LPT-Orsay

Some phenomenological aspects of sterile fermions

- ☞ Motivating sterile neutrinos
- ☞ Theoretical frameworks
- ☞ Direct and indirect searches: LFUV, cLFV, CPV,...
  at high-intensities and colliders

Invisibles 2016, Padova, 12 Septembre 2016

invisiblesPlus elusives

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Beyond the SM: sterile fermions

☞ **Observational problems (not accounted by the SM):**

BAU, DM, ν masses & mixings

☞ **Extending the SM with sterile fermions**: **singlets** under SU(3)$_c\times$SU(2)$_L\times$U(1)$_Y$

Interactions with SM fields: through **mixings** with **active neutrinos**

A priori, **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

keV scale $\leftrightarrow$ warm dark matter candidates; explain pulsar velocities (kicks); 3.5 keV line..

MeV - TeV scale $\leftrightarrow$ experimental testability! (and BAU, DM, m_ν generation...)

Beyond 10^9 GeV $\leftrightarrow$ theoretical appeal: standard seesaw, BAU, GUTs

m_{ν_s}	Motivation	ν-oscillations	laboratory searches
$\lesssim$ eV	ν-oscil. anomalies, dark radiation	massses by seesaw, explain anomalies	oscillation anomalies, β-decays
keV	DM	no if DM	direct searches? , nuclear decays?
MeV	testability	masses by seesaw	intensity frontier, $0\nu\beta\beta$
GeV	testability, minimality	masses by seesaw	intensity frontier, EW precision data, $0\nu\beta\beta$
TeV	minimality, testability	masses by seesaw	LHC
$\gtrsim 10^9$ GeV	grand unification, "naturality"	masses by seesaw	–

m_{ν_s}	CMB	BBN	DM	Leptogenesis
$\lesssim$ eV	explain $N_{\text{eff}} > 3$	may explain $N_{\text{eff}} > 3$	no	no
keV	act as DM, no effect on N_{eff}	effect on N_{eff} too small if DM	good candidate	no
MeV	unaffected	constrains $m_{\nu_s} \gtrsim 200$ MeV	no	possible (finetuning)
GeV	unaffected	unaffected	no	possible
TeV	unaffected	unaffected	no	possible
$\gtrsim 10^9$ GeV	unaffected	unaffected	no	natural

[Adapted from Drewes, '13]

☞ **Extending the SM with sterile fermions**: (testable!) **theoretical frameworks**

▶ **Incorporating ν_R - low scale seesaws: type I seesaw [TeV]** ➞ small Y^ν

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & v\, Y^{\nu T} \\ v\, Y^\nu & M_R \end{pmatrix}$$

$$\Rightarrow m_\nu \approx -v^2 Y_\nu^T \frac{1}{M_R} Y_\nu$$

type I seesaw & MFV ➞ "large" Y^ν

νMSM [GeV] ➞ tiny Y^ν

▶ **Incorporating ν_R and additional sterile fermions: Inverse seesaw (ISS)** ➞ sizeable Y^ν

$$\mathcal{M}_{\text{ISS}} = \begin{pmatrix} 0 & Y_\nu^T v & 0 \\ Y_\nu v & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

$$\Rightarrow m_\nu \approx \frac{(Y_\nu v)^2}{M_R^2} \mu_X$$

Linear seesaw (LSS) ➞ sizeable Y^ν

$$\mathcal{M}_{\text{LSS}} = \begin{pmatrix} 0 & Y_\nu^T v & M_L^T \\ Y_\nu v & 0 & M_R \\ M_L & M_R^T & 0 \end{pmatrix}$$

$$\Rightarrow m_\nu \approx (vY_\nu)\,(M_L M_R^{-1})^T + (M_L M_R^{-1})\,(vY_\nu)^T$$

[see, e.g., Mohapatra et al, 1986,Gonzalez-Garcia et al, 1988, Deppisch et al, '04, Asaka et al, '05, Gavela et al, '09, Ibarra, Petcov et al, '10, Abada, Lucente, '14, ...]

☞ **Extending the SM with sterile fermions**: phenomenological consequences

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

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

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

$\mathbf{U}_{\alpha i}$ ➞ modified lepton mixing - now encodes also active-sterile mixings

(for $N_s = 0$, $\mathbf{U}_{\alpha i} = U_{\text{PMNS}}$)

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

☞ **Huge impact for numerous observables**: high-intensity and colliders (as well as DM, ..)

But also abundant constraints..

☞ **Illustrate these phenomenological consequences via simple ad-hoc extensions**:

SM + N_s sterile fermions

☞ **Extending the SM with sterile fermions**: (testable!) **simple "ad-hoc models"**

First phenomenological studies can be carried for SM $+ \#\nu_s$ ➤ "$3 + N_s$"

No hypothesis on mechanism of neutrino mass generation (seesaw, ...)

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

mixing matrix (angles and CPV phases)

$$U_{(3+N_s)\times(3+N_s)} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Left-handed lepton mixing $U_{\alpha 1-3}$:

$\tilde{U}_{\text{PMNS}}$ (non-unitary)

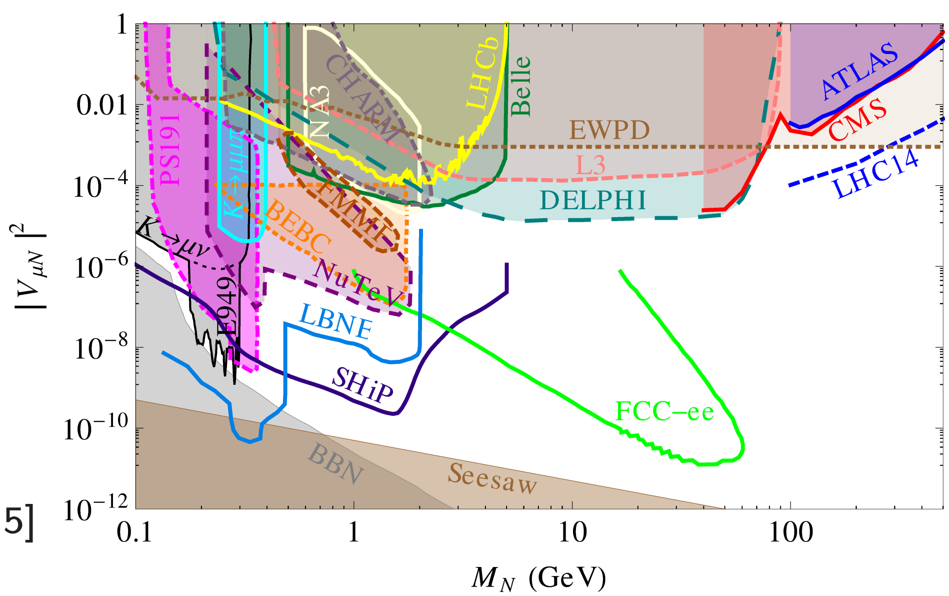
Active-sterile mixing: $\mathbf{U}_{\alpha i}$

$\mathbf{U} = U|_{3\times(3+N_s)}$

☞ **Heavily constrained**

sterile masses and mixings

[Deppisch et al, '15]



☞ Constraints on sterile fermions

- **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 (contd.)

