Lepton flavour violating Higgs decays involving taus

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Why cLFV Higgs decays?

Charged lepton flavour violation (see Adrian’s and Ana’s talks)

- SM: no $\nu$ mass term, lepton number and lepton flavour are conserved
- Neutrino oscillations = Neutral lepton flavour violation
  What about charged lepton flavour violation (cLFV)?

- Ad-hoc SM extension (Dirac $m_\nu + U_{\text{PMNS}}$): cLFV from loop processes
  $\Rightarrow$ negligible, e.g. $\text{Br}(\mu \rightarrow e\gamma) \sim 10^{-54}$ [Petcov, 1977]

- If cLFV observed:
  - Clear evidence of new Physics
  - Probe the origin of lepton mixing
  - Could tell us more about the origin of neutrino masses and mixing

- Searched for in numerous channels:
  - Radiative decays: $\text{Br}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]
  - 3-body decays: $\text{Br}(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8}$ [Belle, 2010]
  - Meson decays: $\text{Br}(B^0 \rightarrow e\mu) < 1.0 \times 10^{-9}$ [LHCb, 2017]
  - Z decays: $\text{Br}(Z^0 \rightarrow e\mu) < 7.5 \times 10^{-7}$ [ATLAS, 2014]
  - Neutrinoless muon conversion: $\mu^-, \text{Au} \rightarrow e^-, \text{Au} < 7 \times 10^{-13}$ [SINDRUM II, 2006]
Many sources of cLFV Higgs decays

- Higgs discovery allows to search for cLFV in the scalar sector

- Many models give rise to cLFV Higgs decays

Tree-level:
- general 2HDM [Diaz-Cruz and Toscano, 2000; Han and Marfatia, 2001; Kanemura et al., 2006; Dorsner et al., 2015 ...]
- 3HDM [Campos et al., 2015; Crivellin et al., 2015; Merchand and Sher, 2017]
- Warped extra-dim / Composite Higgs [Azatov et al., 2009; de Lima et al., 2015]
- RPV SUSY [Arhrib et al., 2013; Huang and Tang, 2015; ...]
- Froggatt-Nielsen [Huitu et al., 2016; Barradas-Guevara et al., 2017; ...]

Loop induced:
- low-scale seesaw models [Pilaftsis, 1992; Arganda, Herrero, Marcano and CW, 2015; Herrero-Garcia et al., 2016; Thao et al., 2017; ...]
- MSSM [Diaz-Cruz, 2002; Brignole and Rossi, 2003; Arana-Catania et al., 2013; Aloni et al., 2016; Alvarado et al., 2016; Gomez et al., 2017; ...]
- SUSY seesaw [Arganda et al., 2005; Diaz-Cruz et al., 2009, Arganda, Herrero, Marcano and CW, 2016 ...]
- Leptoquarks [Dorsner et al., 2015; de Medeiros Varzielas and Hiller, 2015; Cheung et al., 2016 ...]
- Vector-like fermions [Falkowski et al., 2014; Dorsner et al., 2015; Chen and Nomura, 2016 ...]
EFT as a generic description (see Adrian’s talk)

- Effects of particles heavier than the process energy scale described by effective operators, e.g. for cLFV radiative decays

\[
\hat{\mathcal{O}}^D = \frac{C^D}{\Lambda_{NP}^2} \bar{L} H \sigma^{\mu\nu} e_R B_{\mu\nu}
\]

- For cLFV Higgs decays, dominant contribution from [Herrero-Garcia et al., 2016]

\[
\hat{\mathcal{O}}^Y = \frac{C^Y}{\Lambda_{NP}^2} \bar{L} H e_R (H^\dagger H)
\]

giving after EWSB non-diagonal Higgs interactions

\[
-\mathcal{L}^Y = m_i \bar{\ell}^i_L \ell^i_R + Y_{ij} \bar{\ell}^i_L \ell^j_R h + \text{h.c.} \quad \rightarrow \quad Y_{ij} = \frac{m_i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2} \Lambda_{NP}^2} C_{ij}^Y
\]

- cLFV Higgs decays governed by the effective Yukawa coupling \( Y_{ij} \)
Why cLFV Higgs decays?

