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 $\nu$ 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!!**
Neutrino oscillations: gateway to new physics

- Neutrino oscillations provided the 1st laboratory evidence of New Physics
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  such extensions might even allow to address SM caveats
  [ ⇔ 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 flavour
  - tiny leptonic EDMs (at 4-loop level.. $d_e^{\text{CKM}} \leq 10^{-38} \text{e cm}$)

► Extend the SM to accommodate $\nu_\alpha \leftrightarrow \nu_\beta$

Assume **most minimal** extension $\text{SM}_{m_\nu}$

$[\text{SM}_{m_\nu} = \text{“ad-hoc”} \ m_\nu \ (\text{Dirac}), \ U_{\text{PMNS}}]$

► In the $\text{SM}_{m_\nu}$: **(total) Lepton number conserved**; what about lepton flavours? And CP?

► $\text{SM}_{m_\nu}$ - cLFV possible??

\[
\text{BR}(\mu \rightarrow e\gamma) \propto \left| \sum U_{\mu i}^* U_{ei} \frac{m^{\nu_i}}{M^2_W} \right|^2 \sim 10^{-54}
\]

[Petcov, ’77]

**Possible - yes... but not observable!!**

► $\text{SM}_{m_\nu}$ - observable EDMs?

Contributions from $\delta_{\text{CP}}$ (2-loop)...

| \text{leptonic EDMs} | $d_e^{\text{lept}} \leq 10^{-35} \text{e cm}$ |
Leptonic observables: signs of New Physics

- Explore the underlying synergy between $\nu$ 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 addressed here...)
Leptonic observables: current status

[≅ WG4 presentations and reviews, Monday-Friday!]
Leptonic dipole moments

► Electric dipole moments of charged leptons

\[ \mathcal{L}_{\text{EDM}} = -i/2 \, d_\ell \, \bar{\ell} \sigma^{\mu\nu} \gamma_5 \ell F_{\mu\nu} \]

<table>
<thead>
<tr>
<th>EDM (e cm)</th>
<th>Current bounds</th>
<th>Future sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.9 × 10^{-19} [Muon g-2]</td>
<td>( \mathcal{O}(10^{-21}) ) [g-2/EDM Coll.]</td>
</tr>
<tr>
<td>[</td>
<td>4.5 × 10^{-17} [Belle]</td>
<td>-</td>
</tr>
<tr>
<td>[</td>
<td>2.5 × 10^{-17} [Belle]</td>
<td>-</td>
</tr>
</tbody>
</table>

► (Anomalous) magnetic moments of charged leptons

\[ \bar{\mu} = \frac{g_\ell}{2 \, m_\ell} \, \bar{S} \Rightarrow a_\ell = \frac{1}{2} \, (g_\ell - 2) \]

- \( a_\ell \): Best determination of \( \alpha \)
  - \( a_\ell^{\text{the}} = 0.001159652181643(764) \) \( \leftrightarrow 5^{\text{th}} \) order in QED (12,672 diags)!
  - \( a_\ell^{\text{exp}} = 0.00115965218073(28) \)

- \( a_\mu \): Current tension between theory and experiment
  - Very sensitive probe of New Physics close to \( \Lambda_{\text{EW}} \)
  - If \( \delta a_\mu \) confirmed \( \sim \) discrepancies for \( a_{e,\tau} \) and \( d_\ell \! \)

- \( a_\tau \): Short tau lifetime
  - \( a_\tau^{\text{the}} = 0.00117721(5) \) [0701260]
  - \( -0.007 < a_\tau^{\exp} < 0.005 \) [1601.07987]
Lepton number violation: $\Delta L = 2$ observables and searches

- Neutrinoless double beta decays

![Graph showing neutrinoless double beta decays](image)

| Experiment                          | $|m_{\text{ee}}|$ (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

