Sterile Neutrinos and cLFV

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Plan

- **Extending the SM with sterile fermions**

  Motivation and theoretical framework

  Phenomenological impact and observational constraints

- **Sterile neutrinos and cLFV**

  Radiative and 3 body decays; Nucleus-assisted processes

  Rare processes at colliders

- **Sterile neutrinos and cLFV: models of ν-mass generation**

  cLFV at high-intensities and high-energies

- **Outlook**

cLFV and New Physics

- **Flavour violation in charged lepton sector:** Physics beyond SM_{m_ν} !

  Are neutral and charged LFV related?

  Does cLFV arise from ν-mass mechanism? Or entirely different nature?

- **Two approaches to address these questions:** Effective (model-independent)

  (well-motivated) New Physics models

- **LFV in models of New Physics**

  Flavour violating extensions of the SM: Little Higgs, extra dimensions, general SUSY, ...

  Models of neutrino mass generation: Low-scale seesaws, SUSY seesaw, ...

  Hints of an organising principle - LFV and symmetries: LR models, GUTs, ...

- **cLFV arising in SM "minimally" extended via sterile fermions !**

- **Hints on the mechanism of ν-mass generation...?**

- **Sterile fermion extensions of the SM**

Beyond the 3-neutrino paradigm

- **Sterile fermions:** **singlets** under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

  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)**

  Present in several **theoretical models** accounting for $\boldsymbol{\nu}$ **masses and mixings**

- **Interest & phenomenological implications** - strongly dependent on their **mass!**

  eV scale $\leftrightarrow$ extra neutrinos suggested by short baseline ν oscillation anomalies
  (oscillation results not explained within 3 flavour oscillation)

  keV scale $\leftrightarrow$ warm dark matter candidates; explain pulsar velocities (kicks)
  (extensive bounds to be complied with...)

  MeV - TeV scale $\leftrightarrow$ 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 $\leftrightarrow$ theoretical appeal: standard seesaw, BAU, GUTs

Beyond the 3-neutrino paradigm

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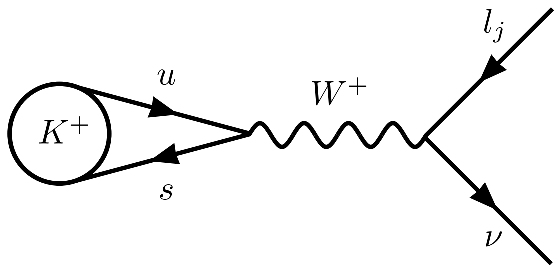
Beyond the 3-neutrino paradigm

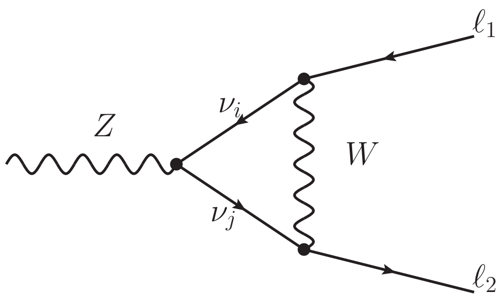
- **Phenomenological impact:** **modified** $W^{\pm}$ **charged currents** and Z^0, H **neutral currents**

  If sufficiently light, sterile νs can be **produced as final states**

- **Contributions to many observables** [low and high energies]

Lepton properties:
- Electric and magnetic moments
- Neutrinoless double beta decay (LNV)
- Violation of flavour universality (e.g. Δr_K)





Rare decays:
- Violation of lepton flavour
- cLFV Z decays
- cLFV and invisible H decays
- [Collider signatures]

- **Already many constraints on the sterile masses and mixings!**

Theoretical frameworks of ν_s

- **Numerous SM extensions aiming at accounting for ν masses and mixings**

  ⇝ **Right-handed neutrinos** (low scale seesaws: type I, νMSM, ...)

  $$\mathcal{L}_{\text{type I}} = -Y^\ell \, \bar{L}_L \, H \, e_R - Y^\nu \, \overline{\nu_R} \, \tilde{H} \, \nu_L - \frac{1}{2} \, \overline{\nu_R} \, M_N \, \nu_R^c \qquad \Rightarrow m_\nu \sim \frac{v^2 \, Y_\nu^2}{M_N}$$

  ⇝ **Other neutral fermions** (ν_R + extra sterile states in Inverse Seesaw, ...)

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

  ⇒ Neutrino oscillation data; leptogenesis; DM (?); very rich phenomenology

- **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 in a **single one**

  ... Not to be confused with oscillation anomaly solution!...

"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:**

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

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

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, ...]

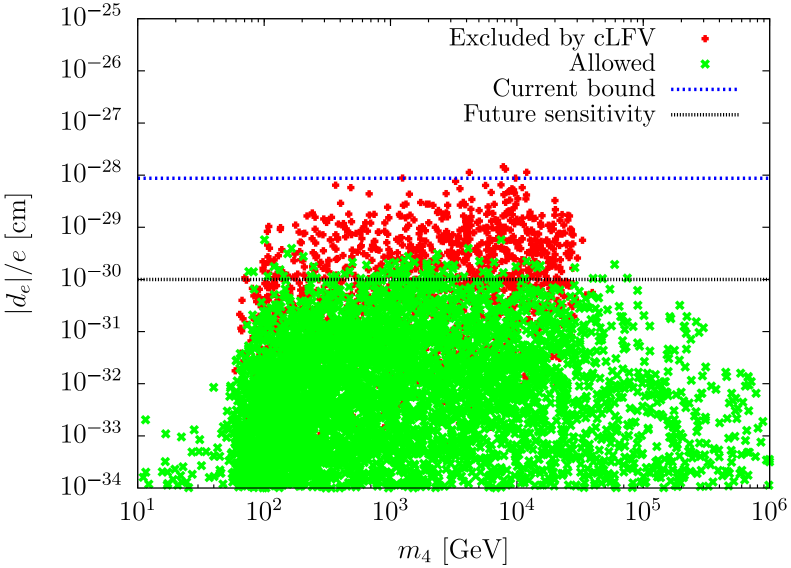
- **Lepton Flavour Violation:** **3 body decays among most stringent...**
  [Gronau et al, '85; Ilakovac & Pilaftsis, '95 - '14;
  Deppisch et al, '05; Dinh et al, '12; Alonso et al, '12; ...]