Neutrinoless double beta decays - $|m_{ee}|$: [EXO-200, KamLAND-Zen, GERDA,...]

[Blenow et al, '10; Lopez-Pavon et al, '13; AA 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; AA 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 fermions: contributions to observables**

➞ **Cosmology and astroparticle**

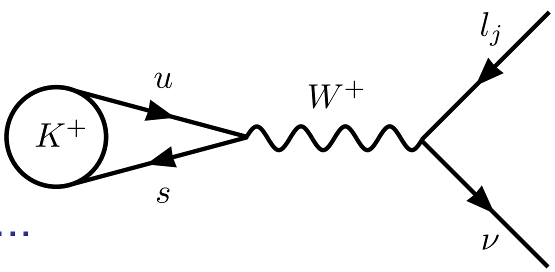
⇒ BAU from leptogenesis (oscillations) [See talk by Hernandez]

⇒ (Warm) dark matter candidates [White paper: Drewes et al, '16, Merle, AA, Lucente, Arcadi, '14, ...

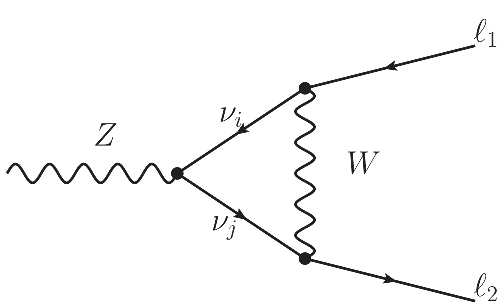
⇒ Astrophysical puzzles: pulsar kicks, ... [e.g. Kusenko, '04 & '09]

➞ **Particle physics**

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



Rare decays:
- Lepton number violation
- Violation of lepton flavour
- cLFV Z decays
- cLFV and invisible H decays
- Collider signatures, ...



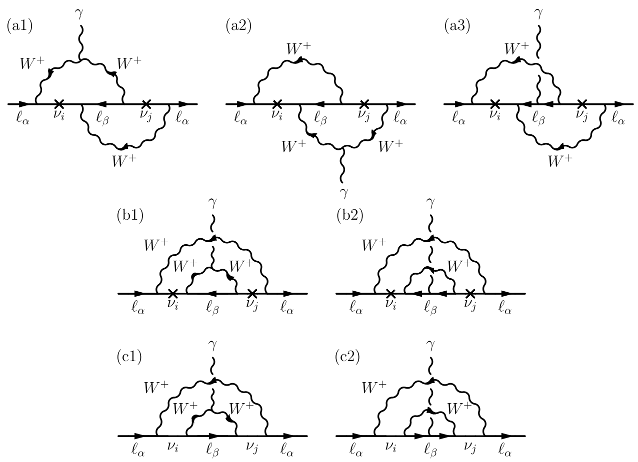
☞ Sterile fermions & CPV: contributions to EDMs

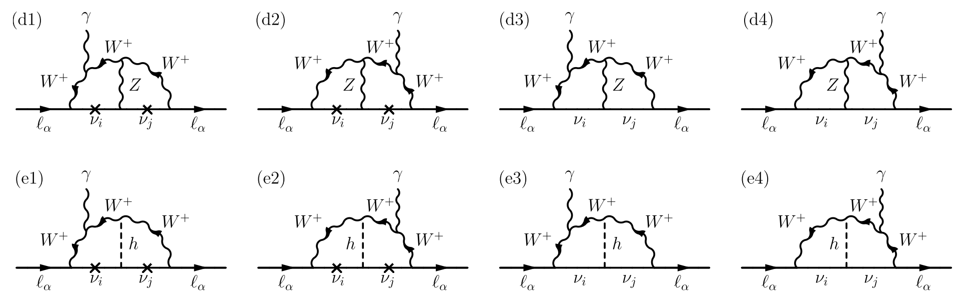
- **Majorana (and Dirac) phases ⇒ lepton EDMs**:

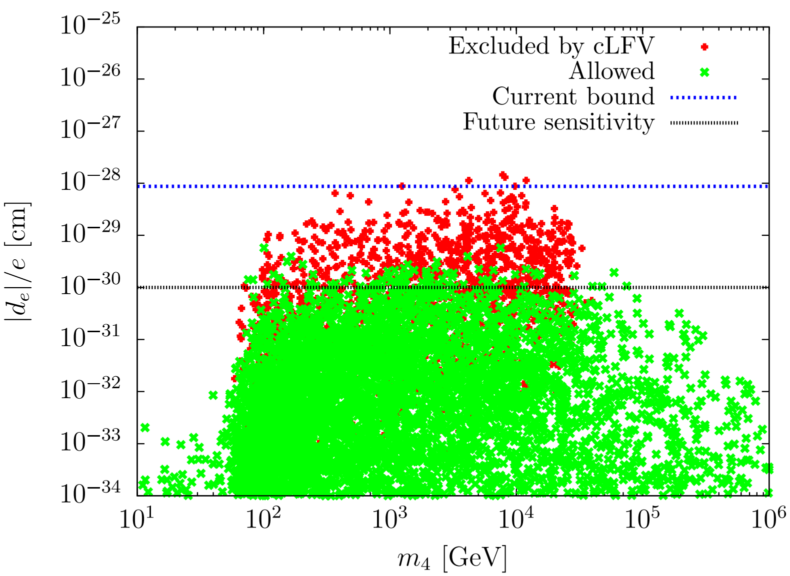
$$d_e = -\frac{g_2^4\, e\, m_e}{4(4\pi)^2 m_W^2} \sum_\beta \sum_{i,j} \left[J^M_{ije\beta} I_M(x_i, x_j) + J^D_{ije\beta} I_D(x_i, x_j) \right],$$

$$J^M_{ij\alpha\beta} \equiv \mathrm{Im}\left(U_{\alpha j} U_{\beta j} U^*_{\beta i} U^*_{\alpha i}\right), \qquad J^D_{ij\alpha\beta} \equiv \mathrm{Im}\left(U_{\alpha j} U^*_{\beta j} U_{\beta i} U^*_{\alpha i}\right)$$

- Many new (2-loop) contributions!