<table>
<thead>
<tr>
<th>LNV decay</th>
<th>Current Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^- \to \ell^- \ell^+ \pi^+$</td>
<td>$6.4 \times 10^{-10}$ $1.1 \times 10^{-9}$</td>
</tr>
<tr>
<td>$D^- \to \ell^- \ell^+ \pi^+$</td>
<td>$1.1 \times 10^{-6}$ $2.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$D^- \to \ell^- \ell^+ K^+$</td>
<td>$9.0 \times 10^{-7}$ $1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^- \to \ell^- \ell^+ K^+$</td>
<td>$2.3 \times 10^{-8}$ $4.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>$B^- \to \ell^- \ell^+ \rho^+$</td>
<td>$3.0 \times 10^{-8}$ $4.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^- \to \ell^- \ell^+ D^+$</td>
<td>$1.7 \times 10^{-7}$ $4.2 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

- Current Bound

<table>
<thead>
<tr>
<th>LNV decay</th>
<th>$\ell = e$</th>
<th>$\ell = \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \to \ell^+ \pi^+ \pi^-$</td>
<td>$2.0 \times 10^{-8}$ $3.9 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\tau^- \to \ell^+ \pi^- K^-$</td>
<td>$3.2 \times 10^{-8}$ $4.8 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\tau^- \to \ell^+ K^+ K^-$</td>
<td>$3.3 \times 10^{-8}$ $4.7 \times 10^{-8}$</td>
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Signals of Lepton Flavour Violation

- Neutrino oscillations \([\nu\text{-dedicated experiments}]\)

- Rare leptonic decays and transitions \([\text{high-intensity facilities}]\)
  \[\ell_i \rightarrow \ell_j \gamma, \ell_i \rightarrow 3\ell_j, \text{mesonic } \tau \text{ decays...}\]
  nucleus assisted \(\mu - e\) transitions (also \(\text{LNV!}\)), Muonium channels...

- Meson decays: lepton flavour violating decays - \(B \rightarrow \tau \mu, ...\) \([\text{high-intensity; LHCb}]\)
  cLFV & Lepton Number violating decays - \(B \rightarrow D e^- \mu^- , ...\)
  violation of lepton flavour universality (e.g. \(R_K\))

- Rare (new) heavy particle decays (typically model-dependent) \([\text{colliders}]\)
  SM boson decays: \(H \rightarrow \tau \mu, Z \rightarrow \ell_i \ell_j\)
  SUSY \(\tilde{\ell}_i \rightarrow \ell_j \chi^0\); FV KK-excitation decays; ...
  LFV final states: for example, \(e^\pm e^- \rightarrow e^\pm \mu^- + E_{\text{miss}}\)

- And many others ... all absent in the SM!
Searches for cLFV: where do we stand?

<table>
<thead>
<tr>
<th>Observable</th>
<th>Bound (90% C.L.)</th>
<th>future sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(\mu \rightarrow e\gamma)$</td>
<td>$4.2 \times 10^{-13}$</td>
<td>$4 \times 10^{-14}$ [ MEG II ]</td>
</tr>
<tr>
<td>$\text{BR}(\mu \rightarrow 3e)$</td>
<td>$1.0 \times 10^{-12}$</td>
<td>$10^{-15}$ [ Mu3e Phase I ]</td>
</tr>
<tr>
<td>$\text{BR}(\mu^{-} e^{-} \rightarrow \mu^{-} e^{-})$</td>
<td>$7 \times 10^{-13}$ (Au)</td>
<td>$10^{-14}$ [ SiC, DeeMe ]</td>
</tr>
<tr>
<td>$\text{BR}(\mu^{-} e^{-} \rightarrow \mu^{-} e^{-})$</td>
<td>$7 \times 10^{-13}$ (Au)</td>
<td>$10^{-17}$ [ Al, Mu2e/COMET ]</td>
</tr>
<tr>
<td>$\text{P}(\text{Mu} \rightarrow \text{Mu})$</td>
<td>$8.3 \times 10^{-11}$</td>
<td>$10^{-14}$ [FNAL ? ]</td>
</tr>
</tbody>
</table>

[\( \Rightarrow \) Y. Ulrich (NLO)!]

[\( \Rightarrow \) See WG4 contributions
Monday-Friday!]

