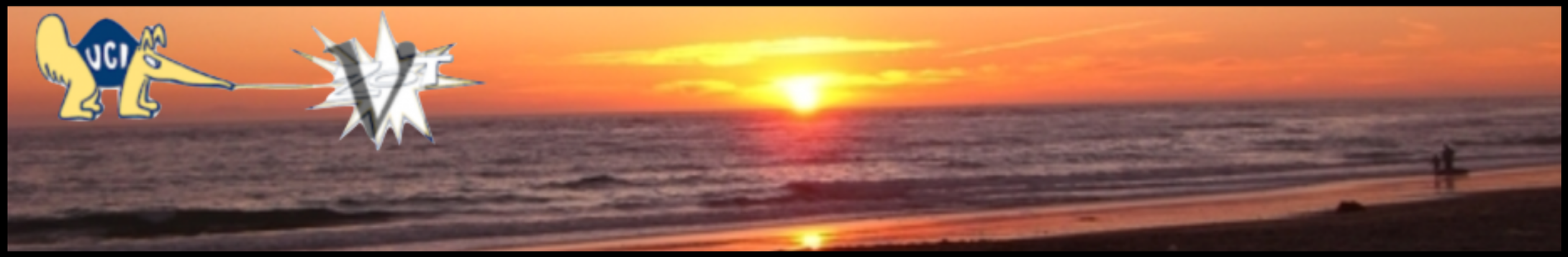
Valentina De Romeri
IFIC Valencia UV/CSIC

Impact of sterile neutrinos on cLFV processes

21st June 2017 - 26th International Workshop on Weak Interactions and Neutrinos (WIN2017)



Based on works done in collaboration with A. Abada, A. Teixeira, S.Monteil, J.Orloff,
JHEP 09 (2014) 074, JHEP 1504 (2015) 051, JHEP 1602 (2016) 083, EPJC77 (2017) n.5, 304

Lepton flavour violation and new physics

By construction, lepton flavour violation (LFV) is forbidden in the SM
(Strict conservation of total lepton number (L) and lepton flavours (L_i))
BUT ... neutral lepton flavour is violated through neutrino oscillations!

- Flavour violation in the charged lepton sector:
  clear signal of NEW PHYSICS beyond SM_{m_ν} (with U_{PMNS})!

- Are neutral and charged LFV (cLFV) related? Does cLFV arise from ν-mass mechanism?

- cLFV signals arising in minimal extensions of the SM by sterile fermion states

$$\boxed{BR(\mu \to e\,\gamma) = 10^{-12} \times (3\ \text{TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2}$$

cLFV →

New Physics (beyond $SM_{m\nu}$) + Lepton Flavour Mixing

$\Lambda \sim \mathcal{O}$ (TeV) — non negligible $\theta_{\ell_i \ell_j}$

(testable at colliders?) — (suggested by neutrino mixing...)

Beyond the 3-neutrino paradigm: Sterile neutrinos

- From the invisible decay width of the Z boson [LEP]:

⇒ extra neutrinos must be sterile (=EW singlets) or cannot be a Z decay product

Any singlet fermion that mixes with the SM neutrinos

• Right-handed neutrinos • Other singlet fermions

- Sterile neutrinos are SM gauge singlets - colourless, no weak interactions, electrically neutral. Interactions with SM fields: through mixings with active neutrinos (via Higgs)
- No bound on the number of sterile states, no limit on their mass scale(s)
- Phenomenological interest (dependent on the mass scale):

eV scale ↔ Short-baseline neutrino oscillation anomalies (reactor antineutrino anomaly, LSND, MiniBooNe...) cannot be explained within 3-flavour oscillations ⇒ need at least an extra neutrino [talks by Giunti, Cao, Diwan…]

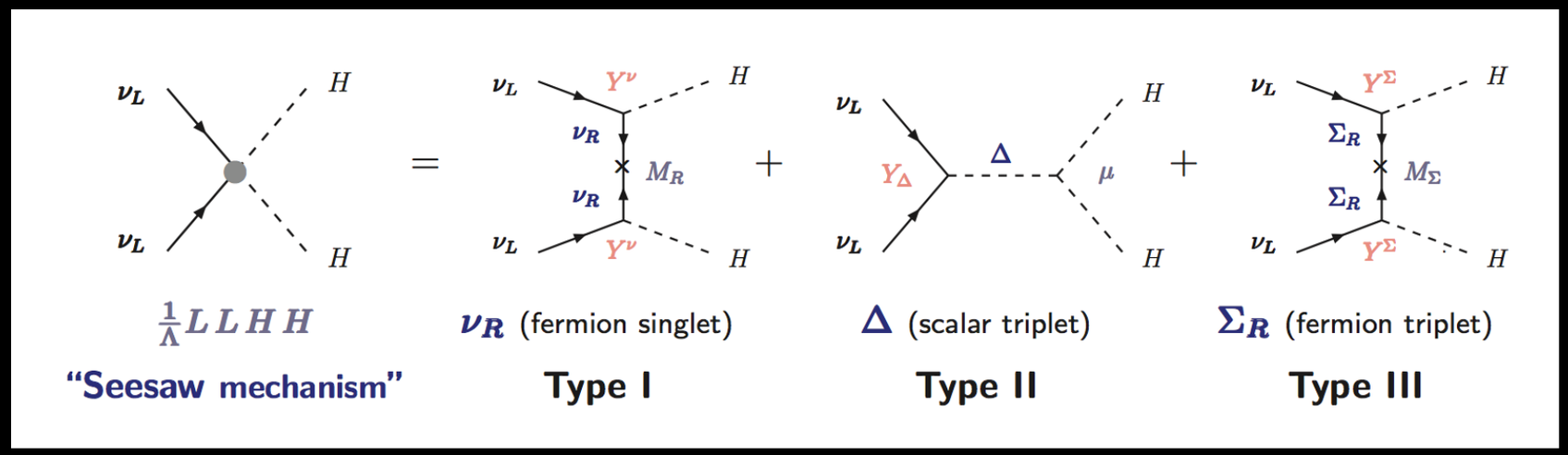
keV scale ↔ motivations for sterile neutrinos from cosmology, e.g warm dark matter or to explain pulsar velocities [talks by Totzauer, Hansen…]

MeV - TeV scale ↔ experimental testability! (and BAU, DM, m_ν generation...) (direct and indirect effects, both at the high-intensity and high-energy frontiers)

Beyond 10^9 GeV ↔ theoretical appeal: standard seesaw, BAU, GUTs

Sterile fermions: theoretical frameworks

- Present in numerous SM extensions aiming at accounting for ν masses and mixings: e.g right-handed neutrinos (Seesaw type-I, νMSM..), other sterile fermions (Inverse Seesaw)



Explain small ν masses with "natural" couplings via new dynamics at heavy scale

(Minkowski 77, Gell-Mann Ramond Slansky 80, Glashow, Yanagida 79,Mohapatra Senjanovic 80,Lazarides Shafi Wetterich 81, Schechter-Valle, 80 & 82, Mohapatra Senjanovic 80,Lazarides 80,Foot 88, Ma, Hambye et al., Bajc, Senjanovic, Lin, Abada et al., Notari et al...)

