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 \(\nu\)-mass generation
  - cLFV at high-intensities and high-energies

- Outlook
cLFV and New Physics

- Flavour violation in charged lepton sector: Physics beyond SM\(m_\nu\)!

  Are neutral and charged LFV related?
  Does cLFV arise from \(\nu\)-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 \(\nu\)-mass generation...?
Sterile fermion extensions of the SM
Beyond the 3-neutrino paradigm

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

**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 $\nu$ **masses and mixings**

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

- **eV scale** ↔ extra neutrinos suggested by short baseline $\nu$ oscillation anomalies
  (oscillation results not explained within 3 flavour oscillation)

- **keV scale** ↔ warm dark matter candidates; explain pulsar velocities (kicks)
  (extensive bounds to be complied with...)

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

- **Beyond $10^9$ GeV** ↔ 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 $\nu$s 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. $\Delta r_K$)

**Rare decays:**

- Violation of lepton flavour
- $c$LFV $Z$ decays
- $c$LFV and invisible $H$ decays
  [Collider signatures]

► Already many **constraints** on the sterile masses and mixings!
Theoretical frameworks of $\nu_s$

- Numerous SM extensions aiming at accounting for $\nu$ masses and mixings

\[ \nabla \text{Right-handed neutrinos} \text{ (low scale seesaws: type I, $\nu$MSM, ...)} \]

\[ \mathcal{L}_{\text{type I}} = -Y^\ell \tilde{L}_L H e_R - Y^\nu \bar{\nu}_R \tilde{H} \nu_L - \frac{1}{2} \bar{\nu}_R M_N \nu_R^c \quad \Rightarrow m_\nu \sim \frac{v^2 y_\nu^2}{M_N} \]

- Other neutral fermions ($\nu_R$ + extra sterile states in Inverse Seesaw, ...)

\[ \mathcal{L}_{\text{ISS}} = -Y^\nu \bar{\nu}_R \tilde{H} L - M_R \bar{\nu}_R X - \frac{1}{2} \mu_X \tilde{X}^c X + \frac{1}{2} \mu_R \bar{\nu}_R \nu_R^c \quad \Rightarrow m_\nu \sim \frac{v^2 y_\nu^2}{M_R} \frac{\mu_X}{M_R} \]

$\Rightarrow$ Neutrino oscillation data; leptogenesis; DM (?); very rich phenomenology

- Simplified “toy models” for phenomenological analyses: SM + $\nu_s$

“ad-hoc” construction (no specific assumption on mechanism of mass generation)

encodes the effects of $N$ additional sterile states in a single one

$\ldots$ Not to be confused with oscillation anomaly solution!...
"Toy model" for phenomenological analyses: SM + $\nu_s$

- **Assumptions:** 3 active neutrinos + 1 sterile state

  $n_L = (\nu_{e}, \nu_{\mu}, \nu_{\tau}, \nu^c_s)^T$

  Interaction basis $\leftrightarrow$ Physical basis

  $U_{4 \times 4}^T M U_{4 \times 4} = \text{diag}(m_{\nu_1}, ..., m_{\nu_4})$

  "Majorana mass": $L_{\text{toy}} \sim n^T_L C M n_L$

- **Active-sterile mixing $U_{\alpha i}$:**

  Rectangular matrix $\leftarrow U = U|_{3 \times 4}$

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

  $3 \times 3$ sub-block, non-unitary!

- **Physical parameters:** 4 **masses** [3 light (mostly active) + 1 heavier (mostly sterile) states]

  6 **mixing angles** [$\theta_{12}, \theta_{23}, \theta_{13}, \& \theta_{i4}$] and 6 **phases** [(3 Dirac and 3 Majorana)]

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

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

  $L_{Z^0} \sim -\frac{g_w}{2 \cos \theta_w} Z_{\mu} \sum_{i,j=1}^{3+n_S} \bar{\nu}_i \gamma^\mu \left[ P_L (U^U)^{ij} - P_R (U^U)^{ij}_* \right] \nu_j$
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 $X^\pm_M \to \ell^\pm \nu_s$
  [Shrock, ’80-'81; Atre et al, ’09; Kusenko et al, ’09; Lello et al,’13]

- **Beam dump experiments:** $\nu_s$ decay products (light mesons, $\ell^\pm$) from $X^\pm_M$ 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. $K^+ \rightarrow \ell^+ \ell^+ \pi^-$
  Lepton Universality Violating (LUV) e.g. $R_{X_M}$, $R(D)$, $R_\tau$
  [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-$\alpha$, 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 $\Rightarrow$ lepton EDMs
  - Non-vanishing contributions: at least two sterile $\nu$
  - $|d_e|/e \geq 10^{-30}$ cm for $m_{\nu_{4,5}} \sim [100 \text{ GeV}, 100 \text{ TeV}]$
  