Further bounds: $\text{BR}(Z \rightarrow l_i l_j)$, ..., $\text{BR}(K, D, B \rightarrow (h) l_i l_j)$, ...
[\( \Rightarrow \) presentation by R. Bernstein!]

\[90\% \text{ CL upper limits on } \tau \text{ LFV decays}\]
Model independent approach

Neutrinoless radiative decay
\[
\text{Br} (\mu \rightarrow e\gamma) = \frac{\alpha e m_\mu^5}{12\pi \Lambda^4 G_\mu} \left( |C_L^D|^2 + |C_R^D|^2 \right).
\]

Neutrinoless three-body decay
\[
\text{Br}(\mu \rightarrow 3e) = \frac{\alpha^2 e m_\mu^6}{12\pi \Lambda^4 G_\mu} \left( |C_L^D|^2 + |C_R^D|^2 \right) \left( 8 \log \left[ \frac{m_\mu}{m_e} \right] - 11 \right) \\
+ \frac{m_\mu^3}{3(16\pi)^3 \Lambda^4 G_\mu} \left( |C_{e e}^{LL}|^2 + 16 |C_{e e}^{VV LL}|^2 + 8 |C_{e e}^{V LR}|^2 \right) \\
+ |C_{e e}^{RR}|^2 + 16 |C_{e e}^{V RR}|^2 + 8 |C_{e e}^{V RL}|^2 \right).
\]

[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: $\text{SM} + \nu_s$
  
  “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 $\nu$ masses and mixings
  
  Models of $\nu$-mass generation - Standard seesaws [type I, type II, type III] & variants
    
    - Low-scale, $\nu$MSM, 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: $\text{SM} + \nu_s$

Assuming that New Physics is encoded into such a simple model, what can we expect and learn?
“Toy model” for phenomenological analyses: SM + $\nu_s$

- **Assumptions:** 3 active neutrinos + 1 sterile state
  - interaction basis $\leftrightarrow$ physical basis
  - $n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s)^T$
  - $n_L = U_{4\times4} \nu$
  - $U_{4\times4}^T M U_{4\times4} = \text{diag}(m_{\nu_1}, ..., m_{\nu_4})$
  - “Majorana mass”: $\mathcal{L}_{\text{toy}} \sim n_T C M n_L$

- **Active-sterile mixing** $U_{\alpha i}$:
  - rectangular matrix $\leftarrow U = U|_{3\times4}$
  - $U_{4\times4} = \begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
    U_{s1} & U_{s2} & U_{s3} & U_{s4}
  \end{pmatrix}$

- **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:**
  - $\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+n_S} U_{\alpha i} \bar{\ell}_\alpha \gamma^\mu P_L \nu_i$
  - $\mathcal{L}_{Z^0} \sim -\frac{g_w}{2\cos\theta_w} Z_\mu \sum_{i,j=1}^{3+n_S} \bar{\nu}_i \gamma^\mu \left[ P_L (U^T U)_{ij} - P_R (U^T U)_{ij}^* \right] \nu_j$
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 $\nu$

▶ $|d_e|/e \geq 10^{-30}$ cm for $m_{\nu_4,5} \sim [100 \text{ GeV}, 100 \text{ TeV}]$

[Abada and Toma, '15]

▶ Independent of active-sterile mixings

Majorana contribution is dominant!

▶ EDM observation: suggest new sources of CPV

⇒ Majorana $\nu$s? ⇔ Leptogenesis??

▶ Sterile states beyond (direct) collider reach...
Sterile neutrinos: impact for LNV observables

- **Lepton number violation: $0\nu 2\beta$ decays**
  - $\nu_s$ can strongly impact predictions for $|m_{ee}|$
  - $\Rightarrow$ augmented ranges for effective mass (*IO and NO*)

- **Observation of $0\nu 2\beta$ signal** in future experiments
  - does not imply Inverted Ordering for light $\nu_s$
  - [Abada, De Romeri and AMT, '14; ...; Giunti et al, '15 ←]

- **Lepton Number Violation in meson and $\tau$ decays**
  - If $\nu_s$ 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]
$\nu_s$ and cLFV: radiative and 3 body decays

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

  - Consider $\mu \rightarrow e\gamma$

  - For $m_4 \gtrsim 10$ GeV sizable $\nu_s$ contributions
    .. but precluded by other cLFV observables

- **Three-body decays** $\ell_i \rightarrow 3\ell_j$ (■) 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: $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$