- **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]**

  Within ACME reach

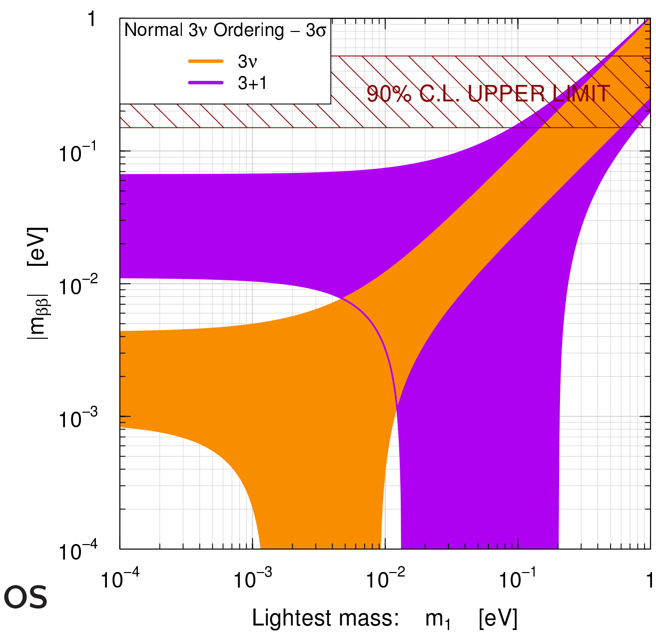
[AA and Toma, '15]

☞ Sterile fermions: lepton number violation

▶ **Lepton number violation: $0\nu2\beta$ decays**

▶ ν_s can strongly impact **predictions for $|m_{ee}|$**

$\Rightarrow$ **augmented ranges** for effective mass *(IH and NH)*

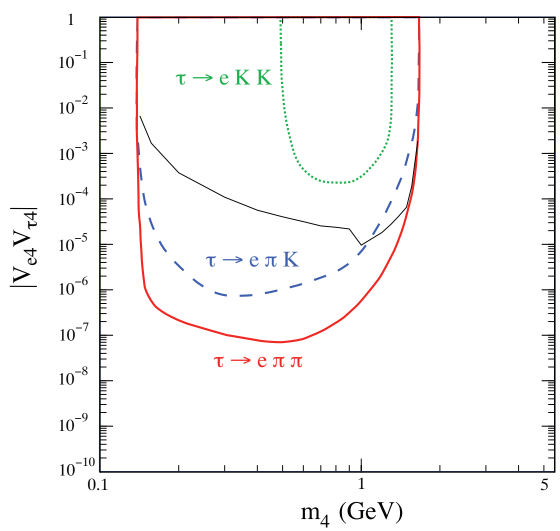


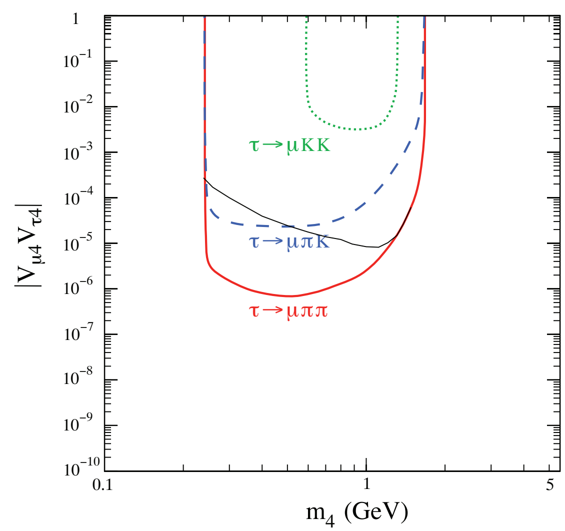
▶ **Observation of $0\nu2\beta$ signal** in future experiments

does not imply Inverted Ordering for light neutrinos

[AA, De Romeri and Teixeira, '14; Lopez-Pavon et al. '13, Girardi, Meroni, Petcov, '13,...; Giunti et al, '15 ⟵]

▶ **Lepton number violation in meson decays**





$$\tau^- \to \ell^+\pi^-\pi^-(K^-K^-)$$
$$\tau^- \to \ell^+\pi^-K^-$$
$$D^-_{(s)} \to \ell^-\ell'^-\pi^+(K^+)$$
$$B^- \to \ell^-\ell'^-\pi^+(K^+, D^+)$$

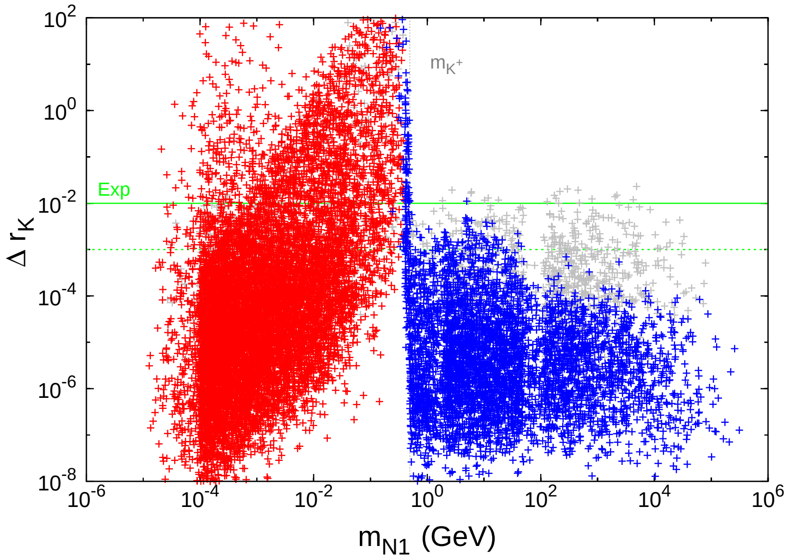
[Belle, BaBar, LHCb - NA62, ...]

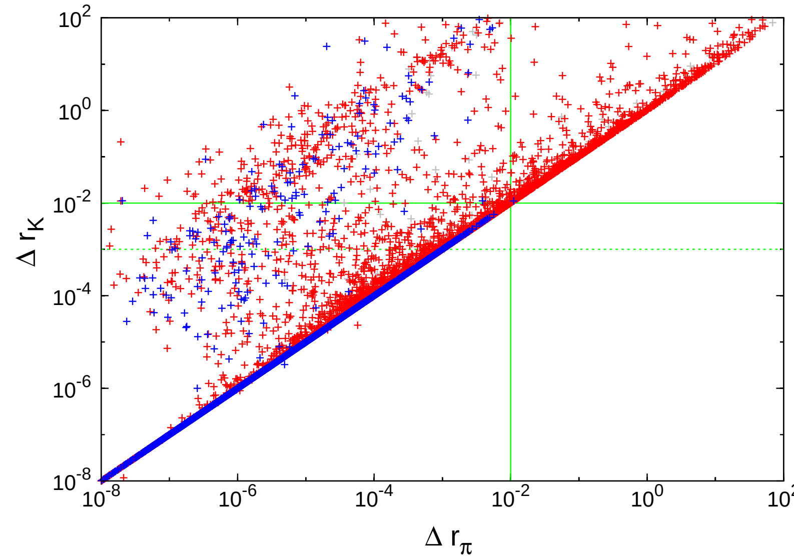
[Atre et al, '09]