- **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 and lepton properties**

Impact for lepton properties

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



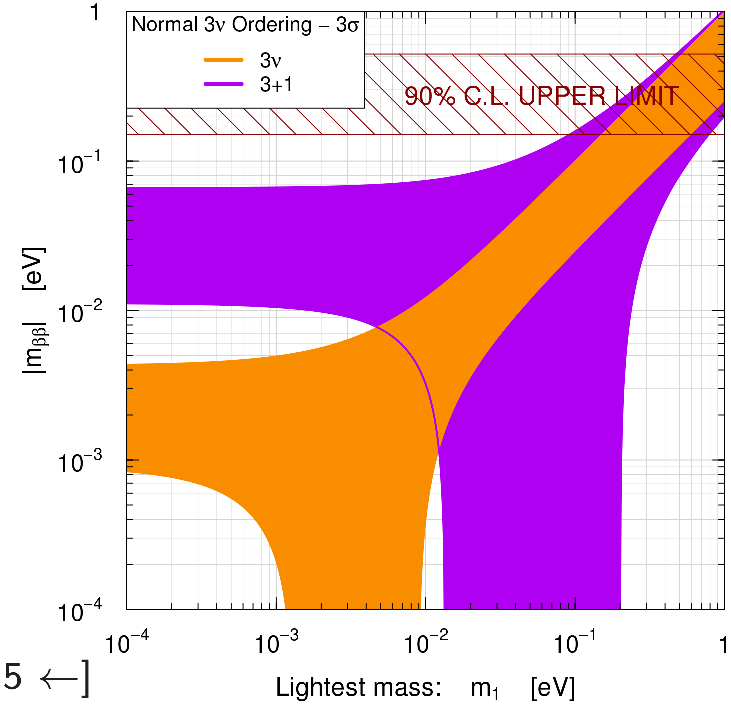
- Majorana (and Dirac) phases ⇒ **lepton EDMs**
- **Non-vanishing** contributions: at least **two sterile ν**
- $|d_e|/e \geq 10^{-30}$ **cm** for $m_{\nu_{4,5}} \sim$ **[100 GeV, 100 TeV]**

[Abada and Toma, '15]

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

    ⇒ **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



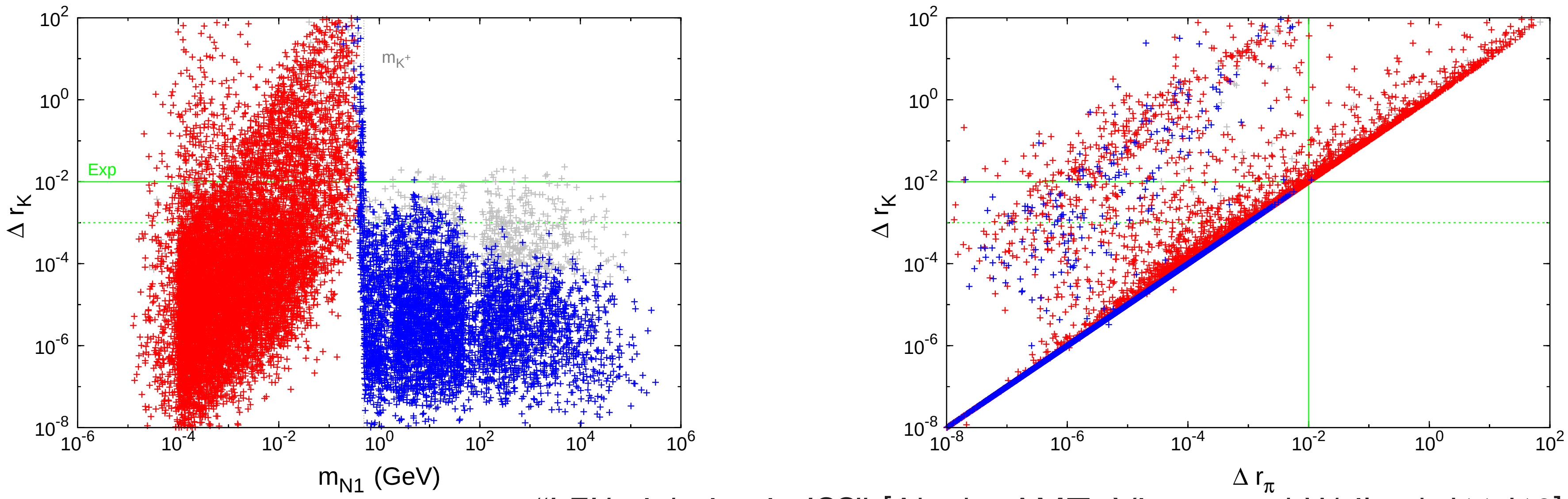
[Abada, De Romeri and AMT, '14; ...; Giunti et al, '15 ←]

Impact for lepton properties

▶ **Lepton Universality Violation in K and π decays**

$R_P = \frac{\Gamma(P \to e\nu)}{\Gamma(P \to \mu\nu)}$ comparison with **SM th predictions** $\Delta r_P = \frac{R_P^{\text{exp}}}{R_P^{\text{SM}}} - 1$

▶ Sizeable active-sterile mixing: **corrections** to $W\ell\nu$ vertex!



"LFU violation in ISS" [Abada, AMT, Vicente and Weiland, '11-'13]

▶ **Sterile neutrino contributions:** $\Delta r_{K,\pi} \gtrsim \mathcal{O}(10^{-2})$ (in contrast with SUSY models)

[Fonseca, Romao and AMT '12]

▶ $\Delta r_{K,\pi} \sim \mathcal{O}(1) \Rightarrow$ one of the **strongest constraints in SM + ν_s models!**

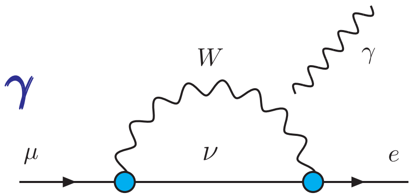
▶ Many **other LFU violation observables** (sensitive to ν_s?!)