LFV observables: depend on powers of Yν and on the mass of the (virtual) NP propagators

- Simplified toy models for phenomenological analysis: "ad-hoc" construction (no specific assumption on mechanism of mass generation) encodes the effects of N additional sterile states in a single one

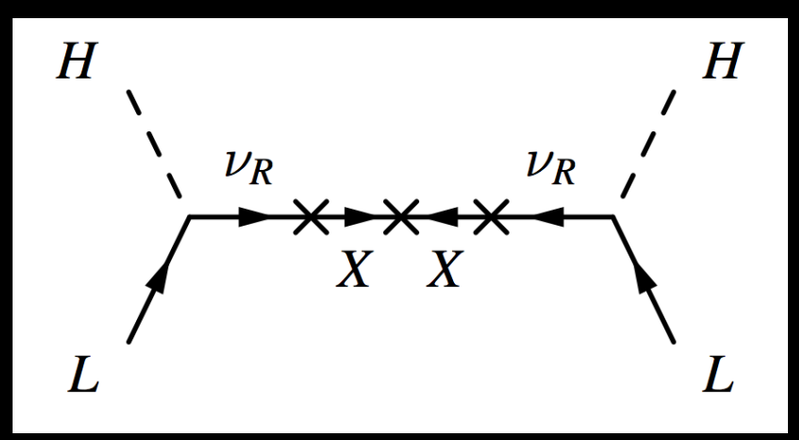
1) Low scale Inverse Seesaw (ISS) (Mohapatra & Valle, 1986)

- Add three generations of SM singlet pairs, ν_R and X (with L=+1)
- Inverse seesaw basis (ν_L,ν_R,X):

$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

$$\Rightarrow \begin{cases} \textbf{3 light } \boldsymbol{\nu} : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2} \boldsymbol{\mu_X} \\ \textbf{3 pseudo-Dirac pairs} : \boldsymbol{m_{N\pm}} \approx \boldsymbol{M_R \pm \mu_X} \end{cases}$$

- Y_ν~O(1) and M_R ~ 1TeV testable at the colliders and low energy experiments.
- Large mixings (active-sterile) and light sterile neutrinos are possible



Parameters:

- M_R (real, diagonal) M_R = (0.1 MeV, 10^6 GeV)
- μ_X (complex,symmetric) μ_X = (0.01 eV, 1 MeV)
- R_{mat} (rotation,complex)
- 2 Majorana and 1 Dirac phases from U_{PMNS}
- Normal (NH) / Inverted (IH) hierarchy

2) "Toy model" for pheno analyses: SM + νs

- Add one sterile neutrino actives-sterile $n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s^c)^T$ → 3 new mixing angles

$$U_{4\times4} = R_{34}.R_{24}.R_{14}.\boxed{R_{23}.R_{13}.R_{12}}$$ UPMNS

- From the interaction to the physical mass basis: $n_L = U_{4\times4}\nu_i$
- Spectrum: 3 light active neutrinos + 1 heavier (mostly) sterile state
- Left-handed leptons mixing: 3x3 sub-block, non unitary!

$$U_{4x4} = \begin{pmatrix} \tilde{U}_{PMNS} & \begin{matrix} U_{eS} \\ U_{\mu S} \\ U_{\tau S} \end{matrix} \\ \begin{matrix} U_{Se} & U_{S\mu} & U_{\tau S} \end{matrix} & \end{pmatrix}$$

Parameters:

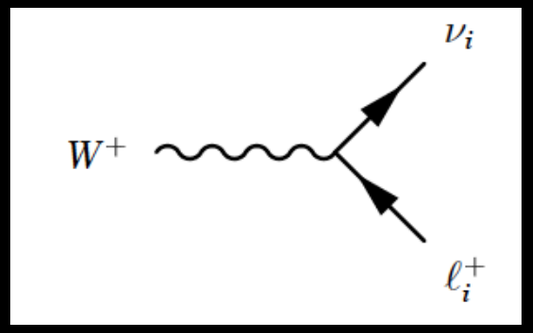
- $\theta_{14}, \theta_{24}, \theta_{34}$
- 3 Majorana and 3 Dirac phases
- Normal (NH) / Inverted (IH) hierarchy

Sterile fermions: phenomenological impact

Modified $W^{\pm}$ charged currents and Z^0, H neutral currents

Leptonic charged currents can be modified due to the mixing with the steriles

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



1. Neutrino oscillation parameters (mixing angles and Δm^2)
2. Unitarity constraints $U_{3\times3} = (1-\eta)U_{PMNS}$ effective theory approach
3. Electroweak precision data e.g. invisible and leptonic Z-decay widths, the Weinberg angle...
4. LHC data (invisible decays) decay modes of the Higgs boson $h \to \nu_R\, \nu_L$ relevant for sterile neutrino masses ~100 GeV
5. Leptonic and semileptonic meson decays (K,B and D) $\Gamma(P \to l\nu)$ with P = K,D,B with one or two neutrinos in the final state
6. Laboratory bounds: direct searches for sterile neutrinos e.g. $\pi^\pm \to \mu^\pm \nu_S$, the lepton spectrum would show a monochromatic line.
7. Lepton flavor violation ($\mu \to e\,\gamma$, $\mu \to eee$ ...)
9. Neutrinoless double beta decay $m_\nu^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (140-700) meV$
10. Cosmological bounds on sterile neutrinos Large scale structure, Lyman-α, BBN, CMB, X-ray constraints (from $\nu_i \to \nu_j \gamma$),SN1987a

Signals of lepton flavour violation

So far we have only upper bounds ... on possible cLFV observables

- Rare leptonic decays and transitions [High intensity facilities]
  - radiative decays
  - three-body decays
  - rare muon transitions in the presence of nuclei
    μ – e conversion (Nuclei), in-flight conversion, muonic atom decay $\mu^- e^- \to e^- e^-$
  - mesonic tau decays ....

