Charged lepton flavor violation in the Grimus-Neufeld model

(based on 2206.00661)

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Overview: Grimus-Neufeld model, neutrino masses and LFV

- Grimus–Neufeld model [GN '89] = SM+2'nd Higgs doublet (2HDM) + 1 sterile neutrino
  - can include neutrino masses and mixings
  - masses and mixings of neutrinos depend on scalar potential parameters
  - can give cLFV processes
- We look at GNM's specific scenario:
  - sterile Majorana neutrino mass is small
    $\Rightarrow$enhanced cLFV decay rates
    $\Rightarrow$Approximate Z_2 symmetry in Yukawa sector
    $\Rightarrow$Makes it similar to other popular models: scotogenic, scoto-seesaw.
- Larger cLFV decay rates make restrictions from experiments possible on scalar+neutrino sector.
  $\Rightarrow$ We put unique limit on 1 parameter in scalar sector from LFV

GN

- The Lagrangian:

$$\mathscr{L} = \mathscr{L}_{2HDM} - \frac{1}{2}MNN - Y_i^{(1)}\ell_i\varepsilon H_1 N - Y_i^{(2)}\ell_i\varepsilon H_2 N + h.c., \quad \ell_i = \begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix}$$

  where ℓ – lepton doublet, N–sterile neutrino, $j = e, \mu, \tau$; H_1 and H_2 in the Higgs basis ($\langle H_2 \rangle = 0$).

- We say that if

$$y^2 \equiv \sum_i \left| Y_i^{(1)} \right|^2 \ll 1$$

  we have approximate Z_2 symmetry in Yukawa sector:

$$\text{SM particles} \to +\text{SM particles}, \quad N, H_2 \to -N, -H_2$$

- y – Z_2 small symmetry breaking parameter
  $\Rightarrow$ tiny seesaw scale (next slide)

tiny $Y_i^{(1)}$ and tiny seesaw

$$\mathscr{L} = \mathscr{L}_{2HDM} - \frac{1}{2} M N N - Y_i^{(1)} \ell_i \varepsilon H_1 N - Y_i^{(2)} \ell_i \varepsilon H_2 N + h.c.$$

- First two additional terms (when $\langle H_1 \rangle \to \frac{1}{\sqrt{2}} v$) lead to two non-vanishing neutrino masses at tree-level (labeled $m_3 < m_4$):

$$m_3 = \frac{y^2 v^2}{2 m_4}, m_4 - m_3 = M, \; y^2 \equiv \sum_i \left| Y_i^{(1)} \right|^2 .$$

  - m_3 is the scale of active neutrinos $m_3 = O(0.01\text{eV})$.
  - Seesaw is when $m_4 \gg m_3$ and so $m_4 \approx M$.
  - originally, by "naturalness" argument: $m_3 = O(0.01\text{eV}), y = O(1) \Rightarrow m_4 = O(\text{GUT})$
  - but if we have $y < O\left(10^{-7}\right) \Rightarrow m_4 < 10\text{GeV}$ – a tiny seesaw scale. (also "natural" because of Z_2)
- The last term in $\mathscr{L}$ induces radiative neutrino mass generation and cLFV.

$Y_i^{(2)}$: radiative mass and cLFV

$$\mathscr{L} = \mathscr{L}_{2HDM} - \frac{1}{2}MNN - Y_i^{(1)}\ell_i\varepsilon H_1 N - Y_i^{(2)}\ell_i\varepsilon H_2 N + h.c., \quad Y_i^{(1)} \ll 1$$

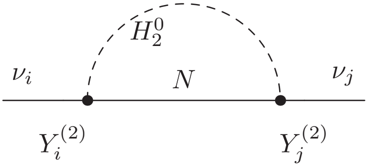


Figure: Radiative mass generation gives m_2^{pole}.