[Presentation by D. Guadagnoli]

- **Sterile neutrinos and cLFV: simple “toy models”**

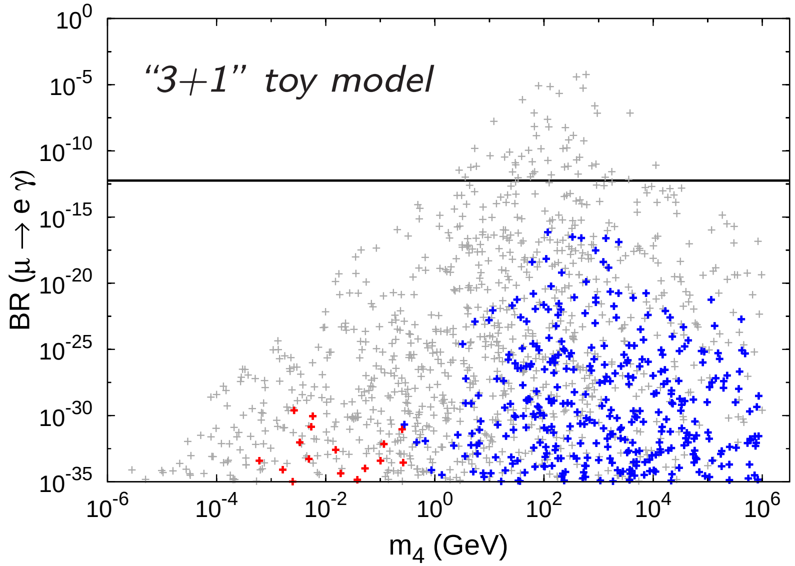
ν_s and cLFV: radiative and 3 body decays

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

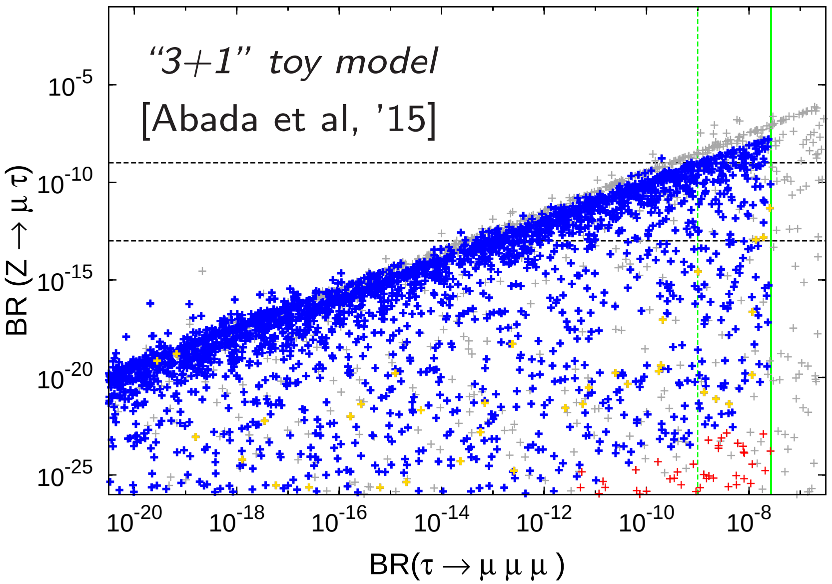


  - Consider $\mu \to e\gamma$
  - For $m_4 \gtrsim 10$ GeV sizable ν_s contributions

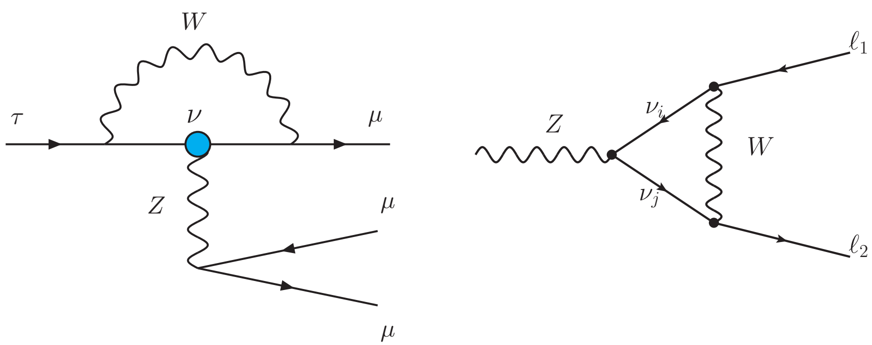
  .. but precluded by other cLFV observables



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



  - Dominated by Z **penguin** contributions



  - Allows to **probe $\mu - \tau$ cLFV** beyond **SuperB reach**
  - **Complementarity probes** of ν_s **cLFV**

    at **low- and high energies!** (and in **LNV**...)

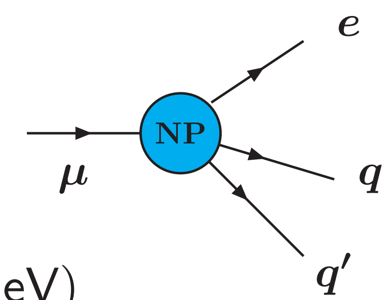
cLFV in "muonic" atoms: $\mu - e$ conversion

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

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

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

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



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

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

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

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

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

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

cLFV in "muonic" atoms: Coulomb enhanced decays

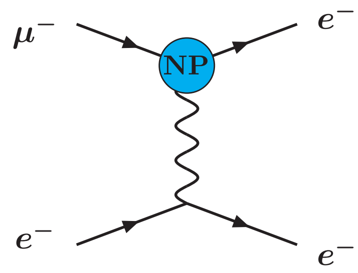
- **Muonic atom decay:** $\mu^- e^- \to e^- e^-$ [Koike et al, '10]

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

- **Coulomb interaction** increases overlap between

  Ψ_{μ^-} and Ψ_{e^-} wave functions

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



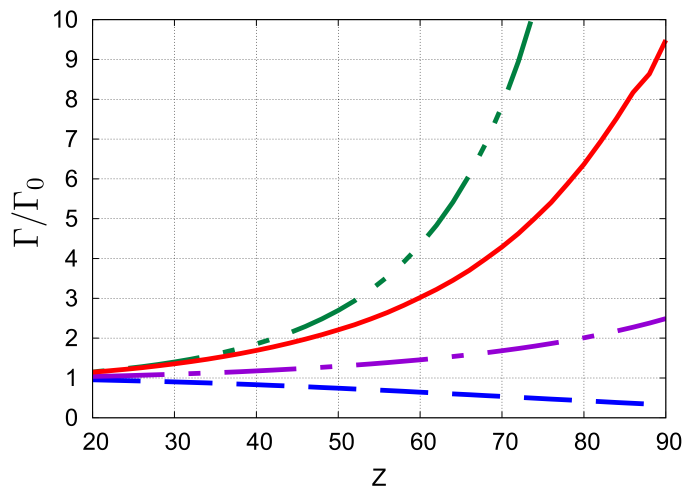
- **Clean experimental signature:** back-to-back electrons, $E_{e^-} \approx m_\mu/2$