see Mihara's talk

- Rare (new) heavy particle decays (typically model-dependent): [colliders]
  - $Z \to l_1^{\mp} l_2$
  - SUSY $\tilde{l}_i \to l_j \chi^0$,FV KK-excitation decays ...
  - impact of LFV for new physics searches at colliders ...
  - e.g. $H \to \tau\mu$

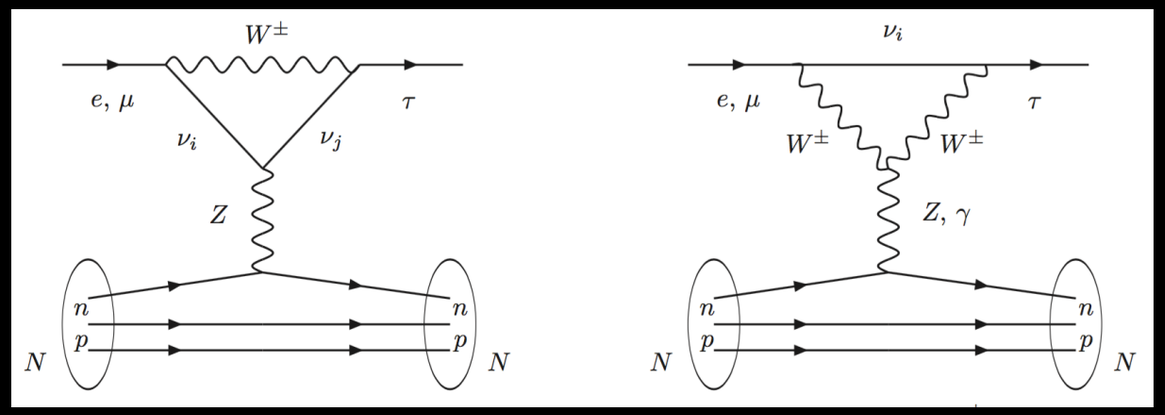
- Neutrino oscillations (neutral lepton flavour violation) [Dedicated experiments]
- Meson decays [LHCb, High intensity facilities]
  Violation of lepton flavour universality e.g. R_K
  LFV final states $B \to \tau\,\mu$ ...
  LNV decays $B^- \to D^+ \mu^- \mu^-$ ...
- And many others ... all without SM theoretical background

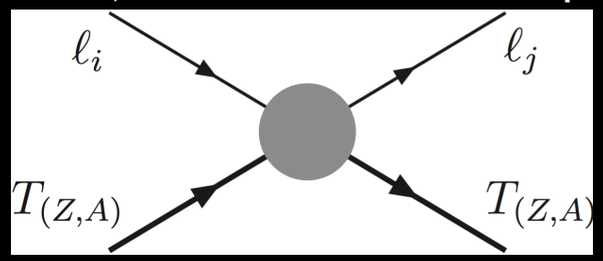
cLFV in flight: μ - τ (and e - μ, e- τ)conversion

- In-flight conversion: μ^- (e^-)+ T(A,Z)→ τ^-+ X^h elastic scattering (T = T′)
- can't occur for muons at rest, but in a higher energy muon beam
- Kinematics requires the beam to have a minimal threshold energy

$$E_{\rm beam} > m_{\ell_j}\left(1+\frac{m_{\ell_j}}{2M_T}\right)$$

- Signal: single muon in association with a severe energy loss in the target
- Identification of taus: direct measurement of tau lepton tracks (such as by emulsions) might not be possible at such a high beam rate. Tag the tau decay products and observe their decay kinematics
- Backgrounds: muon inelastic photo-nuclear interactions in the target, $e^- + N \rightarrow e^- + N + \tau^- + \bar{\nu}_\tau\, \pi^+$ (C.C. + soft pion), $e^- + N \rightarrow \nu_e + N + \tau^- + \bar{\nu}_\tau$
- Future experiments: high-energy, high intensity muon beams are expected to be used at neutrino factories, or even in muon factories (50 GeV muon beams, with around 10^{20}μ/yr.)



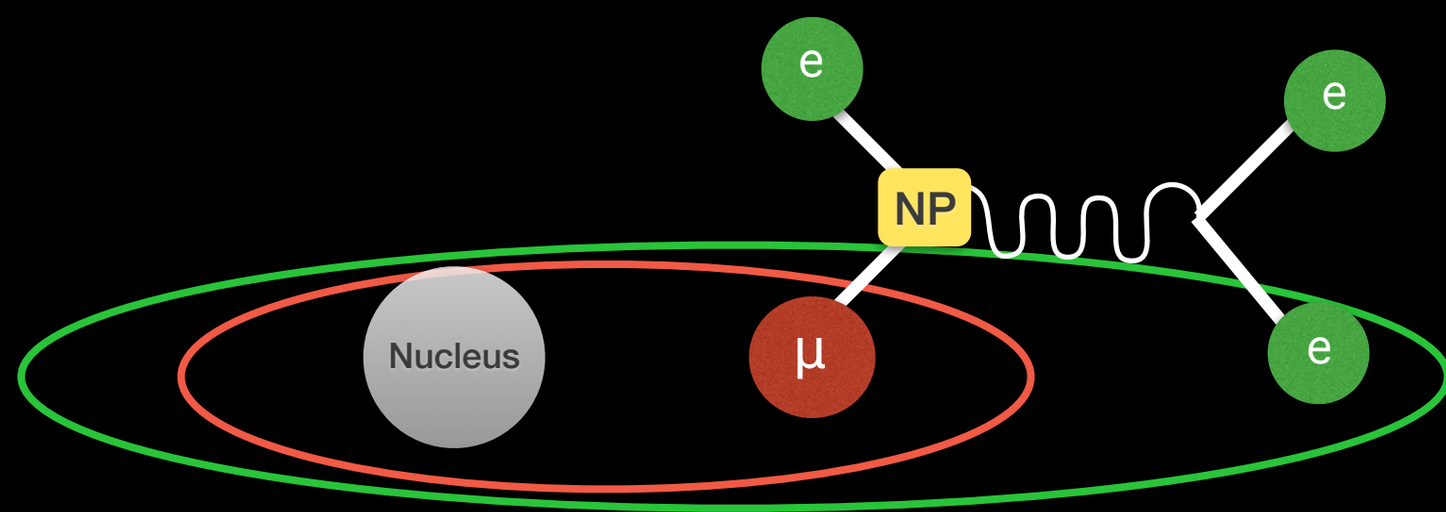


(Gninenko et al., Mod.Phys.Lett. A17 (2002) 1407
Sher and Turan, Phys.Rev. D69 (2004) 017302
Kanemura et al., Phys.Lett. B607 (2005) 165-171
Bolaños et al., Phys.Rev. D87 (2013) no.1, 016004
Liao and Wu, Phys.Rev. D93 (2016) no.1, 016011)

