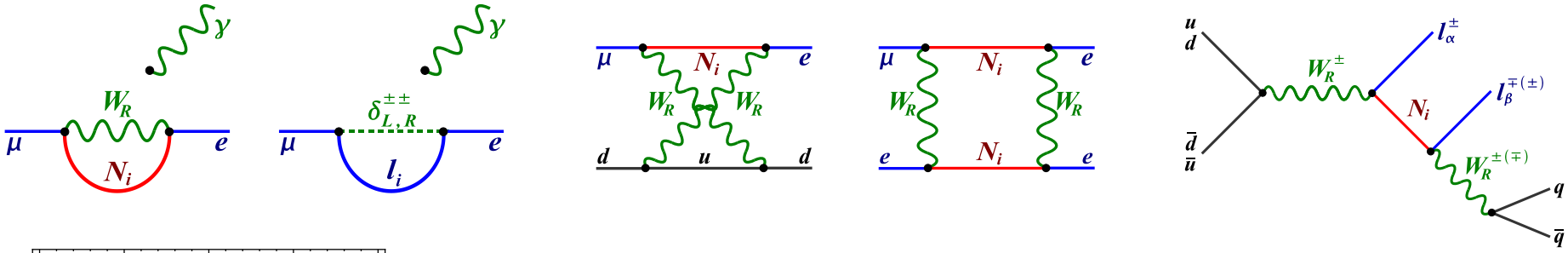
Hints of an organising principle: ν in Left-Right models

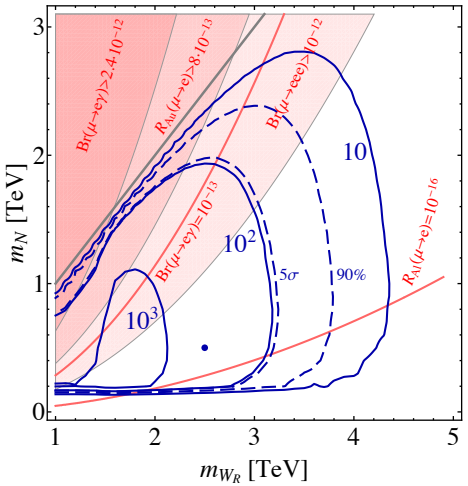
★ **Minimal Left-Right extension of the SM** (non-SUSY)

- extend SM **gauge group:** $SU(2)_L \otimes U(1) \Rightarrow SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- **RH neutrinos automatically included** $M_\nu \approx \begin{pmatrix} y_M v_L & y_D m_{\rm EW} \\ y_D^T m_{\rm EW} & y_M v_R \end{pmatrix}$

  bi-doublet and triplet Higgs; new Z_R, W_R bosons

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





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

  dilepton LFV signatures $pp \to W_R \to e^\pm \mu^\mp + 2$ jets

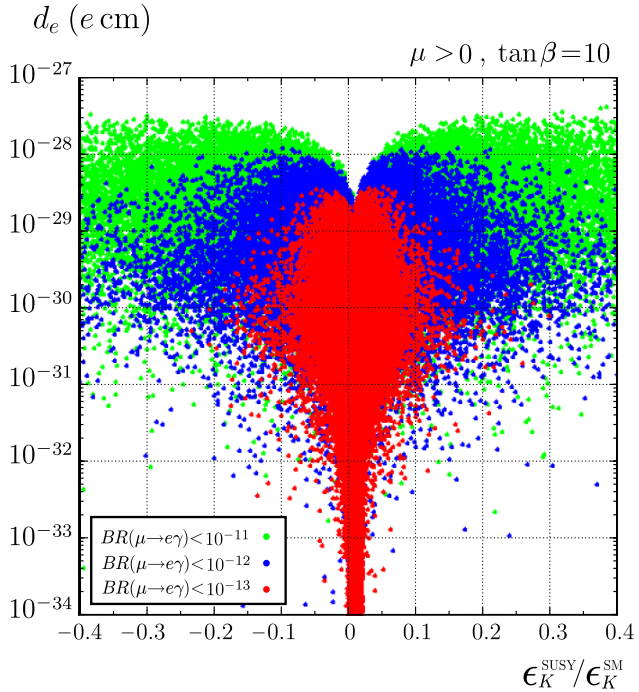
- **Complementarity studies of LHC signatures and low-energy rare decays**

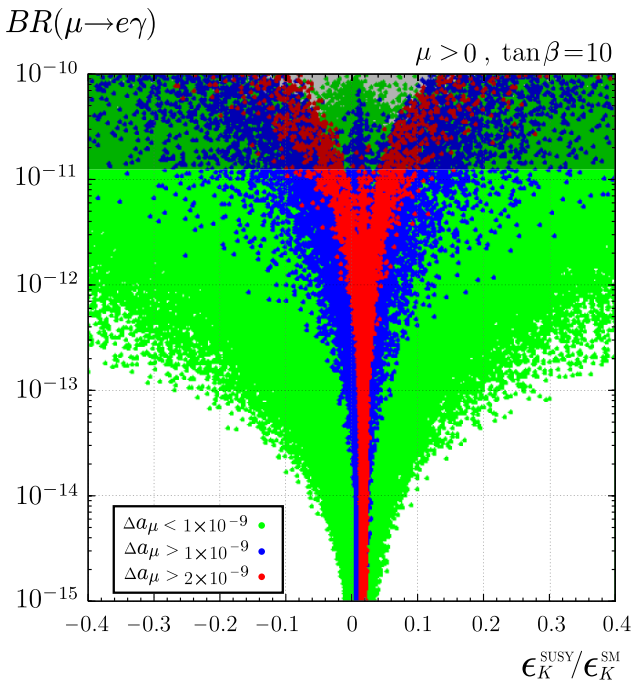
[Das et al, 1206.0656]