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

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

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

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

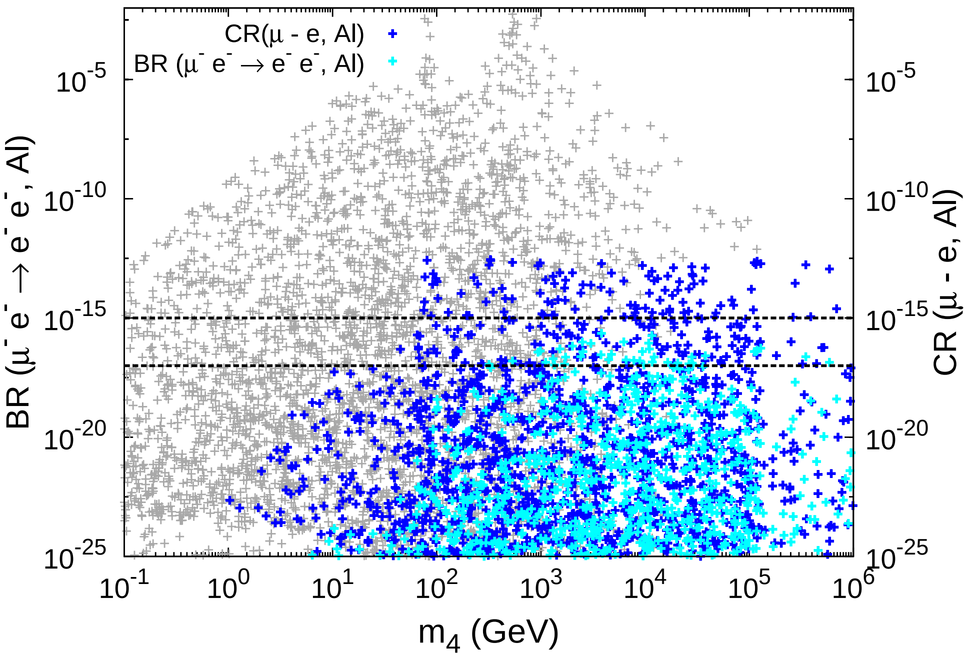


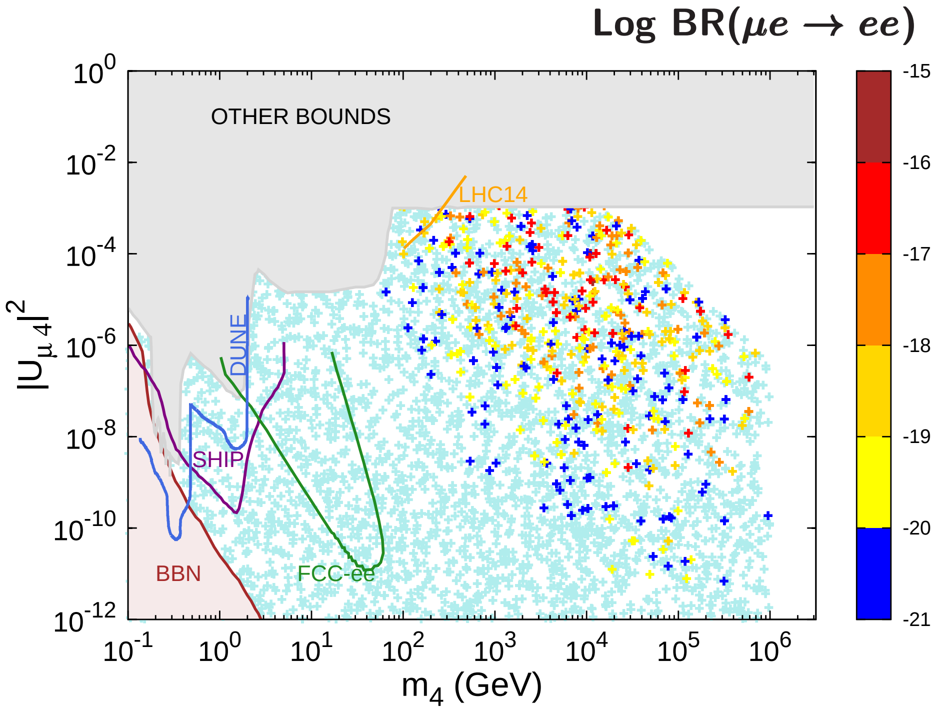
- **Experimental status: New observable!**

  Hopefully included in Physics programmes of **COMET** & **Mu2e** (?)

cLFV in "muonic atoms" and sterile neutrinos

▸ **cLFV muonic atom decay $\mu^- e^- \to e^- e^-$ vs $\mu - e$ conversion (Aluminium target)**





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

▸ **Sizeable values** for BR($\mu^- e^- \to e^- e^-$) - potentially within **experimental reach!**
probe "heavy mass" regimes unaccessible for **SHiP, FCC, LHC, ...**

▸ For **Aluminium**, **CR($\mu - e$)** appears to have **stronger experimental potential**
.. consider **"heavy" targets** to probe BR($\mu^- e^- \to e^- e^-$)

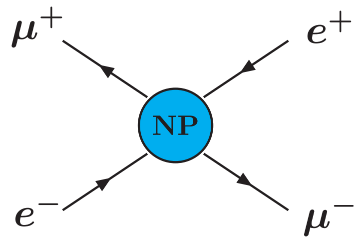
cLFV in "muonic" atoms: Muonium

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

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

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

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



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

  $\mathcal{L}_{\text{eff}}^{\text{Mu}-\overline{\text{Mu}}} \sim G_{\text{M}\overline{\text{M}}}\,[\bar\mu\gamma^\alpha(1-\gamma_5)e]\,[\bar\mu\gamma_\alpha(1-\gamma_5)e]$ $\leftrightsquigarrow$ $|\text{Re}(G_{\text{M}\overline{\text{M}}})| < 0.003 \times G_F$

  Future prospects at **FNAL** ?

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

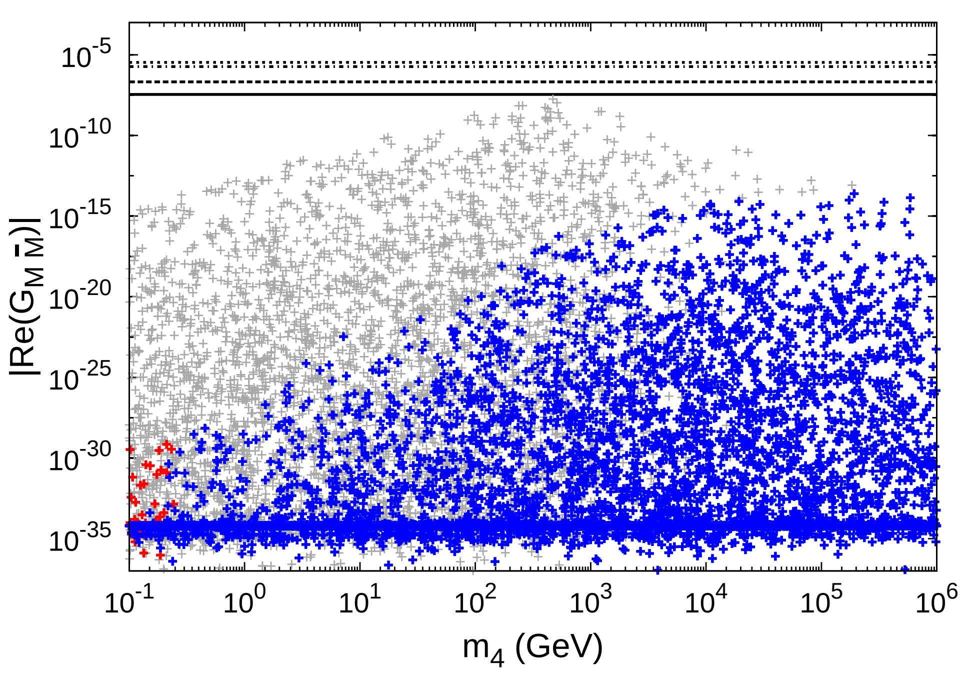
  clear signal compared to SM decay Mu $\to e^+e^-\bar\nu_\mu\nu_e$ (no missing energy)