Rare muonic atom decay $\mu^- e^- \to e^- e^-$

- New process proposed by Koike et al.: decay of a bound μ^- in a muonic atom
- Initial μ^- and e^-: 1s states bound in Coulomb field of the muonic atom's nucleus

see Uesaka's talk



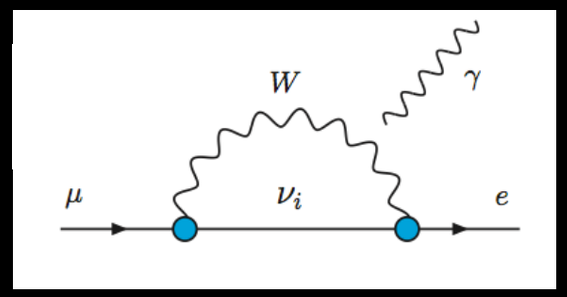
$$\Gamma(\mu^- e^- \to e^- e^-,\ \mathrm{N}) \propto \sigma_{\mu e \to ee} v_{\mathrm{rel}} \left[(Z-1)\,\alpha\, m_e\right]^3/\pi$$

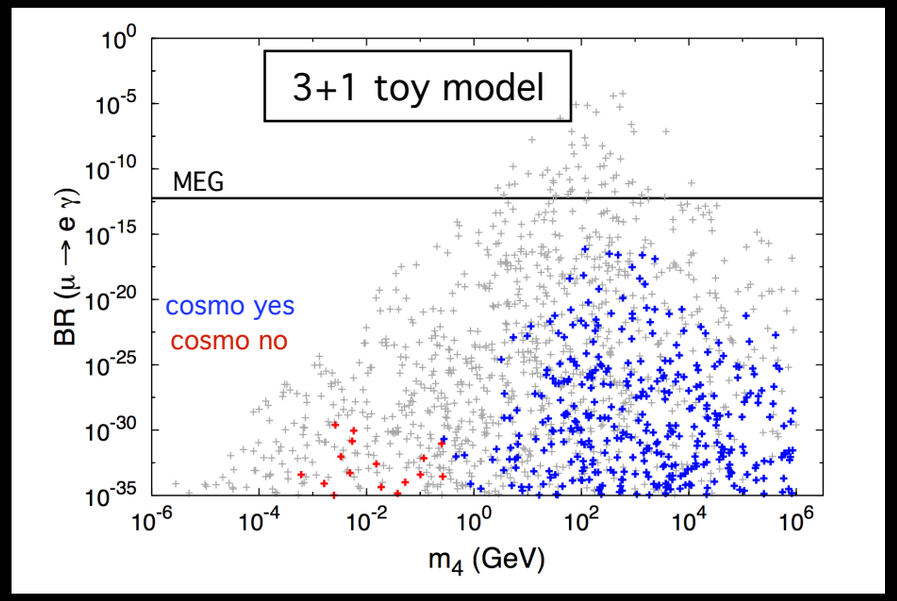
Koike et al. Phys.Rev.Lett. 105 (2010) 121601
Uesaka et al. Phys.Rev. D93 (2016) no.7, 076006

- Elementary process same as $\mu^+ \to e^+e^+e^-$, but with opposite charge
  Clearer experimental signature (back to back electrons) and larger phase space
- Effective Interactions: contact and photonic interactions
- The Coulomb attraction from the nucleus in a heavy muonic atom leads to significant enhancement in its rate (increasing overlap between Ψ_{μ^-} and Ψ_{e^-}) by $(Z-1)^3$
- Distortion effect of e^-e^- and relativistic treatment of the wave function of the bound leptons
- Within the reach of high-intensity muon beams (COMET's Phase II and Mu2e)

ν_s and cLFV: radiative and three-body decays

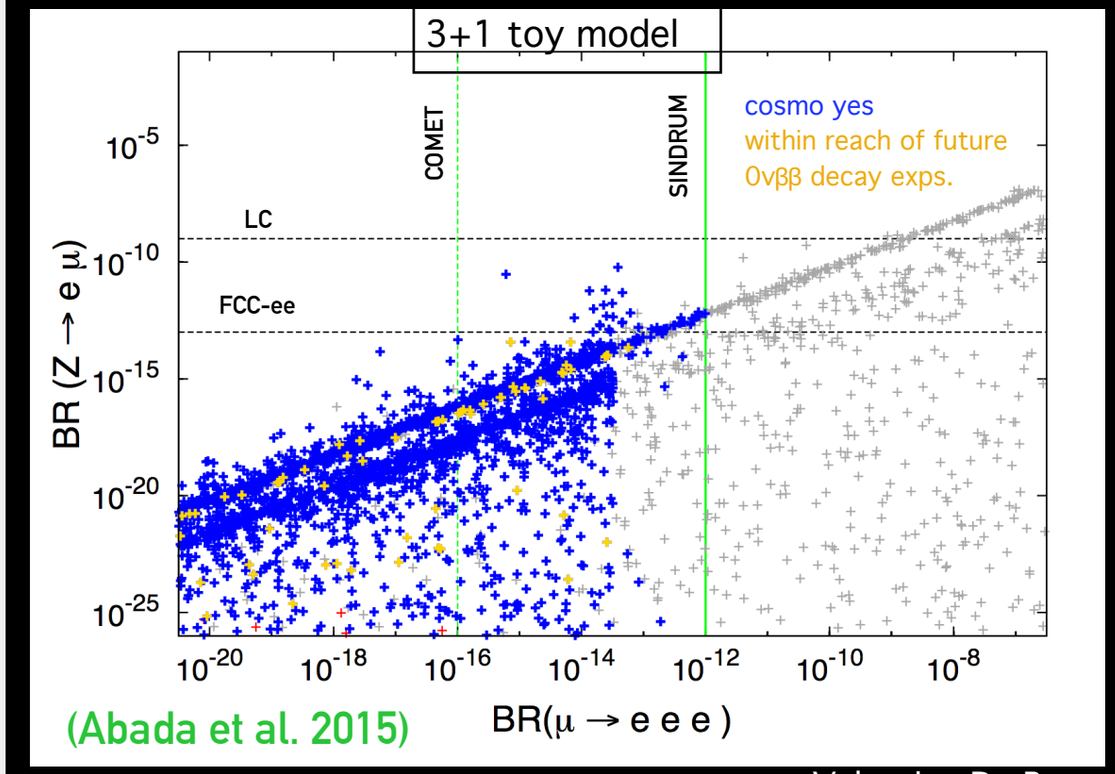
- Radiative decays: $\ell_i \to \ell_j \gamma$
- Consider $\mu \to e \gamma$:

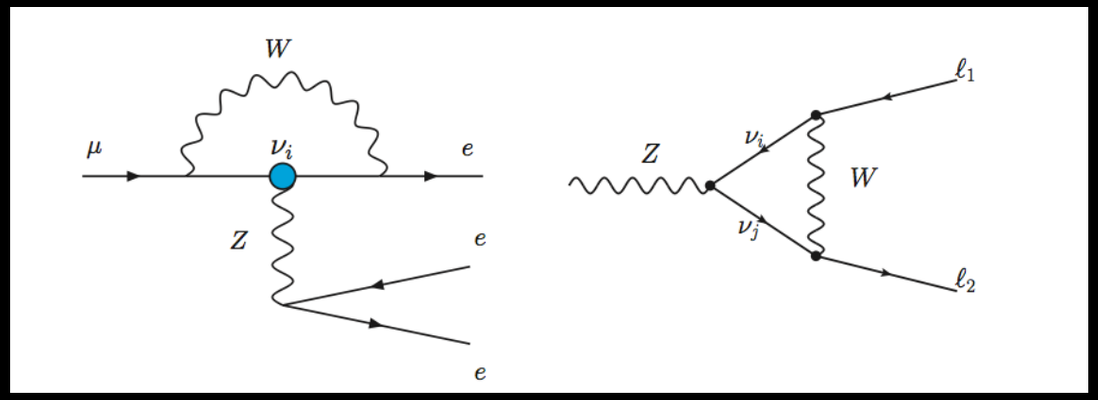




For $m_4 \geq 10$ GeV sizeable ν_s contributions .. but precluded by other cLFV observables

- 3-body decays: $\mu \to eee$



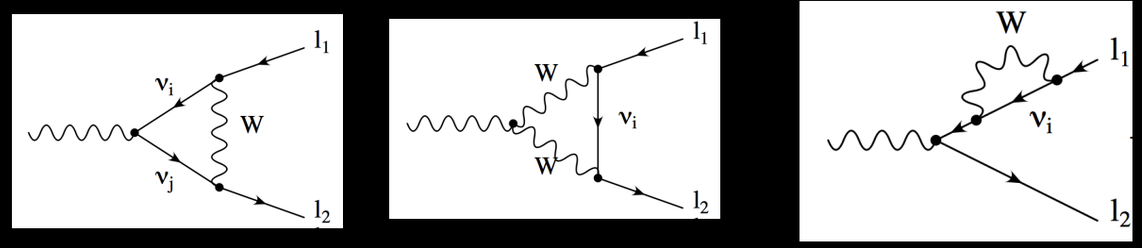


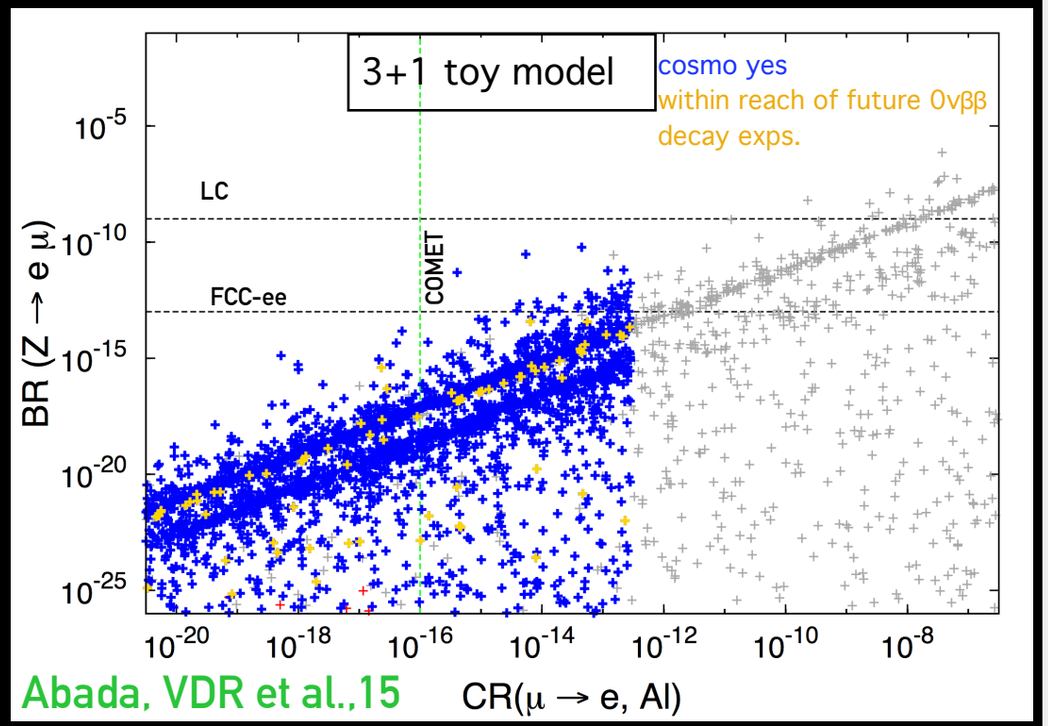
- dominated by Z penguins
  (same contribution to rare Z decay $Z \to e \mu$)