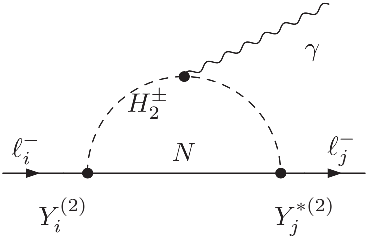
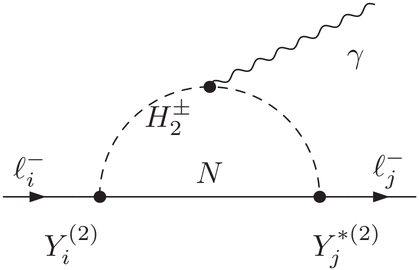


Figure: cLFV decay $\ell_i \to \ell_j\gamma$

- Same diagram exist for scotogenic, scoto-seesaw models.
  $\Rightarrow$keeping $Y^{(1)}$ (or m_4) small thus makes the GN similar to them

$\ell_i \to \ell_j \gamma$

- Light m_4 and m_{H^+} $\Rightarrow$ larger the amplitude
  $\Rightarrow$approximate Z_2 also enchances cLFV decays
- We look at:
  $$M \approx m_4 < 10\,\text{GeV}, \quad m_{H^+} < 1\text{TeV}$$
- Decay rate:

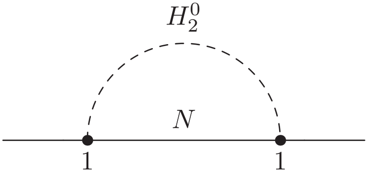


$$\Gamma_{i\to j\gamma} = \frac{m_i^5}{16\pi}|A_{ij}|^2 , \quad \text{where } A_{ij} = \frac{Y_i^{(2)} Y_j^{*(2)}}{m_{H^\pm}^2} \times \text{const. for } m_4 \ll m_{H^+} .$$

- $Y^{(2)}$ to be determined from neutrino masses and mixings at 1-loop
  (recall that it is responsible for radiative mass)

- Define at external momentum $p^2 = 0$, in the Higgs basis:

$\Lambda =$



$$\overset{\text{if } Z_2}{=} \frac{m_4}{32\pi^2} \ln \frac{m_H^2}{m_A^2} \sim \lambda_5 m_4$$

- Yukawa couplings (parameters, not fixed by neutrino data are in red):

$$Y_i^{(2)} = \text{sign}(\Lambda) \sqrt{\frac{m_2^{\text{pole}}}{|\Lambda| \cdot z(r, \omega_{22})}} \left(0, R_{22}, \frac{m_3^{\text{pole}}}{m_2^{\text{pole}}} R_{32}\right)_j U_{ji}, \quad U = \begin{cases} U_{PMNS}^\dagger & \text{for NO} \\ O_{IO} U_{PMNS}^\dagger & \text{for IO} \end{cases},$$

$$R = \begin{pmatrix} \cos r \, e^{i\omega_{22}} & -\sin r \, e^{-i\omega_{32}(r,\omega_{22})} e^{i\phi(\Lambda)} \\ \sin r \, e^{i\omega_{32}(r,\omega_{22})} & \cos r \, e^{-i\omega_{22}} e^{i\phi(\Lambda)} \end{pmatrix}, \quad \begin{pmatrix} \nu_{\text{radiative}} \\ \nu_{\text{seesaw}} \end{pmatrix} = R \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

- r is a mixing angle between seesaw and radiative, ω_{22}– a free phase.

parametrization of $Y_i^{(2)}$

- Decay rate:

$$\Gamma_{i\to j\gamma} = \frac{m_i^5}{16\pi}\left|A_{ij}\right|^2 \,, \text{ where } \; A_{ij} = \frac{Y_i^{(2)} Y_j^{*(2)}}{m_{H^+}^2} \times \text{const. for } m_4 \ll m_{H^+} \,.$$

- Inserting the parametrization for $Y_i^{(2)}$ becomes:

$$A_{ij} = \frac{f\left(r, \omega_{22}, \text{PMNS}, \text{neutrino masses}\right)}{\left|\Lambda\right| m_{H^\pm}^2}$$

- we call $\Lambda m_{H^\pm}^2$ a photon factor.
- We look at experimental constraints for $\ell_i \to \ell_j \gamma$ and put lower bound on $\Lambda m_{H^\pm}^2$ as a function of r, ω_{22}
  - we also give integrated bound on $\left|\Lambda\right| m_{H^\pm}^2$ (for the model to be completely excluded).