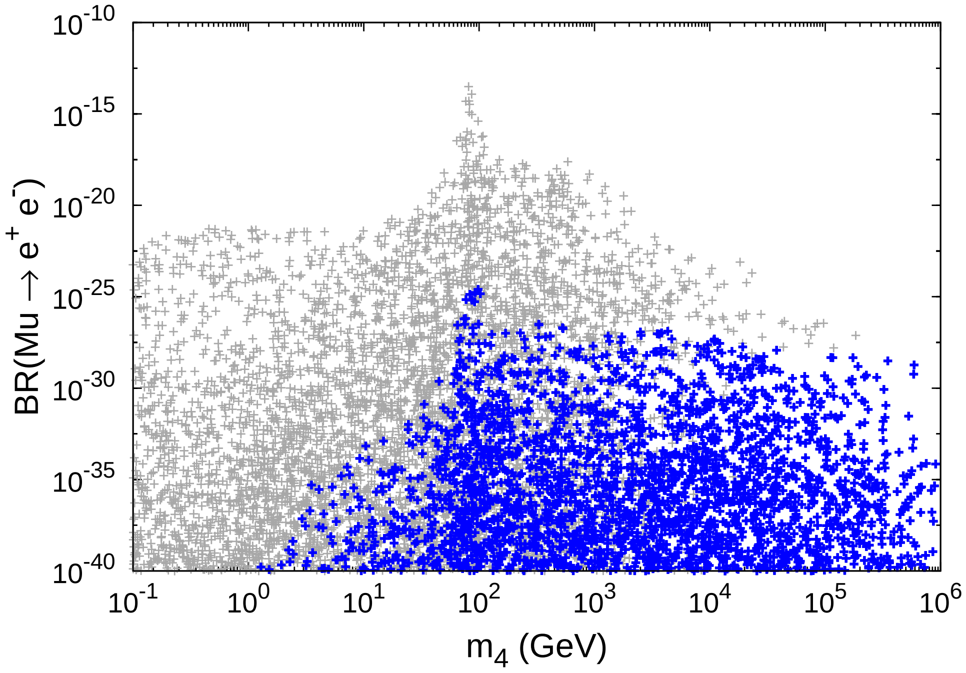
- **Experimental status:** no clear roadmap (nor bounds)...

  Hopefully included in Physics programme of **COMET** & **Mu2e** (?)

Muonium and sterile neutrinos

- **cLFV Muonium processes:** **Mu** $-$ $\overline{\textbf{Mu}}$ **oscillation** **and** **Mu** $\to e^+e^-$ **decay**





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

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

  Within reach of **next generation of experiments?** (e.g. FNAL)

- Maximally expected values **Mu** $\to e^+e^- \sim \mathcal{O}(10^{-25})$ Within experimental reach ?

- **cLFV and sterile fermions: mechanisms of ν-mass generation**

cLFV and ν_s: low scale seesaws

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

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

Low scale seesaws: rich phenomenology (also at LHC), observable cLFV!

Well motivated frameworks: low-scale Type I Seesaw

Inverse Seesaw realisations

ν Minimal Standard Model, ...

... calling upon sterile fermions!

cLFV: low scale type I seesaw

$\rightsquigarrow$ SM + Right-handed neutrinos

$$\mathcal{L}_{\text{type I}} = -Y^\ell \, \bar{L}_L \, H \, e_R \, - Y^\nu \, \overline{\nu_R} \, \tilde{H} \, \nu_L \, - \tfrac{1}{2} \, \overline{\nu_R} \, M_R \, \nu_R^c$$

- Addition of **3 "heavy" Majorana RH** neutrinos to SM; $\text{MeV} \lesssim M_R \lesssim 10^{\text{few}}\,\text{TeV}$

  No *prejudice* on naturality or finetuning of Y^ν...

- **Spectrum and mixings:** 6 physical states

$$\mathcal{M}_\nu^{6\times6} = \begin{pmatrix} 0 & v\,Y^\nu \\ v\,Y^{\nu T} & M_R \end{pmatrix} \qquad U^T \, \mathcal{M}_\nu^{6\times6} \, U = \text{diag}(m_i) \qquad \begin{array}{l} m_\nu \approx -v^2 Y_\nu^T \frac{1}{M_R} Y_\nu \\ m_N \simeq M_{R_i} \end{array}$$

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

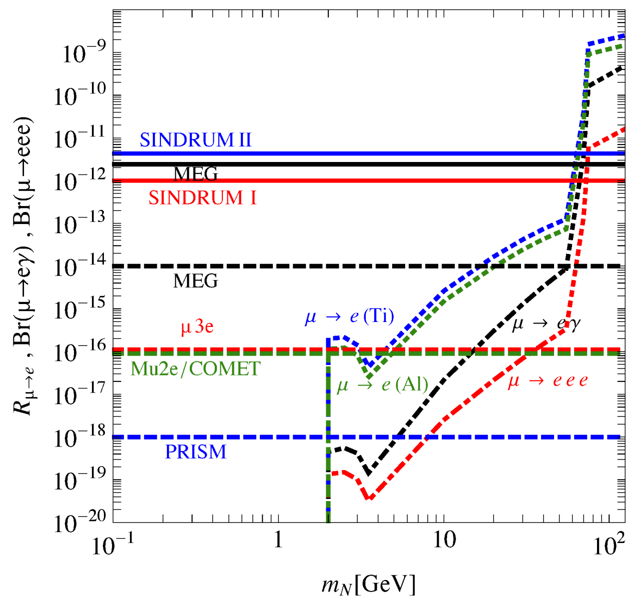
Non-unitary leptonic mixing $\tilde{U}_{\text{PMNS}}$!