☞ Sterile fermions: violation of lepton flavour universality

Lepton Universality Violation in K and π decays: tree level effect

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

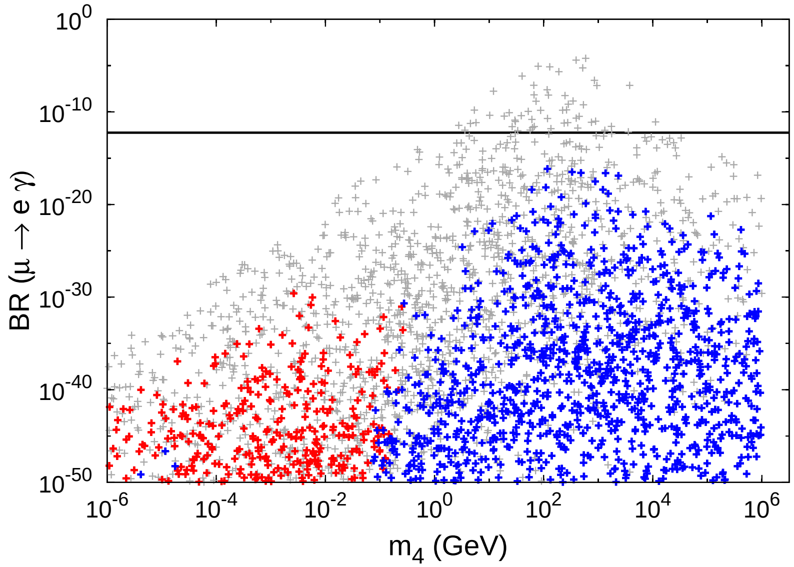




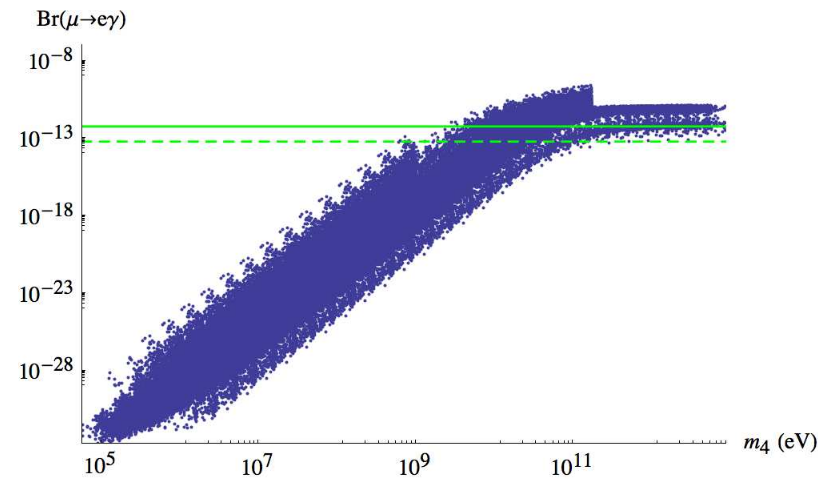
[*"ISS (3,3)"*: AA, Teixeira, Vicente and Weiland, '11-'13]

- **Sterile neutrino contributions:** $\Delta r_{K,\pi} \gtrsim \mathcal{O}(10^{-2})$
- $\Delta r_{K,\pi} \sim \mathcal{O}(1) \Rightarrow$ one of the **strongest constraints in SM + ν_s models!**

☞ Sterile fermions: cLFV in radiative decays $\ell_i \to \ell_j \gamma$ and 3-body decays $\ell_i \to 3\ell_j$



"3+1" toy model, [AA, De Romeri and Teixeira, '15]



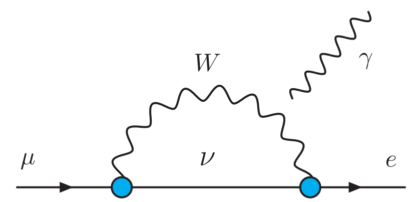
"(2,2) ISS realisation" [AA and Lucente, '14]

- Consider $\mu \to e\gamma$:

  for $m_s \gtrsim 10 - 100$ GeV sizeable ν_s contributions

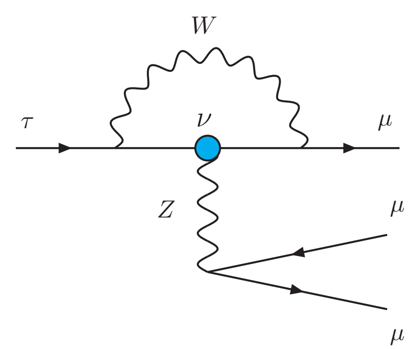
  ... but precluded by invisible Z width

  And by other cLFV observables!