  [Abada and Toma, '15]

- **Lepton number violation: $0\nu2\beta$ decays**
  - $\nu_s$ 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 $\nu_s$

  [Abada, De Romeri and AMT, '14; ...; Giunti et al, '15 ⤷]
Impact for lepton properties

- Lepton Universality Violation in $K$ and $\pi$ decays

$$R_P = \frac{\Gamma(P \rightarrow e\nu)}{\Gamma(P \rightarrow \mu\nu)}$$

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: $\Delta r_{K,\pi} \gtrsim O(10^{-2})$ (in contrast with SUSY models)

[Fonseca, Romao and AMT '12]

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

- Many other LFU violation observables (sensitive to $\nu_s$ ?!)

[ Presentation by D. Guadagnoli ]
Sterile neutrinos and cLFV: simple “toy models”
\( \nu_s \) and cLFV: radiative and 3 body decays

- **Radiative decays:** \( \ell_i \to \ell_j \gamma \)
  - Consider \( \mu \to e\gamma \)
  - For \( m_4 \gtrsim 10 \text{ GeV} \) sizable \( \nu_s \) 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 \( \nu_s \) cLFV at low- and high energies! (and in LNV...)
cLFV in “muonic” atoms: $\mu - e$ conversion

- **Muonic atoms:** 1s bound state formed when $\mu^-$ stopped in target
  - SM processes: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ (decay in orbit); $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1)$ (nuclear capture)

- **cLFV $\mu^- - e^-$ conversion:** $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$
  - coherent conversion, increases with $Z$ (maximal for $30 \leq Z \leq 60$)

- **Event signature:** single mono-energetic electron
  \[ E_{\mu e}^N = m_\mu - E_B(A, Z) - E_R(A, Z), \quad E_{\mu e}^{Al, Pb, Ti} \approx \mathcal{O}(100 \text{ MeV}) \]

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

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

<table>
<thead>
<tr>
<th>CR($\mu - e$, N) bound</th>
<th>material</th>
<th>year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.3 \times 10^{-12}$</td>
<td>Ti</td>
<td>1993</td>
</tr>
<tr>
<td>$4.6 \times 10^{-11}$</td>
<td>Pb</td>
<td>1996</td>
</tr>
<tr>
<td>$7 \times 10^{-13}$</td>
<td>Au</td>
<td>2006</td>
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<table>
<thead>
<tr>
<th>Experiment (material)</th>
<th>future sensitivity</th>
<th>year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mu2e (Al)</td>
<td>$3 \times 10^{-17}$</td>
<td>$\sim 2021$</td>
</tr>
<tr>
<td>COMET (Al) - Phase I (II)</td>
<td>$10^{-15}$ ($10^{-17}$)</td>
<td>$\sim 2018$ (21)</td>
</tr>
<tr>
<td>PRISM/PRIME (Ti)</td>
<td>$10^{-18}$</td>
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<tr>
<td>DeeMe (SiC)</td>
<td>$10^{-14}$</td>
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cLFV in “muonic” atoms: Coulomb enhanced decays

- **Muonic atom decay:** $\mu^- e^- \rightarrow e^- e^-

  Initial $\mu^-$ and $e^-$: 1s state bound in Coulomb field of the muonic atom’s nucleus

- **Coulomb interaction** increases overlap between $\Psi_{\mu^-}$ and $\Psi_{e^-}$ wave functions

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

- **Clean experimental signature:** back-to-back electrons, $E_e^- \approx m_\mu / 2$

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

- **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 $\mu^- e^- \rightarrow e^- e^-$ vs $\mu^- e$ conversion (Aluminium target)

Sizeable values for $\text{BR}(\mu^- e^- \rightarrow e^- e^-)$ - potentially within experimental reach!

probe “heavy mass” regimes unaccessible for SHiP, FCC, LHC, ...

- For Aluminium, $\text{CR}(\mu^- e)$ appears to have stronger experimental potential
  .. consider “heavy” targets to probe $\text{BR}(\mu^- e^- \rightarrow e^- e^-)$
Muonium: hydrogen-like Coulomb bound state \((e^- \mu^+)\); free of hadronic interactions!