Indirect constraints on \( Y_{ij} \)

- \( Y_{ij} \) contributes to [Harnik et al., 2013]
- cLFV lepton decays
- electron EDM
- electron and muon g-2

Good prospects for direct searches of cLFV Higgs decays into \( \tau \)
(See talks by Brian Le and Jian Wang for recent experimental results)
Future sensitivities

- **Current upper limits at 95% C.L** [Aad et al., 2017, Sirunyan et al., 2018]

<table>
<thead>
<tr>
<th></th>
<th>ATLAS (8 TeV)</th>
<th>CMS (13 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(h \to \tau\mu)$</td>
<td>1.41%</td>
<td>0.25%</td>
</tr>
<tr>
<td>$\text{Br}(h \to \tau e)$</td>
<td>1.04%</td>
<td>0.61%</td>
</tr>
</tbody>
</table>

- **HL-LHC sensitivities with 3 ab$^{-1}$, 10% systematics, at 95% C.L** [Banerjee et al., 2016]

<table>
<thead>
<tr>
<th></th>
<th>$e\mu + \not{E}_T$</th>
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<tbody>
<tr>
<td>$\text{Br}(h \to \tau\mu)$</td>
<td>0.76%</td>
</tr>
<tr>
<td>$\text{Br}(h \to \tau e)$</td>
<td>0.61%</td>
</tr>
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</table>

- **ILC sensitivities at 95% C.L, $HZ$ and $VBF$ production channels** [Banerjee et al., 2016]

<table>
<thead>
<tr>
<th></th>
<th>$250 \text{ GeV, 250 fb}^{-1}$</th>
<th>$1 \text{ TeV, 1 ab}^{-1}$</th>
</tr>
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<tbody>
<tr>
<td>$\text{Br}(h \to \tau e)$</td>
<td>0.38%</td>
<td>0.22%</td>
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Expect similar results for $h \to \tau\mu$

- **ILC sensitivity, assuming negligible background, $HZ$ and $VBF$ production channels, polarized beams (-0.8,0.3)** [Chakraborty et al., 2016]:

<table>
<thead>
<tr>
<th></th>
<th>250 GeV, 1350 fb$^{-1}$</th>
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<tr>
<td>$\text{Br}(h \to \tau\mu)$</td>
<td>0.0041%</td>
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2 examples based on low-scale seesaw models

- Taking $M_R \gg m_D$ gives the “vanilla” type 1 seesaw

$$m_\nu = -m_D M_R^{-1} m_D^T,$$

where $m_D = Y_\nu v$

$$m_\nu \sim 0.1 \text{ eV} \Rightarrow \begin{cases} Y_\nu \sim 1 \text{ and } M_R \sim 10^{14} \text{ GeV} \\ Y_\nu \sim 10^{-6} \text{ and } M_R \sim 10^2 \text{ GeV} \end{cases}$$

- $m_\nu$ suppressed by small active-sterile mixing $m_D/M_R$

- Problem: $m_D/M_R$ also controls the heavy neutrinos phenomenology
  Solution: Cancellation in matrix product to get large $m_D/M_R$

- Theorem: $m_\nu = 0 \Leftrightarrow$ Conserved lepton number $L$

  [Kersten and Smirnov, 2007; Moffat, Pascoli, CW, 2017]

  Consequence: Large $m_D/M_R$ in presence of nearly conserved $L$ symmetry

- Examples: the inverse seesaw and its SUSY realisation
An example: the inverse seesaw model

- Lower seesaw scale from approximately conserved lepton number
- Add fermionic gauge singlets $\nu_R (L = +1)$ and $X (L = -1)$

[Mohapatra and Valle, 1986, Bernabéu et al., 1987]

$$L_{\text{inverse}} = -Y_\nu \bar{L}_\phi \nu_R - M_R \nu_R^c X - \frac{1}{2} \mu_X \bar{X}^c X + \text{h.c.}$$

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

$$m_\nu \approx \frac{m_D^2}{M_R^2} \mu_X$$

$$m_{N_1, N_2} \approx \mp M_R + \frac{\mu_X}{2}$$

- Decouple neutrino mass generation from active-sterile mixing
- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1$ TeV
  \Rightarrow within reach of the LHC and low energy experiments
In the Feynman-'t Hooft gauge, same as type I seesaw [Arganda et al., 2005]:

- Formulas adapted from [Arganda et al., 2005]

- Diagrams 1, 8, 10 dominate at large $M_R$

- Enhancement from:
  - $\mathcal{O}(1)$ $Y_\nu$ couplings
  - TeV scale $n_i$
Most relevant constraints

- Neutrino data → Use specific parametrization (modified Casas-Ibarra (C-I) [Casas and Ibarra, 2001] or $\mu_X$ parametrization)

$$v_Y^T = V^\dagger \text{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) R \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U_{PMNS}^\dagger$$

$$M = M_R \mu_X^{-1} M_R^T$$

or

$$\mu_X = M_R^T \ Y_\nu^{-1} \ U_{PMNS}^\ast \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U_{PMNS}^\dagger \ Y_\nu^{-1} M_R v^2$$