Summary of important experiments and observations

- "Important" – one which give strongest constraint.
- We checked that 3-body decays and $\mu \to e$ conversion are **not** important, when $m_{H^\pm} < 1\text{TeV}$.
- $\mu \to e\gamma$ is important in *almost* all of the parameter space.
- $\tau \to e\gamma$ and $\tau \to \mu\gamma$ become important in a tiny parameter space:
  - 3 solutions in $r - \omega$ plane exist for each $Y_e^{(2)} = 0$, $Y_\mu^{(2)} = 0$, or $Y_\tau^{(2)} = 0$
    $\Rightarrow$ around the $Y_e^{(2)} = 0$ and $Y_\mu^{(2)} = 0$ $\mu \to e\gamma$ vanishes, but τ decays do not
    $\Rightarrow$ the "weaker" $\tau \to \mu\gamma$ and $\tau \to e\gamma$ give bound on $\Lambda m_{H^\pm}^2$ in such case
    $\Rightarrow$ we can completely exclude some range for $|\Lambda|\, m_{H^\pm}^2$ with these 3 decay experiments.

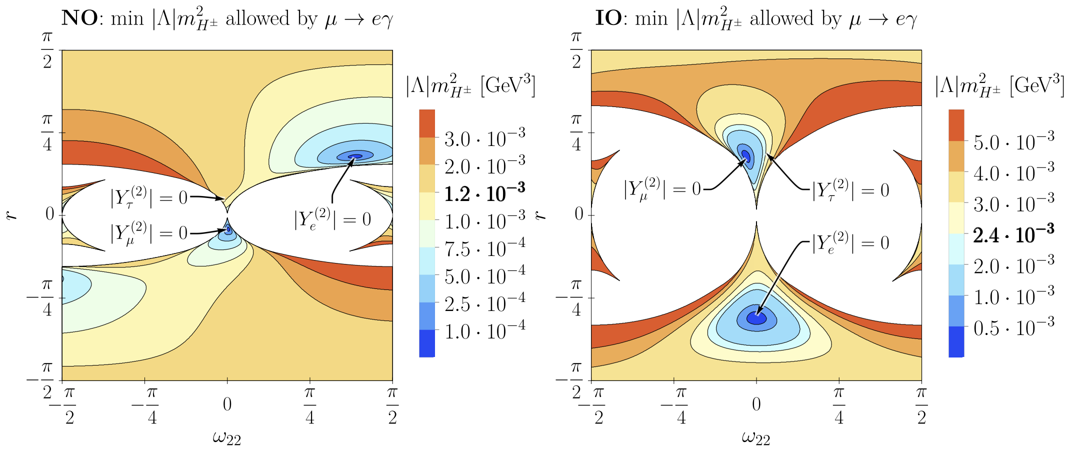


Figure: Lower bound on $\Lambda m_{H^\pm}^2$ from $\mu \to e\gamma$ as a function of r and ω_{22} for NO and IO. White regions are dissalowed by neutrino sector. The $\mu \to e\gamma$ vanishes at two points in $r - \omega$ plane, indicated in the plots by $\left|Y_{e,\mu}^{(2)}\right| = 0$.