- **Heavy states do not decouple** $\Rightarrow$ **modified neutral and charged leptonic currents**

- Rich phenomenology at **high-intensity/low-energy**

cLFV: low scale type I seesaw

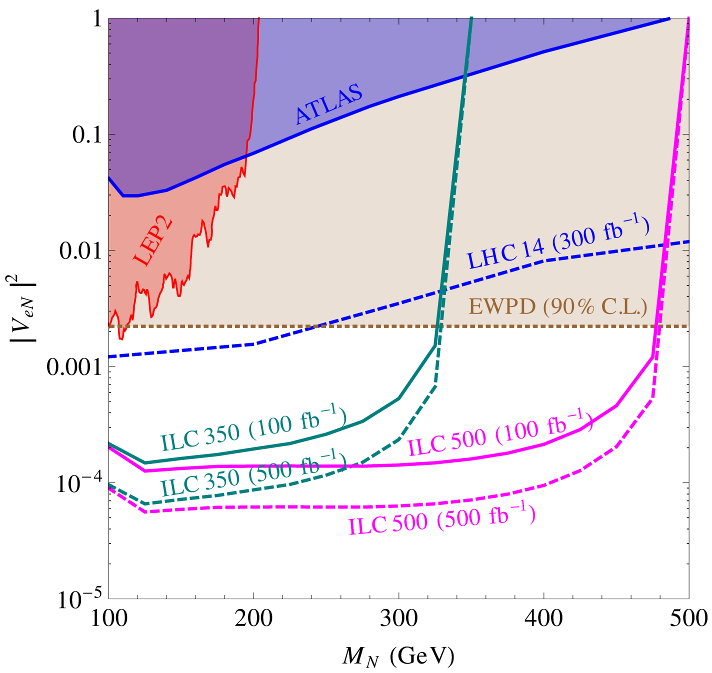
- **At high-intensities: cLFV observables**
  BR($\mu \to e\gamma$), BR($\mu \to 3e$), CR($\mu - e$, N)
  within **experimental reach!**

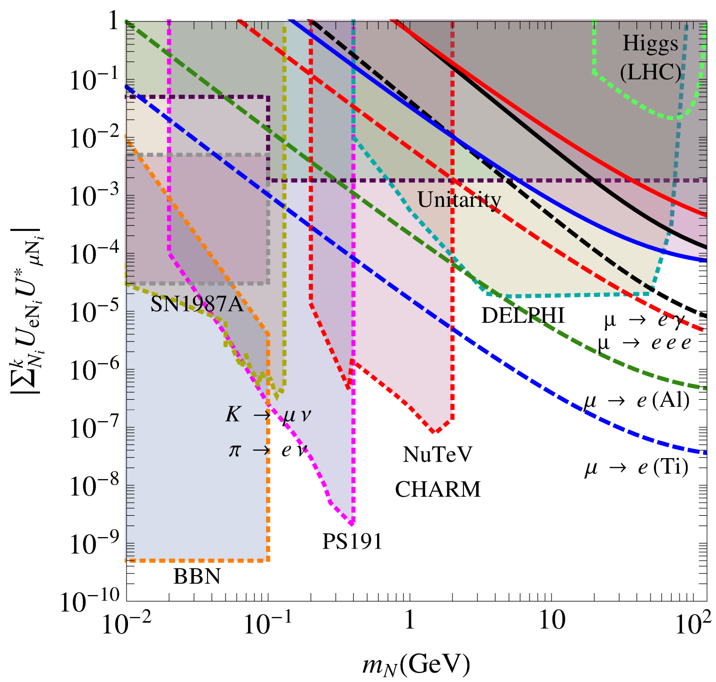


- **At colliders: direct searches** for **seesaw mediators**

[Banerjee et al, 1503.05491]

[Alonso et al, 1209.2679]





- **Searches** at **high-intensity facilities and colliders** ⇒ **complementary probes of seesaw!**

cLFV: Inverse Seesaw (ISS) realisations

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

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

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

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

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

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

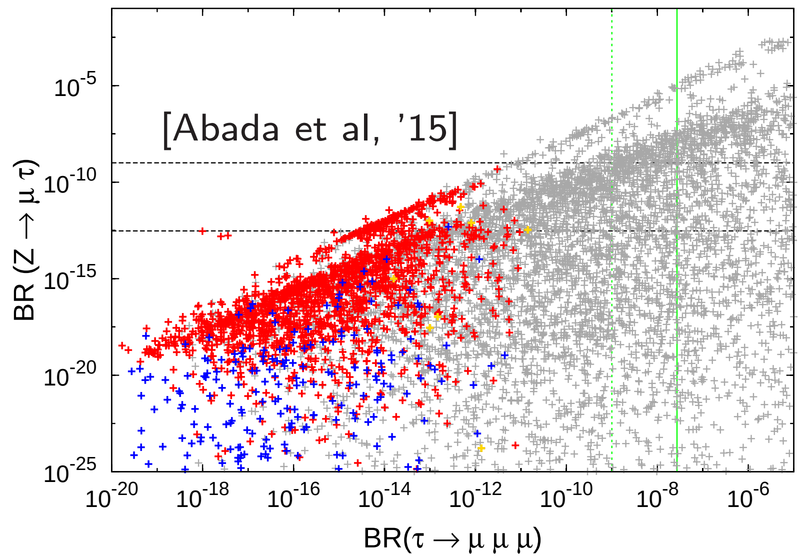
- **Non-unitarity $\tilde{U}_{\text{PMNS}}$ $\Rightarrow$ modified neutral and charged leptonic currents**
- **New (virtual) states & modified couplings:** many new "observable" phenomena

cLFV, non-universality, signals at colliders!