Hints of an organising principle: SUSY seesaw and GUTs

★ **Supersymmetric Grand Unified Theories** - "Type I"

- **Reduce arbitrariness of Yukawa couplings Y^q, Y^ℓ, Y^ν...**





- **SU(5) + RH neutrinos SUSY GUTs**
- **Correlated CP violation and flavour violating observables in lepton and hadron sectors!**

[Buras et al, 1011.4853]

▸ Model-independent approach:

New Physics and low-energy observables

Models of New Physics: some more examples

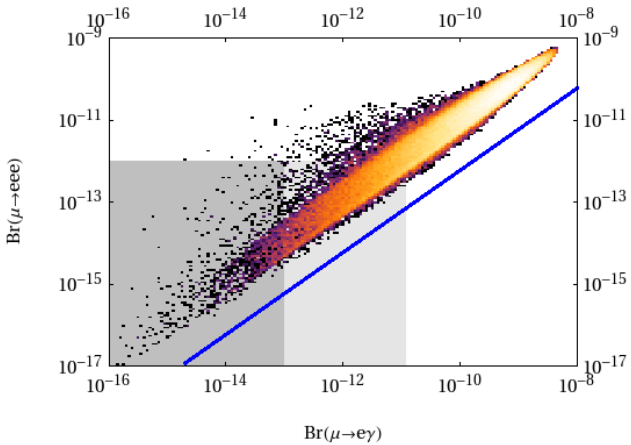
- **"Geometric" flavour violation - extra dimensional Randall-Sundrum models**

  $e-\mu$ 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)

  [Beneke et al, 1508.01705]

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

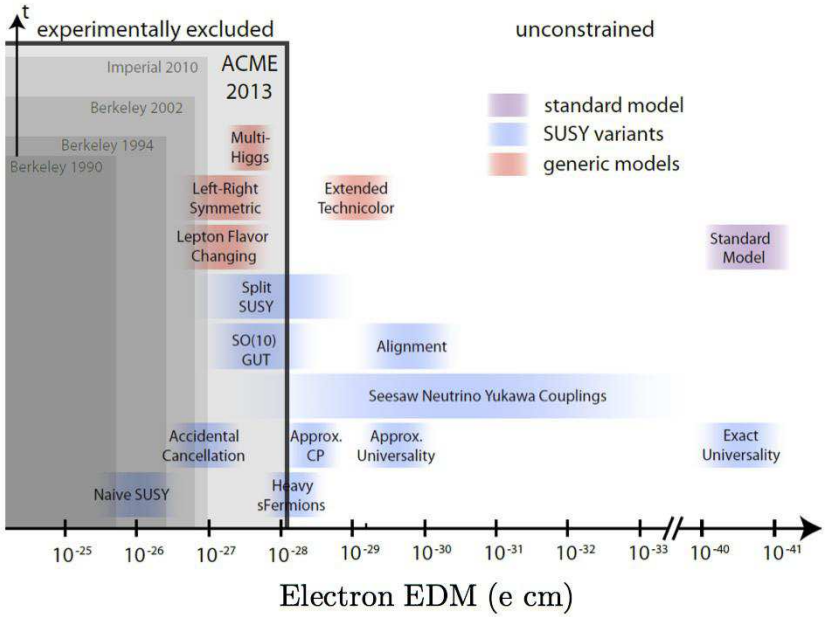


distinctive patterns for ratios of observables (testability!)

BR($\mu \to e\gamma$) - disfavour important regions in parameter space!

[Blanke et al, '09]

- **And more observables to test them!**



[From A. West, PIC2015]

Effective approach

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

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

- **Dimension 5 -** $\Delta\mathcal{L}^5$ **(Weinberg): neutrino masses** (**LNV**, $\Delta L = 2$)

  a unique operator $\mathcal{O}^5_{ij} \sim (L_i\, H)(H\, L_j)$

- **Dimension 6 -** $\Delta\mathcal{L}^6$ **:** kinetic corrections, **cLFV**, EWP tests, **EDMs**, t physics...

  some examples **(dipole and 3-body)**

  Dipole: $\mathcal{O}^6_{\ell_i \ell_j \gamma} \sim L_i \sigma^{\mu\nu} e_j H F_{\mu\nu}$ **radiative decays** $\ell_i \to \ell_j \gamma$, χ-flipping $\ell^\pm$ dipole moments, ...

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

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

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

  [$\rightsquigarrow$ presentation by G.M. Pruna, ...]

- **Higher order -** $\Delta\mathcal{L}^{7,8,..}$ **:** $0\nu 2\beta$, ν (transitional) magnetic moments, NSI, unitarity violation...

Constraining $\mathcal{L}^{\text{eff}}$: cLFV example

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

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]

- **Despite its generality, caution in interpreting these effective limits!**
  - limits assume **dominance of one operator; NP leads to several (interference...)**
  - contributions from **higher order operators** may be non-negligible if Λ **is low...**
  - **multiple "new physics" scales:** $\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{1}{\Lambda_{\text{LNV}}}\mathcal{C}^5(m_\nu) + \frac{1}{\Lambda^2_{\text{LFV}}}\mathcal{C}^6(\ell_i \leftrightarrow \ell_j) + \ldots$

- **Can these limits be used to extract information about $\mathcal{C}^5(m_\nu)$??**