νs and cLFV: rare Z decays

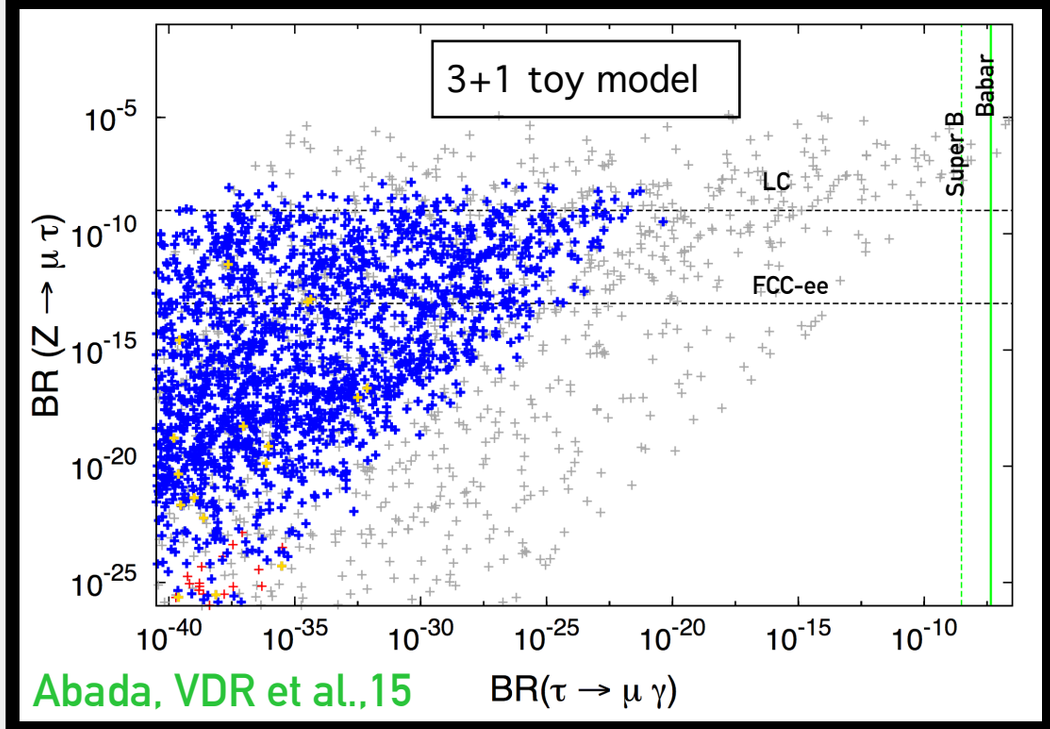
- rare cLFV Z decays at a high luminosity Z factory:

$$Z \to l_i^{\mp} l_j^{\pm}$$





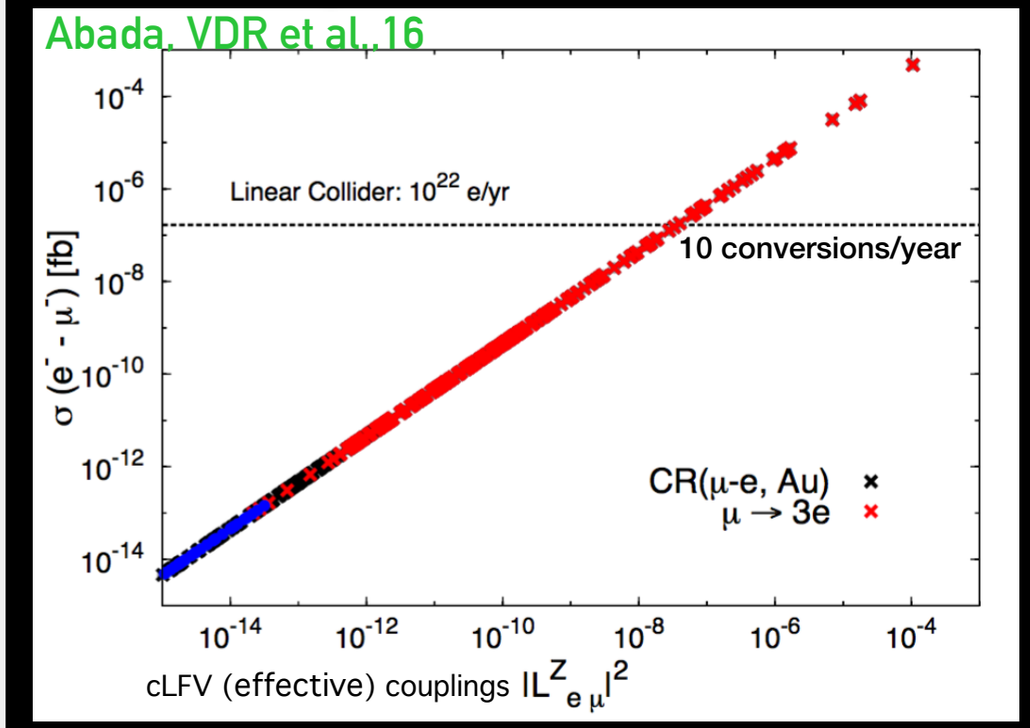
Abada, VDR et al.,15

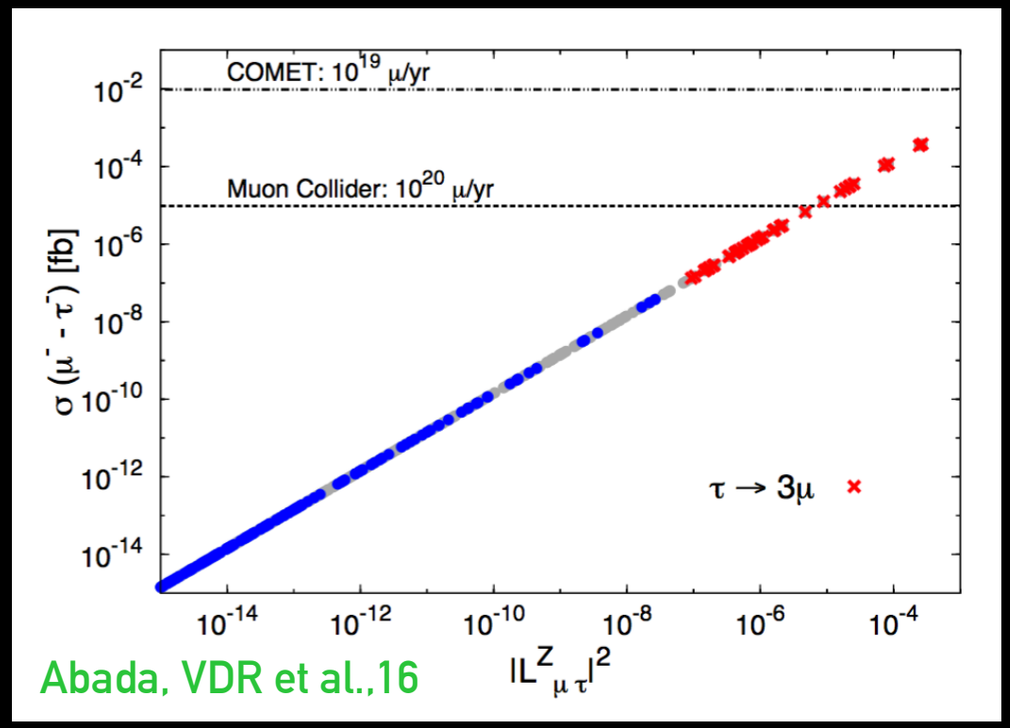


Abada, VDR et al.,15

- allows to probe cLFV in mu-tau sector beyond superB reach
- also studied for ISS and νMSM (Abada, VDR et al.,15, Abada et al., '15 De Romeri et al. '16)
- Other searches for sterile neutrinos at colliders:
  - searches for heavy N at LHC $q q' \to \tau \mu + 2$ jets
  - cLFV Higgs decays (e.g. Arganda et al.14,15)
  - other new signatures, related to sterile neutrinos: Higgs production, displaced vertices, … (Antusch et al. '15,'16)