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

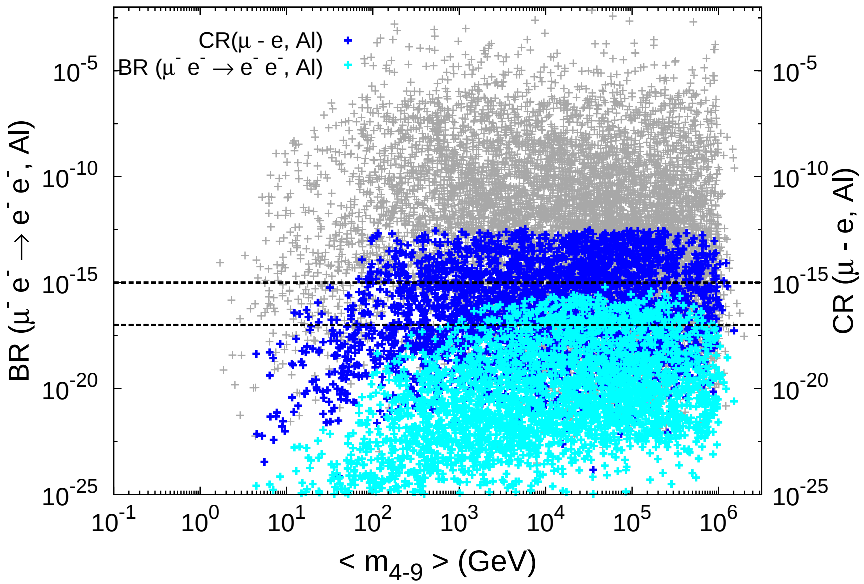
cLFV: (3,3) ISS realisation

- **At high energies (FCC-ee): BR($Z \to \tau\mu$)** allows to **probe $\mu - \tau$ cLFV** beyond **SuperB reach**

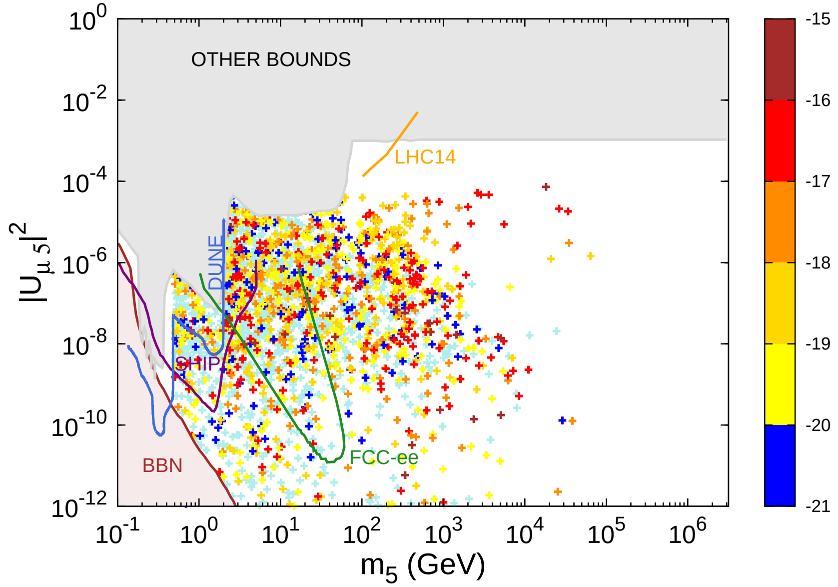


- **Rich low-energy phenomenology (cLFV, LFU, ...)**
  For $M_R \gtrsim \Lambda_{EW}$: cLFV observables within **exp reach**
  NA62, Mu2e, COMET, FCC...

(3,3) ISS realisation [Abada, De Romeri and AMT, '15]



Log BR($\mu e \to ee$)



- **Sizeable values for the different observables!**
  Within reach of **high-intensity facilities and colliders** ⇒ complementary probes!

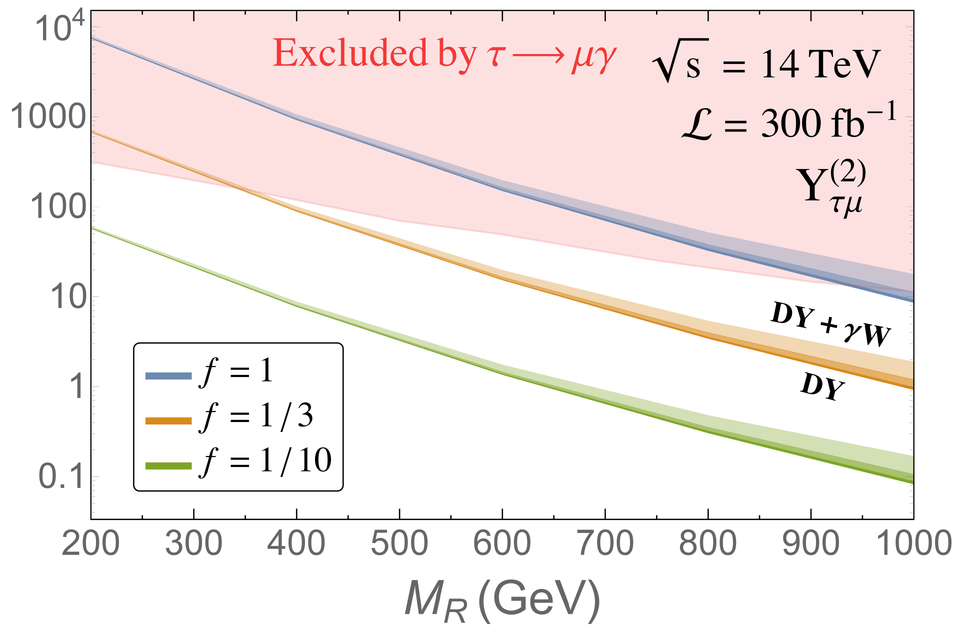
cLFV: (3,3) ISS realisation at colliders

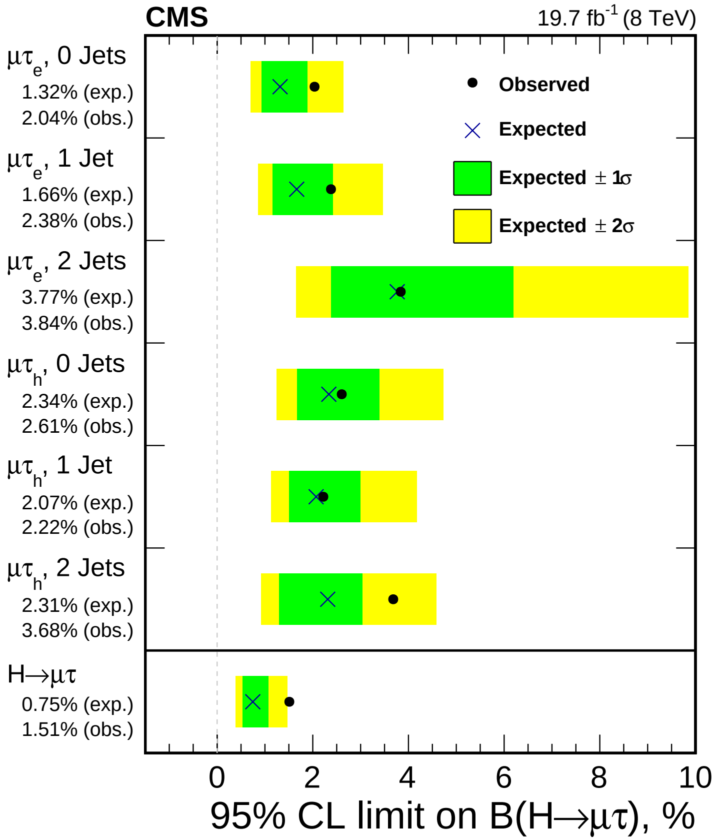
- **cLFV exotic events at the LHC**
  - Searches for **heavy N** at the LHC