Very lowest $\Lambda m^2_{H^\pm}$ from τ decays

- The special solutions of $Y^{(2)}_{e,\mu} = 0$ makes $\mu \to e\gamma$ vanish, but τ decays have non-zero prediction at those points:
  - τ decays give bounds $\Lambda m^2_{H^\pm}$ on , when $Y^{(2)}_{e,\mu} = 0$

Process and parameter point	NO, $\lvert\Lambda\rvert\, m^2_{H^\pm}$ [GeV^3]	IO, $\lvert\Lambda\rvert\, m^2_{H^\pm}$ [GeV^3]
$\tau \to e\gamma$ at $Y^{(2)}_{\mu} = 0$	$1.9 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$
$\tau \to \mu\gamma$ at $Y^{(2)}_{e} = 0$	$1.3 \cdot 10^{-5}$	$7.6 \cdot 10^{-6}$

Table: Lower bound on $\Lambda m^2_{H^\pm}$ in special points.

what if $\tau \to \mu\gamma$ observed in Belle-II?

(It is tight)

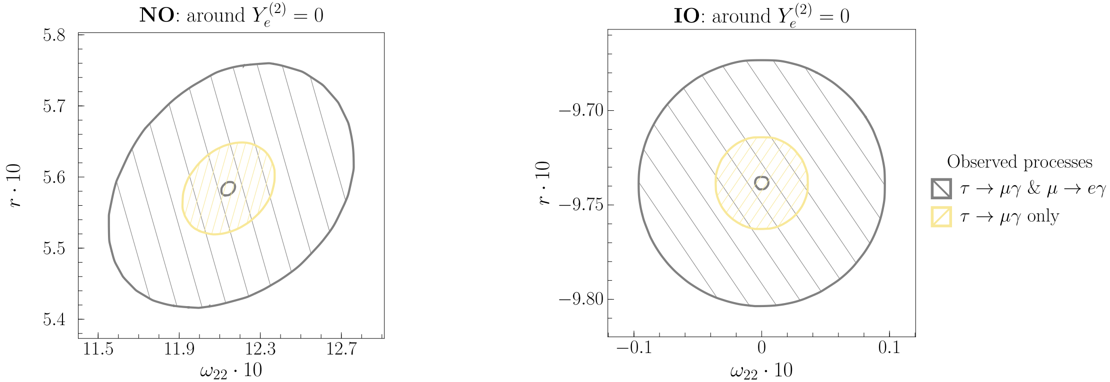


Figure: Space for possible observation of $\tau \to \mu\gamma$ in Belle-II around $Y_e^{(2)} = 0$

what if $\tau \to e\gamma$ observed in Belle-II?

(It is tight)

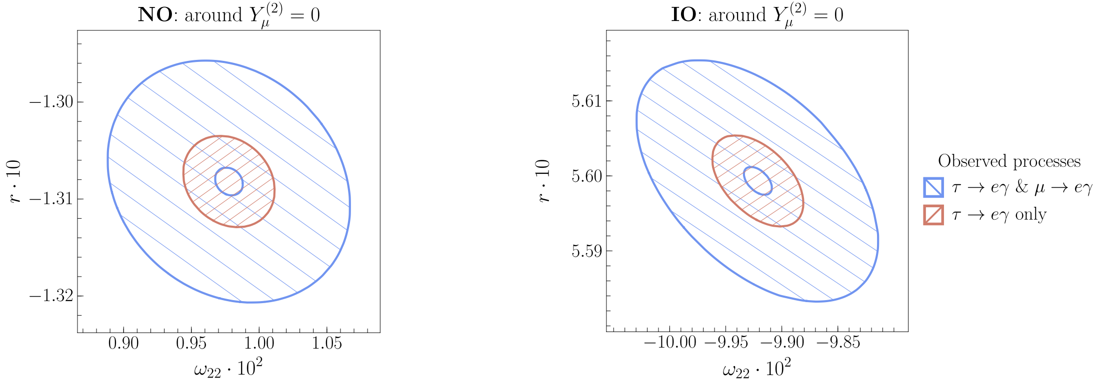


Figure: Space for possible observation of $\tau \to \mu\gamma$ in Belle-II around $Y_\mu^{(2)} = 0$

what if $\tau \to \ell\gamma$ observed in planned experiments?