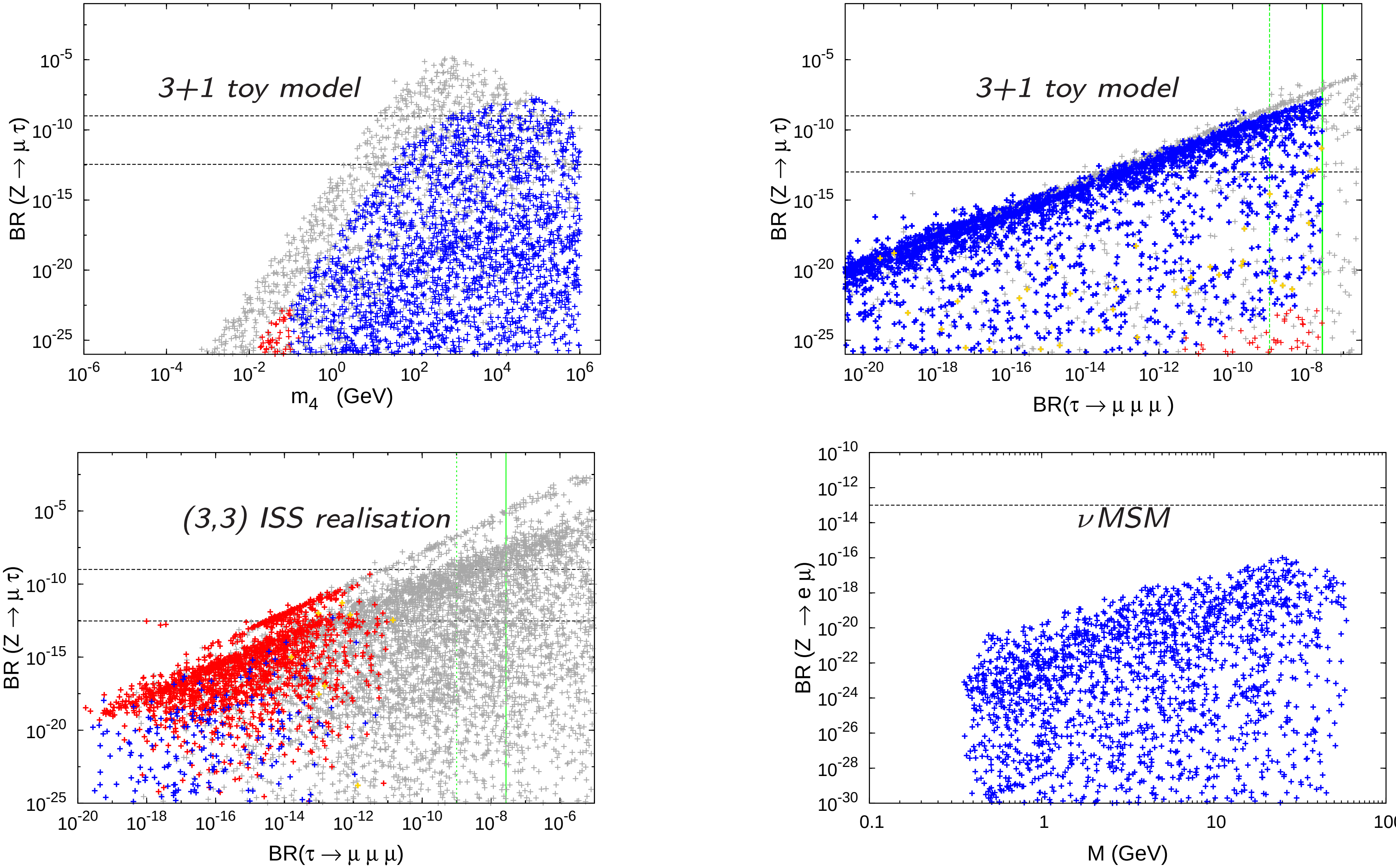
- **Particularly constraining: BR($\mu \to 3e$), CR($\mu - e$, N)**

  Dominated by Z penguin contributions for $m_s \gtrsim M_Z$



☞ Sterile fermions: cLFV at high- and low-energies

[AA, De Romeri, Monteil, Orloff, Teixeira, '15]



- **Complementarity probes** of ν_s **cLFV** at **low- and high energies!** (and in LNV...)
- $Z \to \mu\tau$ at FCC-ee: allows to **probe $\mu - \tau$ cLFV** beyond **SuperBelle reach**

[see also De Romeri et al, '16]

☞ Sterile fermions: cLFV in muonic atoms

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

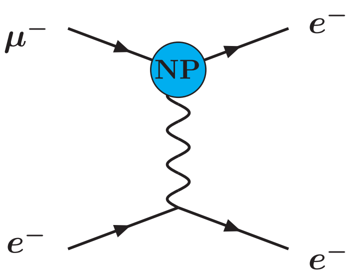
  Interesting laboratory to study cLFV! $\boldsymbol{\mu - e}$ conversion

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

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

- **Experimental status:** **New observable!**

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



- **Coulomb interaction** increases overlap between

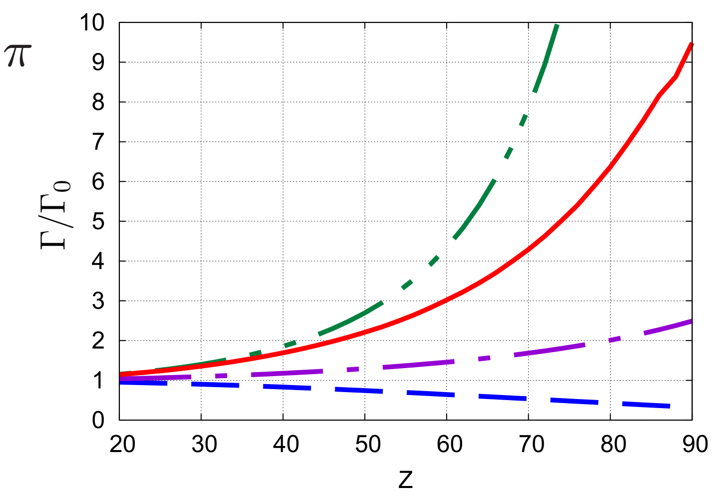
  Ψ_{μ^-} and Ψ_{e^-} wave functions

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

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

  $\boldsymbol{\Gamma/\Gamma_0 \gtrsim 10\times(Z-1)^3}$ [Uesaka et al, '15-'16]

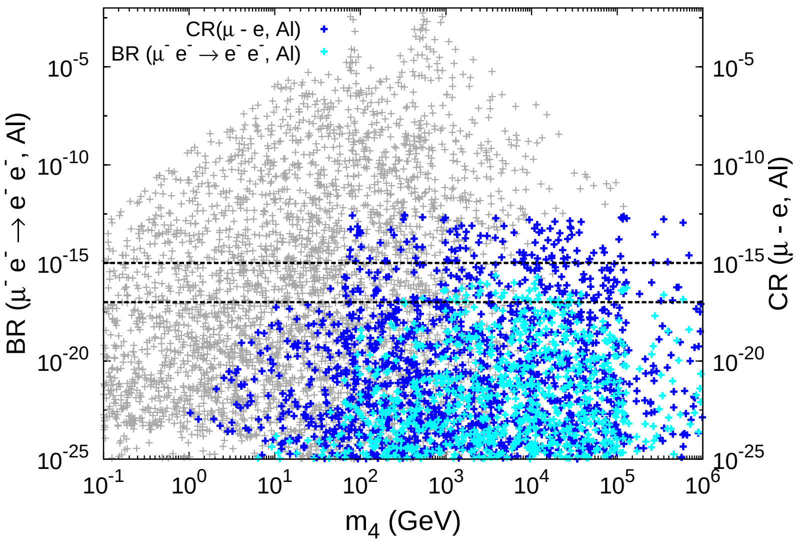
  Consider experimental setups for **Pb, U !?**