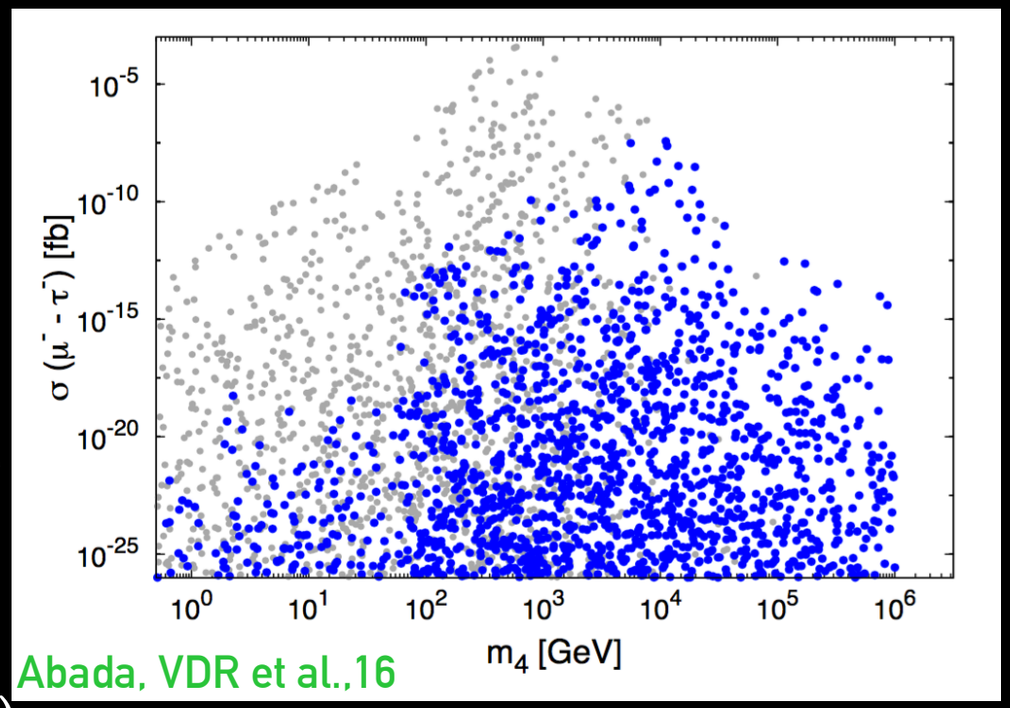
νs and cLFV: In-flight cLFV conversion





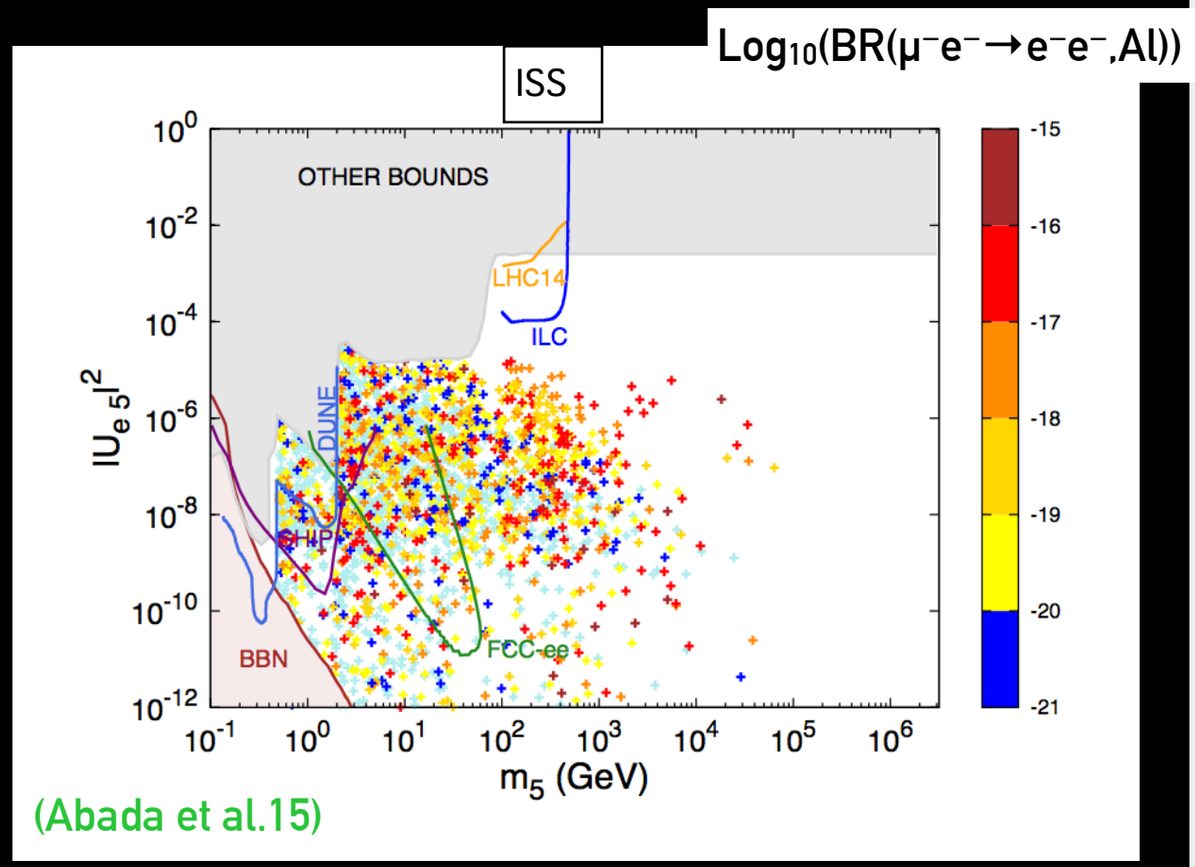
$$\left.\frac{d\sigma^{i\to j}}{dQ^2}\right|_Z = \frac{G_F^2}{32\,\pi\,E_{\rm beam}^2}\,H^Z_{\mu\nu}\,L^{Z\mu\nu}_{ij}$$