- Muonic atom decay: $\mu^- e^- \rightarrow e^- e^-$  
  **Coulomb interaction** increases overlap between $\Psi_{\mu^-}$ and $\Psi_{e^-}$
  **Rate strongly enhanced in large $Z$ atoms**  [Uesaka et al, ’15-’16]

- cLFV in muonic atoms from $\nu_s$:
  $\mu^- e^- \rightarrow e^- e^-$  (■) vs
  $\mu^- e$ conversion  (■) in Aluminium

- For Aluminium, $\text{CR}(\mu^- e)$ has
  stronger experimental potential
  .. consider “heavy” targets to probe
  $\text{BR}(\mu^- e^- \rightarrow e^- e^-)$

  “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

- “3+1” toy model  

[Abada et al, ’15]

- 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 $\nu_s$ 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

\[ \nu_L \nu_L H H \]

\[ \nu_R \text{ (fermion singlet)} \]

\[ \Delta \text{ (scalar triplet)} \]

\[ \Sigma_R \text{ (fermion triplet)} \]

\[ \frac{1}{\Lambda} \]

“Seesaw mechanism”

Type I

Type II

Type III

Observables: depend on powers of \( Y^\nu \) \( \sim \) large rates \( \Rightarrow \) sizable \( Y^\nu \)

and on the mass of the (virtual) NP propagators

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

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; \( \text{MeV} \lesssim m_{N_i} \lesssim 10^{\text{few}} \text{TeV} \)

- Spectrum and mixings: \( m_\nu \approx -v^2 Y_\nu^T M_N^{-1} Y_\nu \) \( U^T M_\nu^{6 \times 6} U = \text{diag}(m_i) \)
  \[
  U = \begin{pmatrix}
    U_{\nu\nu} & U_{\nu N} \\
    U_{N\nu} & U_{NN}
  \end{pmatrix}
  \]
  \( U_{\nu\nu} \approx (1 - \varepsilon) U_{\text{PMNS}} \) \( \text{Non-unitary leptonic mixing } \tilde{U}_{\text{PMNS}} \)

- Heavy states do not decouple \( \Rightarrow \text{modified neutral and charged leptonic currents} \)

- 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

$$\mathcal{M}_{\text{ISS}}^{9\times9} = \begin{pmatrix} 0 & Y_{\nu}v & 0 \\ Y_{\nu}^T v & 0 & M_R \\ 0 & M_R & \mu_X \end{pmatrix} \Rightarrow \begin{cases} 
3 \text{ light } \nu : m_\nu \approx \frac{(Y_{\nu}v)^2}{(Y_{\nu}v)^2 + M^2_R} \mu_X \\
3 \text{ pseudo-Dirac pairs } : m_{N^\pm} \approx M_R \pm \mu_X 
\end{cases}$$

- Non-unitarity $\tilde{U}_{\text{PMNS}} \Rightarrow$ 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

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

[Abada, DeRomeri, AMT, '15]
Low scale: Inverse Seesaw (ISS)

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

  ![Graph showing BR($Z \to \mu \tau$) vs BR($\tau \to \mu \mu \mu$)]

  - Still dominated by $Z$ penguin contributions
  - Other cLFV bounds preclude large $\text{BR}(\tau \to 3\mu)$...
  - Contrary to “3+1 toy model”, flavour textures & parameters constrained by $\nu$ 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...

  ![Graph showing electron EDM versus $m_i$]
The “triplet” seesaws

★ Weinberg operator realised via triplet scalars $\Delta$ (type II) or fermions $\Sigma$ (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 $\ell_i \to 3\ell_j$ at tree level!

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

► Use ratios of observables to constrain and identify mediators!

$\text{Type I}$

$\text{Type II}$

$\text{Type III}$

$$\text{BR}(\mu \to e\gamma) / \text{BR}(\mu \to 3e) = 1.3 \times 10^{-3}$$

$$\text{BR}(\tau \to \mu\gamma) / \text{BR}(\tau \to 3\mu) = 1.3 \times 10^{-3}$$

$$\text{BR}(\mu \to e\gamma) / \text{CR}(e - \mu, Ti) = 3.1 \times 10^{-4}$$

[Hambye, 2013]
The “triplet” seesaws

- **cLFV bounds on the seesaw mediators:** a comparative (“effective”) view

  \( m_N \lesssim 100 \text{ TeV} \times \left( \frac{10^{-14}}{\text{BR}(\mu \rightarrow e\gamma)} \right)^\frac{1}{4} \times f(Y_{\ell_i \ell_j}^\nu) \)