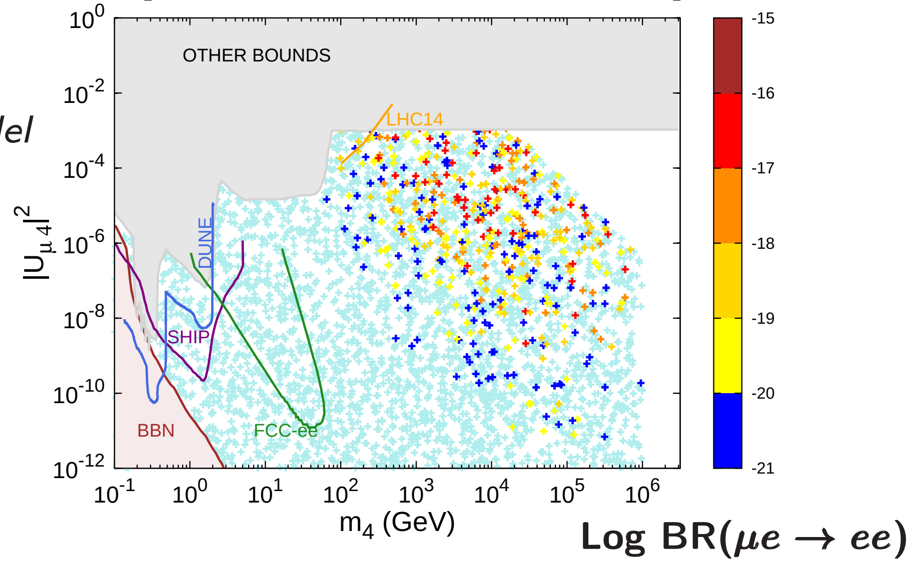


☞ Sterile fermions: cLFV muonic atom decays

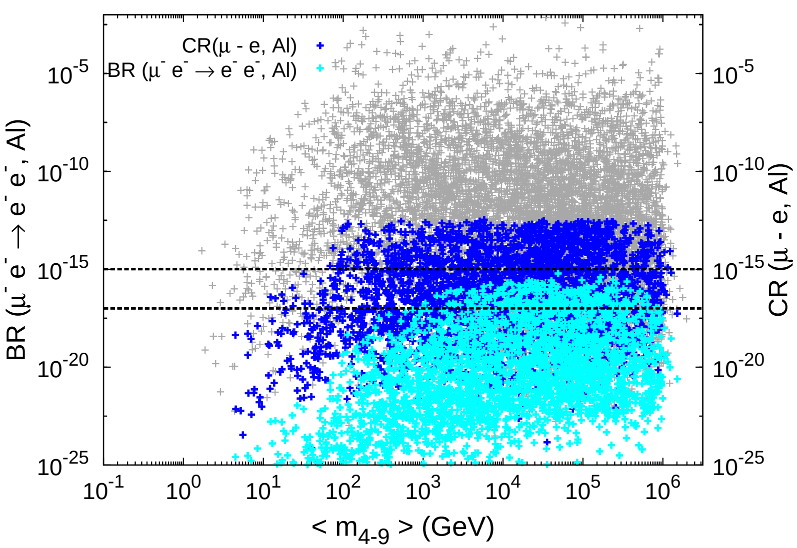
[AA, De Romeri, Teixeira, '15]

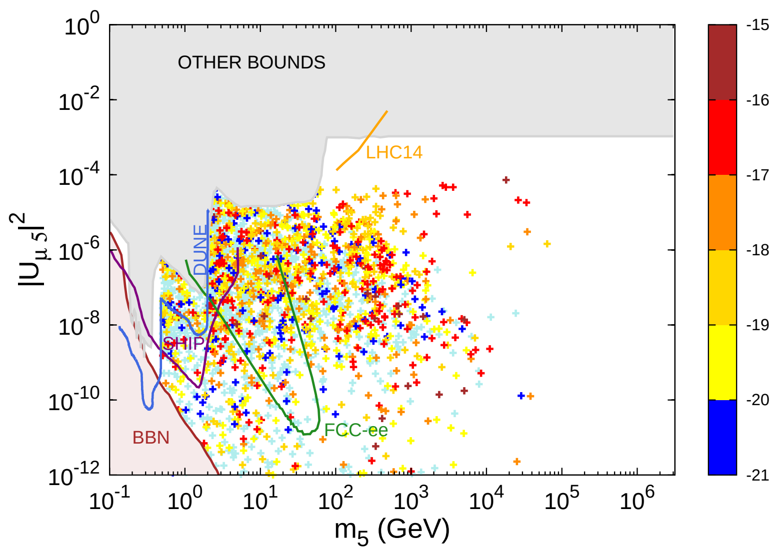
3+1 toy model





(3,3) ISS





▶ **Sizeable values** for BR($\mu^- e^- \to e^- e^-$) - potentially within **experimental reach!**

▶ For **Aluminium**, CR($\mu - e$) appears to have **stronger experimental potential**

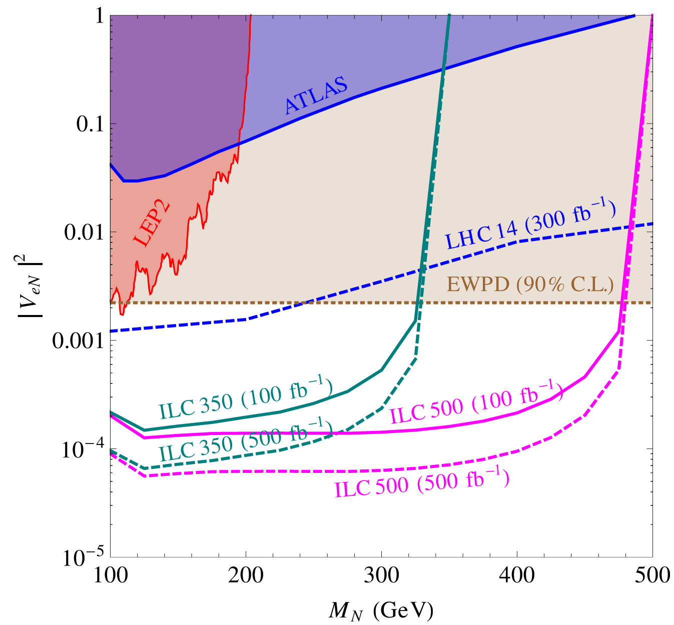
.. consider **"heavy" targets** to probe BR($\mu^- e^- \to e^- e^-$)

☞ Sterile fermions: searches at the LHC and beyond

▶ Searches for ν_s by ATLAS and CMS
"smoking-gun" (LNV) channel:
$p\,p \to W^* \to N\,\ell^\pm \to \ell^\pm + \ell^\pm + 2\,$jets

▶ Promising prospects for FCC-ee, ILC, CEPC...
[Banerjee et al, 1503.05491]

▶ Further searches carried for LFV final states and/or other exotic channels

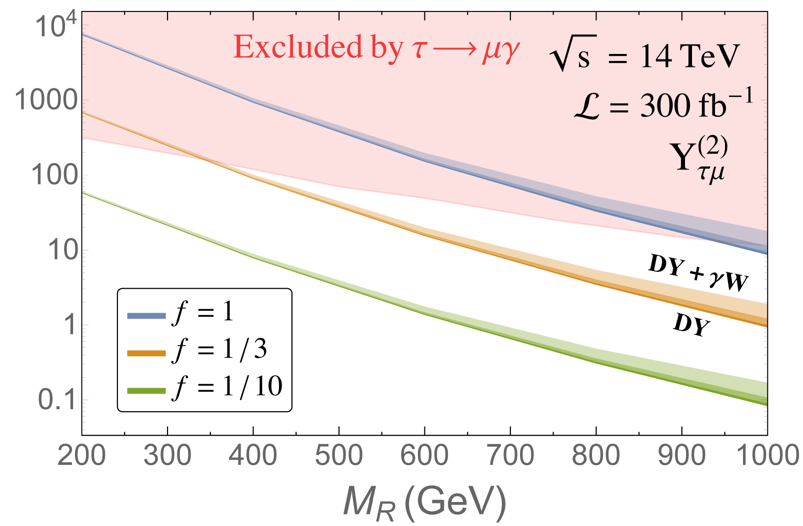


▶ **cLFV exotic events at the LHC**

▶ Searches for **heavy N** at the LHC

$q\,q' \to \tau\,\mu + 2$ **jets** (no missing E^T!)