Mu – 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: \(\Pr(Mu \rightarrow \overline{Mu}) < 8.3 \times 10^{-11}\) \cite{Willmann et al, 1999}

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

Future prospects at FNAL?

cLFV Mu decay: \(Mu \rightarrow e^+ e^-\)

Clear signal compared to SM decay \(Mu \rightarrow e^+ e^- \bar{\nu}_\mu \nu_e\) (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: $\mu - \overline{\mu}$ oscillation and $\mu \to e^+ e^-$ decay

![Graph with data points and axes labeled $|\text{Re}(G_{\mu\hat{m}})|$ and $m_4$ (GeV)]

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

  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 $\nu$-mass generation
cLFV and $\nu_s$: low scale seesaws

“Standard” fermionic seesaws: $Y' \sim O(1) \Rightarrow M_{\text{new}} \approx 10^{13-15}$ 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

$\nu$ Minimal Standard Model, ...

... calling upon sterile fermions!
cLFV: low scale type I seesaw

\( \sim \text{SM} + \text{Right-handed neutrinos} \)

\[
\mathcal{L}_{\text{type I}} = -Y^\ell \bar{L}_L H e_R - Y^\nu \bar{\nu_R} \tilde{H} \nu_L - \frac{1}{2} \bar{\nu_R} M_R \nu_R^c
\]

- 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 \( Y^\nu \) ...

- 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} \quad U^T \mathcal{M}_\nu^{6\times6} U = \text{diag}(m_i) \quad m_\nu \approx -v^2 Y^\nu_T \frac{1}{M_R} Y^\nu \\

m_N \approx M_{R_i}
\]

\[
U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \quad U_{\nu\nu} \approx (1 - \varepsilon) U_{\text{PMNS}} \quad \text{Non-unitary leptonic mixing } \tilde{U}_{\text{PMNS}}!
\]

- 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
  \[ BR(\mu \rightarrow e\gamma), BR(\mu \rightarrow 3e), CR(\mu - e, N) \]
  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

$\sim$ SM + Right-handed neutrinos + Extra steriles

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

- Addition of 3 "heavy" RH neutrinos and 3 extra "sterile" fermions $X$ to SM $\sim$ ISS(3,3)

- Spectrum and mixings: 9 physical states

$$M_{\text{ISS}}^{9 \times 9} = \begin{pmatrix}
0 & Y_\nu \nu & 0 \\
Y_\nu^T v & 0 & M_R \\
0 & M_R & \mu_X
\end{pmatrix} \Rightarrow \left\{ \begin{array}{l}
3 \text{ light } \nu : \ m_\nu \approx \frac{(Y_\nu \nu)^2}{M_R^2} \mu_X \\
3 \text{ pseudo-Dirac pairs} : \ m_{N\pm} \approx M_R \pm \mu_X
\end{array} \right.$$

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

$\Rightarrow$ accommodate $m_\nu^{\text{light}}$ with sizeable $Y^\nu$ 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): \(\text{BR}(Z \rightarrow \tau \mu)\) allows to probe \(\mu - \tau\) cLFV beyond SuperB reach

- Rich low-energy phenomenology (cLFV, LFU, ...)

  For \(M_R \gtrsim \Lambda_{\text{EW}}\): cLFV observables within exp reach NA62, Mu2e, COMET, FCC...

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

- 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
    
    \[ q q' \rightarrow \tau \mu + 2 \text{ jets} \]  
    (no missing \( E_T \)!)  
    
    - After cuts, **significant number of events!**

  [Arganda et al, 1508.05074]

- **cLFV Higgs decays in ISS:**
  
  \[ \text{BR}(H \rightarrow \ell\tau) \lesssim 10^{-5}.. \]

  [Arganda et al, 1405.4300]

  [CMS Coll., '15]
cLFV and $\nu_s$: $\nu$MSM

► **Minimal “type I seesaw-like” extension:** SM + 3 $\nu_R$

New states account for $m^\text{light}_\nu$, offer DM candidate, allow for BAU via leptogenesis

⇒ tiny Yukawa couplings; heavily constrained parameter space (th, cosmo, exp..)

[Canetti et al, '13]

► **$\nu$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!
    - ⇒ 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 $\text{BR}(\ell_i \rightarrow \ell_j \gamma)$, $\text{BR}(\ell_i \rightarrow 3\ell_j)$, $\text{CR}(\mu - e, N)$ and $\text{BR}(\mu^- e^- \rightarrow e^- e^-)$
    - ⇒ potentially within experimental reach
  - Analysis carried for simple “3+1 toy model” and mechanisms of $\nu$ mass generation
    - low-scale type I, Inverse Seesaw, $\nu$MSM
  - Interplay at high-intensity & high-energy: probe the underlying source of LFV