  \( m_N \lesssim 300 \text{ TeV} \times \left( \frac{10^{-16}}{\text{BR}(\mu \rightarrow 3e)} \right)^\frac{1}{4} \times f(Y_{\ell_i \ell_j}^\nu) \)

  \( m_N \lesssim 2000 \text{ TeV} \times \left( \frac{10^{-18}}{\text{CR}(\mu - e, Ti)} \right)^\frac{1}{4} \times f(Y_{\ell_i \ell_j}^\nu) \)

  \( m_\Delta \lesssim 70 \text{ TeV} \times \left( \frac{10^{-14}}{\text{BR}(\mu \rightarrow e\gamma)} \right)^\frac{1}{4} \times f(Y_{\ell_i \ell_j}^\Delta) \)

  \( m_\Delta \lesssim 2200 \text{ TeV} \times \left( \frac{10^{-16}}{\text{BR}(\mu \rightarrow 3e)} \right)^\frac{1}{4} \times f(Y_{\ell_i \ell_j}^\Delta) \)

  \( m_\Delta \lesssim 600 \text{ TeV} \times \left( \frac{10^{-18}}{\text{CR}(\mu - e, Ti)} \right)^\frac{1}{4} \times f(Y_{\ell_i \ell_j}^\Delta) \)

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

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

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

  \( f(Y_{\ell_i \ell_j}) \sim \text{combination of } \sqrt{Y} \sqrt{Y} \)
Embedding the seesaw in larger frameworks
Supersymmetric type I seesaw

- Large $Y\nu$: sizable contributions to cLFV observables

  cLFV driven by the exchange of virtual SUSY particles

- $Y\nu$ unique source of LFV: synergy of high- and low-energy observables

- Isolated cLFV manifestations ⇒ disfavours SUSY seesaw hypothesis

- "Correlated" cLFV observations ⇒ strengthen SUSY seesaw hypothesis!

  $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}} (\tilde{e}_L, \tilde{\mu}_L) \gtrsim \mathcal{O}(0.5\%)$ and $\mu \to e\gamma |_{\text{MEG}} \checkmark$!! 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 $Y^q$, $Y^\ell$, $Y^\nu$, ...: ⇒ 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 $\nu_R$ and vector-like partners

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

  $\Rightarrow$ correlated observables!

\[
\frac{\text{BR}(h\to\ell_i\ell_j)}{\text{BR}(\ell_i\to\ell_j\gamma)} \approx \frac{4\pi}{3\alpha} \frac{\text{BR}(h\to\ell_i\ell_i)_{\text{SM}}}{\text{BR}(\ell_i\to\ell_j\nu_i\bar{\nu}_j)}
\]

- **Synergy** between **FV Higgs decays and cLFV**! Flavour conserving EDM and $\delta a_\mu$ as well!

[Falkowski et al, '14]
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 $\Rightarrow G_f = U(1)_{L_e+L_\mu} \times U(1)_{L_\tau}$

\[
Y^\nu = \begin{pmatrix}
\epsilon_e & ae^{-i\pi/4} & ae^{i\pi/4} \\
\epsilon_\mu & be^{-i\pi/4} & be^{i\pi/4} \\
\epsilon_\tau & \kappa_1 & \kappa_2
\end{pmatrix}
\]

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

[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

[Deppisch and Pilaftsis, '10]
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, $\nu$-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..., $\mu N (eN) \stackrel{H}{\rightarrow} \tau X$, ...]
  - [→ M. Yamanaka]
  - and sub-sub set of New Physics models aiming at accounting for $\nu$ 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 → Mu** conversion

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

- Also consider cLFV Mu decay: $\text{Mu} \rightarrow e^+ e^-$

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

  Within **FNAL experimental reach**??

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

  Within experimental reach?