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



[Arganda et al, 1508.05074]

▶ **Resonant mono-Higgs production at FCC-ee**

$N \to H\,\nu \rightsquigarrow$ sizeable deviations from SM mono-Higgs

▶ Sensitive probe of ν_s at high-energies! [Antusch et al, '15]

☞ Sterile fermions: further appeal

▶ GeV sterile neutrinos ➞ (testable) BAU from leptogenesis via oscillations

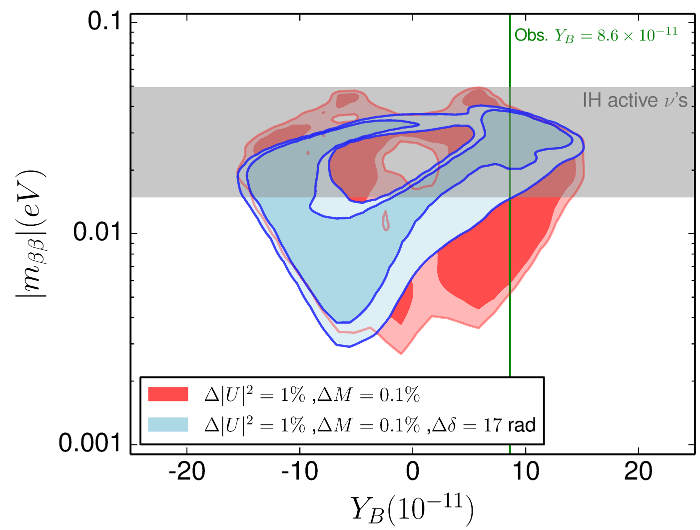
Synergy with (LNV) low-energy observables:

$0\nu 2\beta$ decays

Spectrum & mixings (SHiP),

determination of δ_{CP} (DUNE, HyperK)

[Hernandez et al, '16]

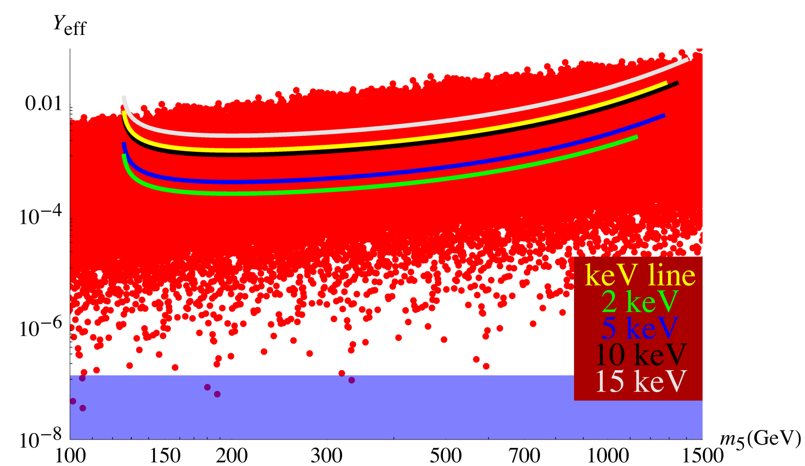


▶ Sterile neutrinos ➞ viable warm dark matter candidates [for a review, see Drewes et al, '16]

$\Rightarrow$ impact on structure formation;

signal from γ-rays (3.5 keV line), ...

"(2,3) ISS" [AA, Arcadi and Lucente, '14]



☞ Conclusions

- **SM + Sterile fermions** constitute the “most minimal BSM" ...

  ...**embedded in several well motivated frameworks**

- **Sterile neutrinos** contribute to a vast array of observables: CPV, LNV, LFUV, cLFV, ...

  ... at high and low energy

- **Sterile neutrinos:** key rôle in cosmology as well

- **Sterile neutrinos testable at the three frontiers:** high intensity, high energy and cosmology

  and in LNV neutrinoless double beta decays

Could the NP be "SM + sterile fermions"?

Additional observables

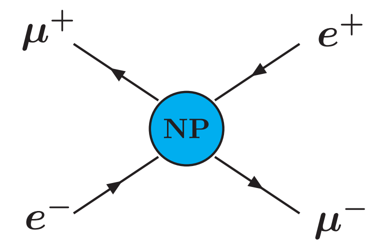
cLFV in "muonic" atoms: Muonium

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

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

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

  Future prospects at **FNAL** ?

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

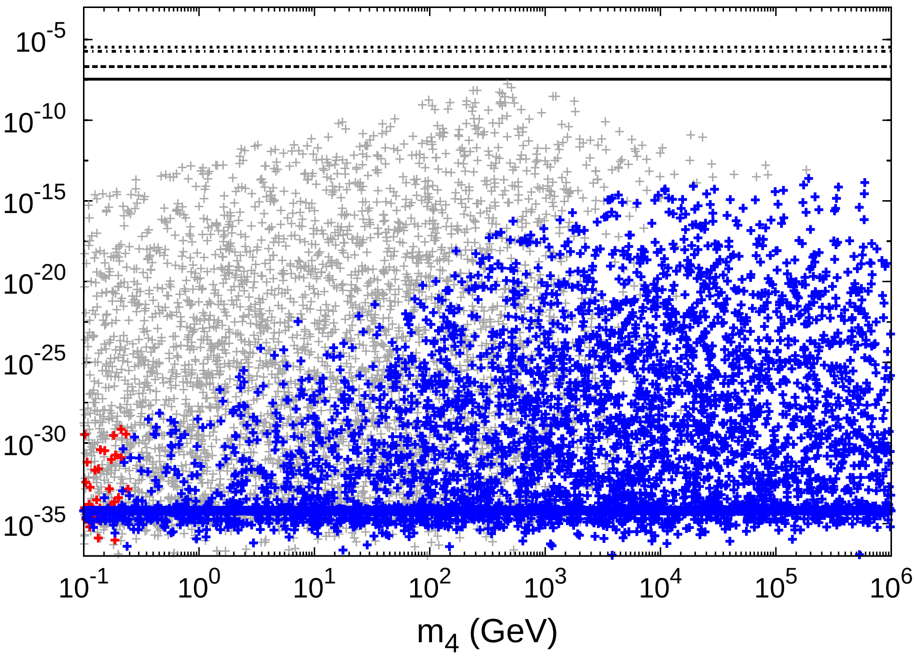
  clear signal compared to SM decay $\text{Mu} \to e^+ e^- \bar{\nu}_\mu \nu_e$ (no missing energy)