- Focus on the photon dipole and Z-penguin contributions
- Large values of cross sections are precluded due to conflict with CR(μ – e, Au) and BR(li→ 3lj)
- Maximally expected values: at most ~ O(10^{-8} fb), for the case of μ–τ conversion
- The expected number of conversions lies beyond experimental sensitivity (below O(10^{-2} events/year))

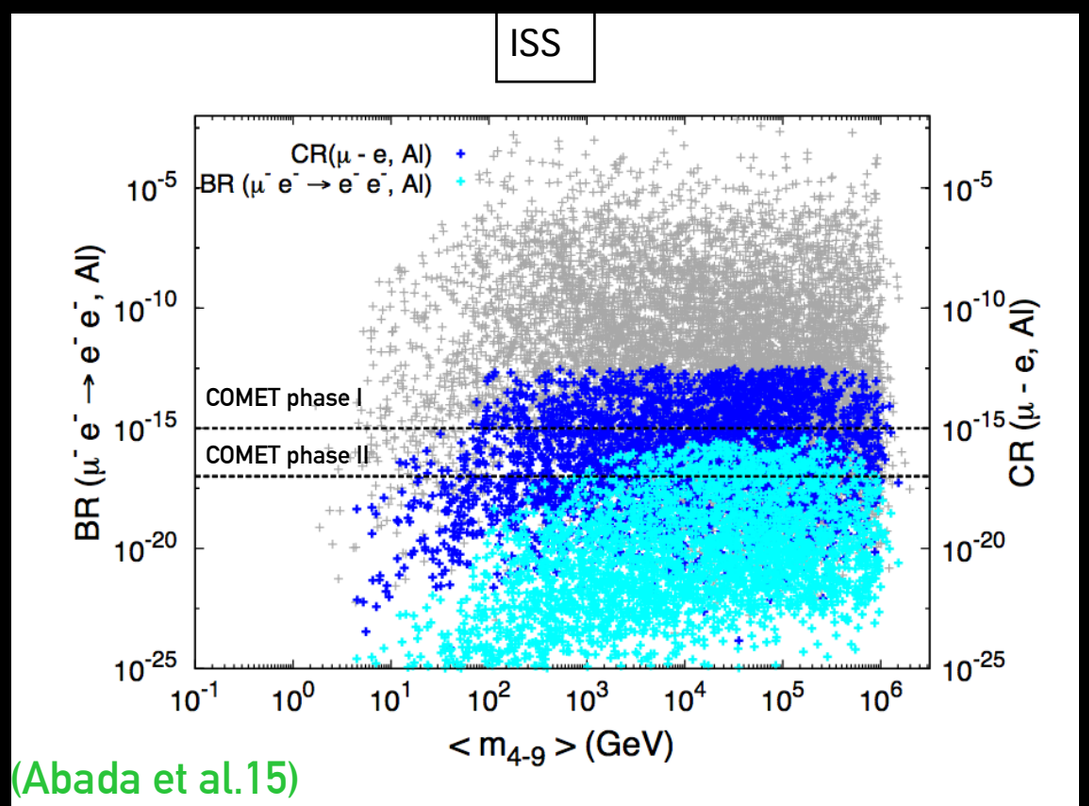


Vs and cLFV: nucleus-assisted processes

- BR($\mu^- e^- \to e^- e^-$,Al) vs CR(μ^- e, Al)
- Sizeable values for BR($\mu^- e^- \to e^- e^-$) - potentially within experimental reach! [COMET]
- Within reach of high-intensity facilities and colliders (SHiP, FCC, LHC, DUNE…) ⇒ complementary probes!



(Abada et al.15)



(Abada et al.15)

- For Aluminium [COMET], CR(μ – e) appears to have slightly stronger experimental potential
- Rate strongly enhanced in large Z atoms (consider heavy targets)

Consider experimental setups for Pb, U !?

Summary

- cLFV observables can provide (indirect) information on the underlying NP model
- We have considered extensions of the SM (ISS and 3+1) which add to the particle content of the SM one or more sterile neutrinos

- Sterile neutrinos provide sizeable contributions to many observables (some leading to stringent constraints)
  - Among these, cLFV observables receiving contributions from Z-mediated penguins like $\mu \to e$ conversion in nuclei and $\mu \to eee$ impose strong constraints on the sterile neutrinos induced $BR(Z \to e^{\pm}\mu^{\mp})$.

- We have explored indirect searches for the sterile states at a high-luminosity Z factory (FCC-ee) and high-intensity facilities (COMET), emphasising the underlying synergy: regions of the parameter space of both models can be probed via cLFV Z decays at FCC-ee, through cLFV radiative decays and also $0\nu\beta\beta$.

- FCC-ee could probe cLFV in the μ-τ sector, in complementarity to the reach of low-E exps.

- Important sterile contributions to $CR(\mu - e, N)$ and $BR(\mu^- e^- \to e^- e^-)$, potentially within COMET and Mu2e reach
  - Analysis also carried for another well motivated model: νMSM

Summary

- cLFV observables can provide (indirect) information on the underlying NP model
- We have considered extensions of the SM (ISS and 3+1) which add to the particle content of the SM one or more sterile neutrinos
- Sterile neutrinos provide sizeable contributions to many observables (some leading to stringent constraints)
  - Among these, cLFV observables receiving contributions from Z-mediated penguins like μ→e conversion in nuclei and $Z \to e^{\pm}\mu^{\mp}$ impose strong constraints on the sterile neutrinos induced BR($Z \to e^{\pm}\mu^{\mp}$).
- We have explored indirect searches for the sterile states at a high-luminosity Z factory (FCC-ee) and high-intensity facilities (COMET), emphasising the underlying synergy: regions of the parameter space of both models can be probed via cLFV Z decays at FCC-ee, through cLFV radiative decays and also 0νββ.
- FCC-ee could probe cLFV in the μ-τ sector, in complementarity to the reach of low-E exps.
- Important sterile contributions to CR(μ – e, N) and BR($\mu^- e^- \to e^- e^-$), potentially within COMET and Mu2e reach
  - Analysis also carried for another well motivated model: νMSM

Thank you!