- Charged lepton flavour violation
  → For example: $\text{Br}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ [MEG, 2016]

- Lepton universality violation: less constraining than $\mu \rightarrow e\gamma$

- Electric dipole moment: 0 with real PMNS and mass matrices

- Invisible Higgs decays: $M_R > m_H$, does not apply

- Yukawa perturbativity: $|\frac{Y_\nu^2}{4\pi}| < 1.5$
Predictions using the modified C-I parametrization

- Grows with $M_{R_3}$ and $\mu_X^{-1}$ due to $Y_\nu$ growth in C-I parametrization
- Different dependence on parameters for cLFV Higgs decays and cLFV radiative decays
- Similar behaviour with degenerate heavy neutrinos
- Excluded by $\mu \rightarrow e\gamma$
- Non-perturbative $Y_\nu$
- $\text{Br}(H \rightarrow \tau\mu) \leq 10^{-9}$
Large cLFV Higgs decay rates from textures

- Possibility to evade the $\mu \to e\gamma$ constraint?
- Approximate formulas for large $Y_\nu$:

$$\text{Br}_{\mu \to e\gamma}^{\text{approx}} = 8 \times 10^{-17} \text{GeV}^{-4} \frac{m_\mu^5}{\Gamma_\mu} \left| \frac{v^2}{2M_R^2} (Y_\nu Y_{\nu}^\dagger)_{12} \right|^2$$

$$\text{Br}_{H \to \mu\tau}^{\text{approx}} = 10^{-7} \frac{v^4}{M_R^4} \left| (Y_\nu Y_{\nu}^\dagger)_{23} - 5.7 (Y_\nu Y_{\nu}^\dagger Y_\nu Y_{\nu}^\dagger)_{23} \right|^2$$

$$= 10^{-7} \frac{v^4}{M_R^4} \left| 1 - 5.7 [(Y_\nu Y_{\nu}^\dagger)_{22} + (Y_\nu Y_{\nu}^\dagger)_{33}] \right|^2 \left| (Y_\nu Y_{\nu}^\dagger)_{23} \right|^2$$

- Different dependence on the seesaw parameters
- Solution: Textures with $(Y_\nu Y_{\nu}^\dagger)_{12} = 0$ and $\frac{|Y_{\nu \nu}|^2}{4\pi} < 1.5$
- Examples:

$$Y_{\tau\mu}^{(1)} = f \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \quad Y_{\tau\mu}^{(2)} = f \begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix}, \quad Y_{\tau\mu}^{(3)} = f \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$
Producing large $H \to \tau \mu$ rates

- Numerics done with the full one-loop formulas
- Dotted: excluded by $\tau \to \mu \gamma$
  Solid: allowed by cLFV, LUV, etc
- $\text{Br}^{\text{max}}(H \to \mu \bar{\tau}) \sim 10^{-5}$
- Same maximum branching ratio with hierarchical heavy N

- Similarly, $\text{Br}^{\text{max}}(H \to e \bar{\tau}) \sim 10^{-5}$ for $Y^{(i)}_{\tau e} (=Y^{(i)}_{\tau \mu}$ with rows 1 and 2 exchanged)

- Out of LHC reach, $\text{Br}^{\text{max}}$ directly proportional to $\tau \to | \mu \gamma \rangle$
  $\Rightarrow$ Observation at the LHC could exclude inverse seesaw
**The supersymmetric inverse seesaw model**

- MSSM extended by singlet chiral superfields $\hat{N}$ and $\hat{X}$ with $L = -1$ and $L = +1$

- Defined by the superpotential:

$$\mathcal{W} = W_{MSSM} + Y_\nu \hat{N} \hat{L} \hat{H}_u + M_R \hat{N} \hat{X} + \frac{1}{2} \mu_X \hat{X} \hat{X}$$

- New couplings, e.g.

$$A_{Y_\nu} Y_\nu \hat{N} \hat{L} H_u + h.c.$$  

- Light right-handed sneutrinos:

$$M_{\hat{N}}^2 = m_{\hat{N}}^2 + M_R^2 + Y_\nu Y^\dagger_\nu \nu_u^2 \sim (1 \text{TeV})^2$$

$\Rightarrow$ Natural Yukawa couplings with a TeV new Physics scale
Typically in SUSY, cLFV through RGE-induced slepton mixing \( (\Delta m_L^2)_{ij} \)

[Borzumati and Masiero, 1986, Hisano et al., 1996, Hisano and Nomura, 1999]

\[ (\Delta m_L^2)_{ij} \propto (Y^\dagger Y)_{ij} \ln \frac{M_{GUT}}{M_R} \]