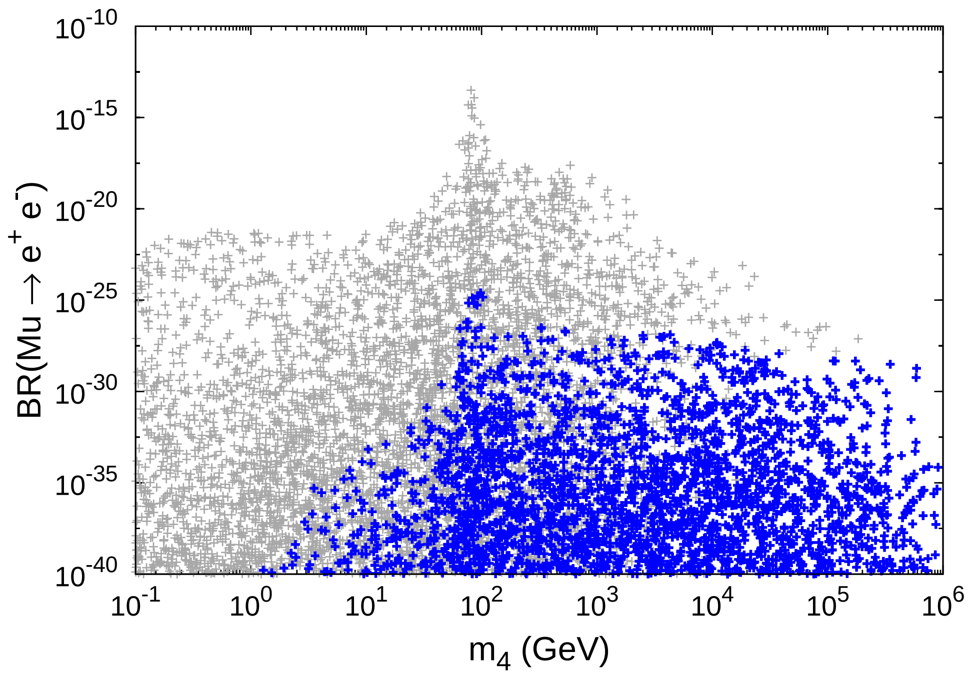
- **Experimental status:** no clear roadmap (nor bounds)...

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

Muonium and sterile neutrinos

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



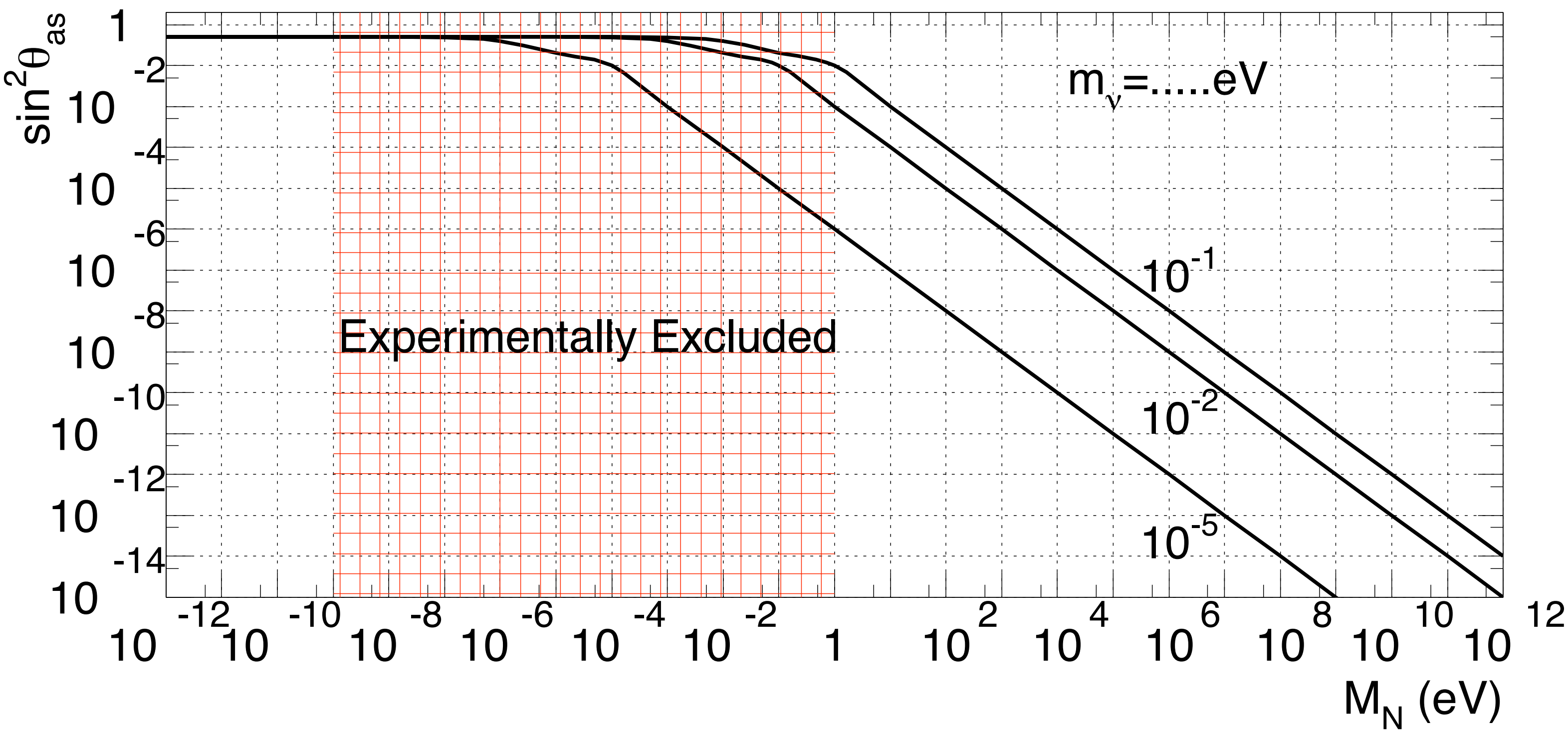


"3+1" toy model [AA, De Romeri and Teixeira, '15]

▶ **Large values** of $G_{\mathrm{M\bar{M}}}$ 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 ?



[de Gouvea et al, '09]