  "3+1" toy model [Abada, De Romeri and AMT, '15]
cLFV in-flight conversion

- Energetic beam of leptons ($e, \mu$) directed on fixed (dense) target

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

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

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

Large values of $\ell_i \rightarrow \ell_j$ precluded due to conflict with CR($\mu - e$, Au) and $BR(\ell_j \rightarrow 3\ell_i)$

$N_{\text{signal}}$ beyond experimental sensitivity - even for very intense lepton beams
cLFV and $\nu_8$: $\nu_{\text{MSM}}$

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

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

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

![Graph showing constraints on $U^2$ vs. $M$] [Canetti et al, '13]

- **$\nu_{\text{MSM}}$: very difficult prospects for cLFV**

![Graph showing constraints on BR($\mu e \rightarrow ee$) vs. $M$] [Abada et al, '15]
Hints of an organising principle: $\nu$ in Left-Right models

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

► extend SM gauge group: $\text{SU}(2)_L \otimes \text{U}(1)$ $\Rightarrow$ $\text{SU}(2)_L \otimes \text{SU}(2)_R \otimes \text{U}(1)_{B-L}$

► RH neutrinos automatically included

$$M_\nu \approx \begin{pmatrix} y_{MvL} & y_{DM_{EW}} \\ y_{TM_{EW}} & y_{MvR} \end{pmatrix}$$

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 $pp \rightarrow W_R \rightarrow e^\pm \mu^\mp + 2 \text{ jets}$

► 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 $Y^q$, $Y^\ell$, $Y^\nu$...

► 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

\[ e - \mu \text{ bounds constrain NP scale beyond LHC reach: } T_{KK} \gtrsim 4 \text{ TeV (} \sim KK^{(1st)} \gtrsim 10 \text{ TeV) } \]

future sensitivities: exclude (general) anarchic RS models up to 8 TeV (\( \sim m_{KK-g} \gtrsim 20 \text{ TeV) } \)

[Beneke et al, 1508.01705]

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

distinctive patterns for ratios of observables (testability!)

\[ BR(\mu \rightarrow e\gamma) \] - 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

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

- Dimension 5 - $\Delta \mathcal{L}^5$ (Weinberg): neutrino masses ($\text{LN}_\nu$, $\Delta L = 2$)

  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 $\ell_i \rightarrow \ell_j \gamma$, $\chi$-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 $\ell_i \rightarrow \ell_j \ell_k \ell_l$, ...

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

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

  $\rightarrow$ presentation by G.M. Pruna, ...]

- Higher order - $\Delta \mathcal{L}^{7,8,...}$: $0\nu2\beta$, $\nu$ (transitional) magnetic moments, NSI, unitarity violation...
Constraining $\mathcal{L}^{\text{eff}}$: cLFV example

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

**Hypotheses on:**

1. **size of “new couplings”**
   - [Natural couplings] $C^6_{ij} \sim \mathcal{O}(1)$

2. **scale of “new physics”**
   - [Natural scale - delicate.]
     - direct discovery $\Lambda \sim \text{TeV}$

**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 $\Lambda$ is low...
- **multiple “new physics” scales:** $\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{1}{\Lambda_{\text{LNV}}} C^5(m_\nu) + \frac{1}{\Lambda_{\text{LFV}}^2} C^6(\ell_i \leftrightarrow \ell_j) + \ldots$

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

| Effective coupling (example) | Bounds on $\Lambda$ (TeV) (for $|C^6_{ij}| = 1$) | Bounds on $|C^6_{ij}|$ (for $\Lambda = 1$ TeV) | Observable |
|-----------------------------|---------------------------------|---------------------------------|------------|
| $C^\mu_\ell e$, $C^\tau_\ell e$, $C^\tau_\mu e$ | 6.3 $\times 10^4$ | 2.5 $\times 10^{-10}$ | $\mu \rightarrow e\gamma$ |
| $C^\mu_\ell e$, $C^\mu_\tau e$, $C^\tau_\mu e$ | 6.5 $\times 10^2$ | 2.4 $\times 10^{-6}$ | $\tau \rightarrow e\gamma$ |
| $C^\mu_\ell e$, $C^\mu_\tau e$, $C^\tau_\mu e$ | 6.1 $\times 10^2$ | 2.7 $\times 10^{-6}$ | $\tau \rightarrow \mu\gamma$ |

[Foruglio et al, 2015]