Contribute to all cLFV observables → Dominant in most SUSY seesaw models

Type I seesaw \( (Y_\nu \sim 1, M_R \sim 10^{14}\text{GeV}) \) → \( (\Delta m_L^2)_{ij} \propto 5 \)

Inverse seesaw \( (Y_\nu \sim 1, M_R \sim 1\text{TeV}) \) → \( (\Delta m_L^2)_{ij} \propto 30 \)

→ one-loop \( \tilde{N} \)-mediated processes are no longer suppressed

cLFV Higgs decays from SUSY loops  

(1) In the Feynman-’t Hooft gauge, same as SUSY type I seesaw  

[Arganda et al., 2005]  

Formulas adapted from  

[Arganda et al., 2005]  

Enhancement from: -\mathcal{O}(1) \ Y_\nu \ couplings  

-TeV scale $\tilde{\nu}$  

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Results in SUSY ISS

- $M_R$ degenerate and real, $m_A = 800$ GeV, 
squark parameters safe from LHC (direct searches, Higgs mass)
- ▲: allowed by cLFV radiative decays, ×: excluded
- At low $M_R$: dominated by chargino-sneutrino loops
  At large $M_R$ / small $f$: dominated by neutralino-slepton loops
- Can adjust other parameters ($A_\nu$, $m_{\tilde{\nu}_R}$) to reach $\text{Br}(h \rightarrow \tau \bar{\mu}) \sim 1\%$
  (Dips in BR($h \rightarrow \tau \bar{\mu}$) and BR($\tau \rightarrow \mu \gamma$) do not exactly coincide)
Observation of cLFV would be a clear signal of new Physics

cLFV Higgs decays: complementary to other cLFV searches

LHC searches of cLFV Higgs decays already give the best constraints in the $\tau$ sector

Many models are predicting rates within LHC reach, e.g. general 2HDM, SUSY seesaw, 3HDM, Froggatt-Nielsen, leptoquarks
Backup slides
Constraints: focus on $\mu \rightarrow e\gamma$

- $M_R$ and $\mu_X$ real and degenerate, Casas-Ibarra (C-I) parametrization
- Constrains $\mu_X$
- Perturbativity $\rightarrow |\frac{Y_\nu^2}{4\pi}| < 1.5$ (Dotted line = non-perturbative couplings)

$$\frac{v^2(Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} \approx \frac{1}{\mu_X} \left( \frac{U_{PMNS} \Delta m^2_{\text{PMNS}} U_{PMNS}^T}{2m_{\nu_1}} \right)_{km}$$
Dependence on ISS parameters: $\mu_X$ and $M_R$

- $R = 1$, $M_R$ and $\mu_X$ degenerate and real, C-I parametrization
- Dips come from interferences between diagrams
- Can be understood using the mass insertion approximation
Dependence on Casas-Ibarra parameters: $R$ matrix

- $M_R$ and $\mu_X$ degenerate and real
- Independent of $R$ for real mixing angles
- Increase with complex angles, but increase limited by $\mu \rightarrow e\gamma$

\[\Rightarrow \text{Complex } R \text{ matrix doesn't change our results}\]
Searching for maximal $\text{Br}(H \rightarrow \bar{\tau}\mu)$

- $M_R$ and $\mu_X$ degenerate and real
- Excluded by $\mu \rightarrow e\gamma$
  Non-perturbative $Y_\nu$
- $\text{Br}(H \rightarrow \bar{\tau}\mu) \leq 10^{-10}$
- End of the story?

Log$_{10}$BR $(H \rightarrow \mu\tau)$

$M_R$ (GeV) vs. $\mu_X$ (GeV)

$R = 1$

$m_{\nu_1} = 0.1 \text{ eV}$
Impact of the $R$ matrix for hierarchical N

Contrary to degenerate case, $R$ dependence

Varying $\theta_1$: Same conclusions as before

Dotted = non-perturbative couplings
Cross = Excluded by $\mu \to e\gamma$

$\theta_2 \sim \pi/4$: $\text{Br}(H \to e\bar{\tau}) > \text{Br}(H \to \mu\bar{\tau})$

Results quite insensitive to $\theta_3$
Constraints from EWPO

- Active sterile mixing is controlled by $\theta \sim m_D M_R^{-1}$
- Large mixing $\rightarrow$ possible conflict with EWPO
- Limits taken from [del Aguila et al., 2008] at 90% C.L.:
  
  $|V_{eN}|^2 < 3.0 \times 10^{-3}$
  $|V_{\mu N}|^2 < 3.2 \times 10^{-3}$
  $|V_{\tau N}|^2 < 6.2 \times 10^{-3}$