(It is tight)

Observed processes	NO, $\lvert\Lambda\rvert\, m^2_{H^\pm}$ [GeV^3]	IO, $\lvert\Lambda\rvert\, m^2_{H^\pm}$ [GeV^3]
$\tau \to \mu\gamma$ & $\mu \to e\gamma$	$9.43 \cdot 10^{-5}$	$5.12 \cdot 10^{-5}$
$\tau \to \mu\gamma$ only	$9.07 \cdot 10^{-5}$	
$\tau \to e\gamma$ & $\mu \to e\gamma$ $\tau \to e\gamma$ only	$6.28 \cdot 10^{-6}$	$1.34 \cdot 10^{-5}$

Table: Upper bound on $\lvert\Lambda\rvert\, m^2_{H^\pm}$ in special points, if $\tau \to \ell\gamma$ is observed

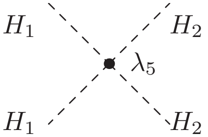
- Extremely tight parameter space around fine tuned point
  $\Rightarrow$ it is "unnatural" in GNM to expect tau decays in Belle-II
- We define "typical" scenario in GNM, in which these regions are excluded
  - we will give "typical" bound on $\lvert\Lambda\rvert\, m^2_{H^\pm}$ in "typical" scenario
  - but also give "absolute" bound on $\lvert\Lambda\rvert\, m^2_{H^\pm}$ including all parameter range in $r - \omega_{22}$.

Final results

$$\begin{aligned} &\text{absolute for NO(IO):} && |\Lambda|\, m_{H^\pm}^2 > 1.9(4.0)\cdot 10^{-6}\ \text{GeV}^3\,, \\ &\text{typical (no } \tau \to e(\text{or } \mu)\gamma \text{ expected):} && |\Lambda|\, m_{H^\pm}^2 \gtrsim 10^{-4}\ \text{GeV}^3\,. \end{aligned} \tag{1}$$

- For easy interpretation, let us assume Z_2 and $m_{H^\pm} \approx m_A \approx m_H \approx O(v)$:

$$|\Lambda|\, m_{H^\pm}^2 = \frac{m_{H^\pm}^2 m_4}{32\pi^2} \ln \frac{m_H^2}{m_A^2} \approx |\lambda_5|\, m_4 \cdot \frac{v^2}{32\pi^2}\,,$$



which leads to:

$$\begin{aligned} &\text{absolute for NO(IO):} && |\lambda_5| > 1(2)\cdot 10^{-2}\,\frac{\text{keV}}{m_4}\,, \\ &\text{typical (no } \tau \to e(\text{or } \mu)\gamma \text{ expected):} && |\lambda_5| \gtrsim \frac{\text{keV}}{m_4}\,. \end{aligned} \tag{2}$$

Conclusions

- Small λ_5 and m_4 can give signatures in cLFV in GNM.
  - Signatures for large m_4 are not likely (give way weaker constraints)
- For any 2HDM potential, we have limits on $|\Lambda|\, m_H^{\pm}$ from cLFV to tell if neutrinos can be realised as in GNM (in tiny seesaw)
- Results directly apply to scoto-seesaw model and give qualitative behaviour for scotogenic model too (both of them have exact Z_2, but more sterile neutrinos)
- There is a 2 orders of magnitude difference between "completely excluded" and most likely (or "typically") excluded value.

Thank you!

Relating to experiments

- We order $m_2^{\text{pole}} < m_3^{\text{pole}}$, so

$$\begin{aligned} \text{NH:} \quad & m_2^{\text{pole}} = \sqrt{\Delta m_{21}^2}\,, \; m_3^{\text{pole}} = \sqrt{\Delta m_{31}^2}\,, \\ \text{IH:} \quad & m_2^{\text{pole}} = \sqrt{\Delta m_{31}^2}\,, \; m_3^{\text{pole}} = \sqrt{\Delta m_{21}^2 + \Delta m_{31}^2}\,. \end{aligned}$$