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

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

[Arganda et al, 1508.05074]





- **cLFV Higgs decays in ISS:**

  $$\mathrm{BR}(H \to \ell\tau) \lesssim 10^{-5}..$$

  [Arganda et al, 1405.4300]

[CMS Coll., '15]

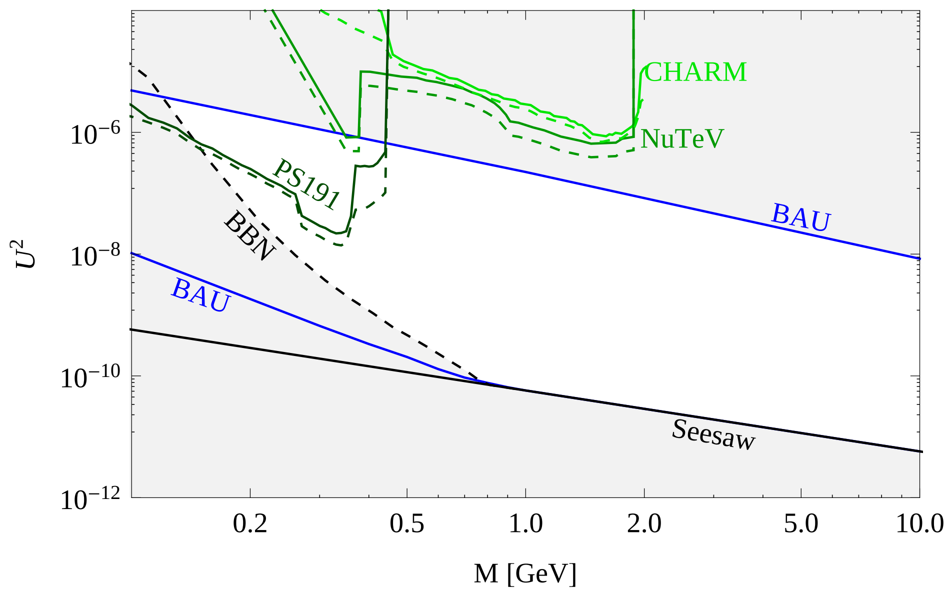
cLFV and ν_s: νMSM

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

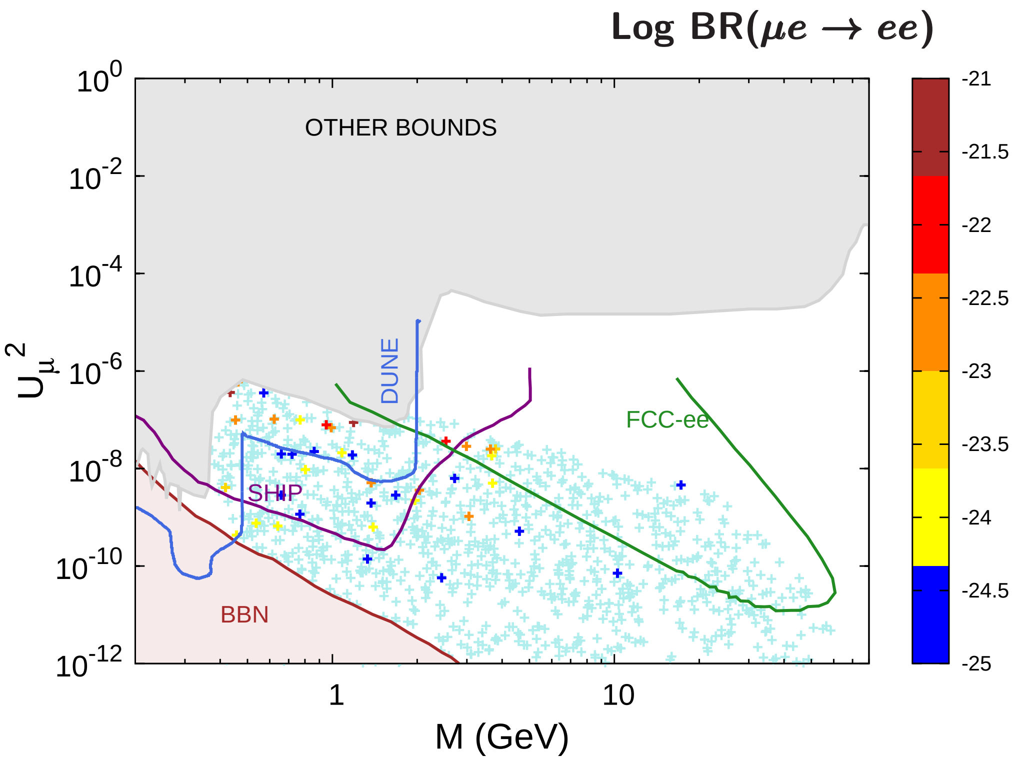
  New states account for m_ν^{light}, offer DM candidate, allow for BAU via leptogenesis

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

[Canetti et al, '13]



[Abada et al, '15]



- ν**MSM: very difficult prospects for cLFV**

- **Concluding remarks**

cLFV and sterile neutrinos: outlook

- **Lepton flavour violation and New Physics**

  cLFV observables can provide (indirect) **information on the underlying NP model**

  Numerous observables currently being searched for!

  $\Rightarrow$ **very intensive worldwide experimental programme**

- **Extending the SM with sterile fermions**

  Theoretically and phenomenologically motivated; impact on many **observables!**

  Sterile states: actively searched for at **high energy, high intensity and in cosmology**

- **Sterile neutrinos and cLFV**

  Sizable contributions to many observables (some leading to **stringent constraints**)

  including **BR($\ell_i \to \ell_j \gamma$)**, **BR($\ell_i \to 3\ell_j$)**, **CR($\mu - e$, N)** and **BR($\mu^- e^- \to e^- e^-$)**

  $\Rightarrow$ potentially within **experimental reach**

  Analysis carried for simple "3+1 toy model" and **mechanisms of ν mass generation**

  low-scale type I, Inverse Seesaw, νMSM

  Interplay at high-intensity & high-energy: probe the **underlying source of LFV**