Loop-level lepton flavor violation in the minimal left-right symmetric model

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based on

Shufang Qiang, Pei-Wen Wu & YCZ, 2512.abcde & 2512.ijklm

Motivation: lepton flavor violation (LFV) beyond SM

- Neutrino mass generation.
  (see other talks at this workshop)

- Charged LFV is always connected to beyond SM scalars.

LFV in LRSM

Parity violation

Figure: C. N. Yang, T. D. Lee & C. S. Wu

Left $\neq$ Right

Minimal Left-Right Symmetric Model

Pati & Salam '74; Mohapatra & Pati '75; Senjonavić & Mohapatra '75

- Minimal left-right symmetric extension:

$$SU(2)_L \times U(1)_Y \to SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Matter fields are left-right symmetric

left-handed	right-handed
$\begin{pmatrix} u_L \\ d_L \end{pmatrix} = Q_L$	$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \Psi_L$	$\Psi_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix}$

Minimal scalar sector

Pati & Salam '74; Mohapatra & Pati '75; Senjonavić & Mohapatra '75

$$
\begin{array}{c}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
\Big\Downarrow \, \Delta_R\,(\mathbf{1},\mathbf{3},2) \\
SU(2)_L \times U(1)_Y \\
\Big\Downarrow \, \Phi\,(\mathbf{2},\mathbf{2},0) \\
U(1)_{\mathrm{EM}}
\end{array}
$$

$$
\begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3 \text{ (CP-even)}
$$

$$
\begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow h,\ \underbrace{H_1^0,\ A_1^0,\ H_1^\pm}_{\text{heavy doublet}}
$$

Note: Left-handed triplet Δ_L could decouple from the TeV scale physics.

[Chang, Mohapatra & Parida '84, Deshpande, Gunion, Kayser & Olness '91]

FCNC in LRSM

- Tree-level: heavy bidoublet scalars H_1^0 and A_1^0 contributing to neutral K & $B_{d,s}$ meson mixing.
- 1-loop level: heavy W_R boson contributing to neutral K & $B_{d,s}$ meson mixing.
- 1-loop level: heavy W_R boson contributing to FCNC decays, e.g. $b \to s\gamma$, $b \to sg$, $b \to s\ell^+\ell^-$, $b \to s\nu\bar{\nu}$ [Cocolicchio et al, 1989].
- 1-loop level: light H_3:

$$K \to \pi + H_3, \; B \to K + H_3 \quad \Longrightarrow \quad v_R \gtrsim \mathrm{TeV}\,.$$

LFV in LRSM

- Tree-level: LFV induced by $H_{L,R}^{\pm\pm}$.
- Tree-level: Keung-Senjanović process [Das, Deppisch et al,1206.0256; Das et al, 1709.06553]:

$$pp \to W_R \to \ell_\alpha^\pm N \to \ell_\alpha^\pm \ell_\beta^{\mp(\pm)} jj$$

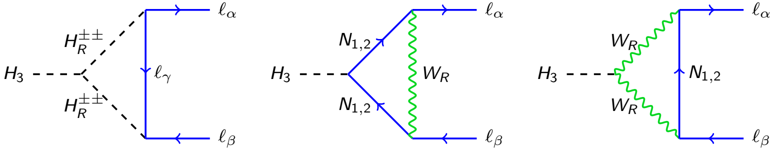
- 1-loop level: W_R and N_i in the LRSM contribute to lepton $g-2$, $\mu \to e\gamma$, $\mu \to 3e$ & $\mu - e$ conversion in nuclei [Cirigliano, Kurylov, Ramsey-Musolf, Vogel, hep-ph/0404233; Das, Deppisch et al, 1206.0256; Aguilar-Saavedra, Deppisch et al, 1203.5998], with

$$v_R \gtrsim \mathcal{O}(10\,\mathrm{TeV})\,.$$

- 1-loop level: Z, $Z_R \to q_\alpha \bar{q}_\beta$, $\ell_\alpha^+ \ell_\beta^-$ $(\alpha \neq \beta)$ [Perez & Soriano '92; Pilaftsis, hep-ph/9502330].
- For LNV, see the talks by Hao Ma, Xiao-Dong Ma, Ramsey-Musolf, Deppisch, Jiangming Yao.

Loop-level LFV couplings of H_3

- Loop-level LFV couplings of H_3 in the LRSM:



- The LFV couplings $\alpha \neq \beta$ originate from heavy neutrino mixing:

$$N_i = U_{i\alpha} N_\alpha$$

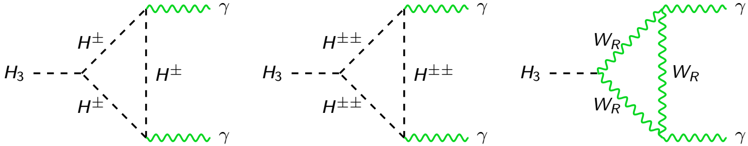
- Relatively light H_3 such that the decays of H_3 into heavy particles are highly suppressed:

$$H_3 \to H_i H_j, \; N_i N_j, \; V_R V_R \, .$$

- $H_1 - H_3$ mixing $\Longrightarrow$ tree-level LFV couplings of H_3.
  [Dev, Mohapatra & YCZ, 1602.05947]

$H_3 \to \gamma\gamma$ at 1-loop level

- Feynman diagrams for $H_3 \to \gamma\gamma$ in the LRSM:

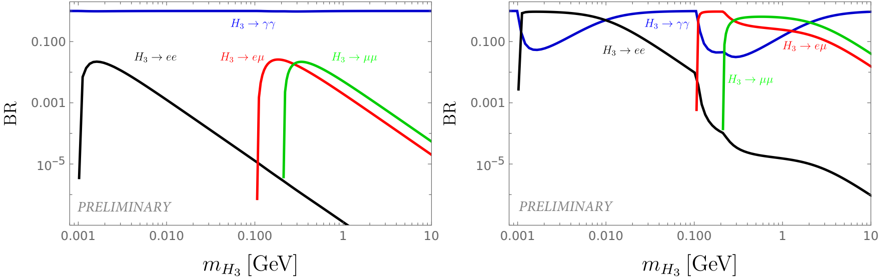


- In the limit of light H_3, all diagrams are suppressed by the v_R scale.

- Relatively light H_3 such that the decays of H_3 into heavy particles are highly suppressed:

$$H_3 \to H_i H_j,\ N_i N_j,\ V_R V_R\,.$$

BR: $N_{e,\mu}$ mixing



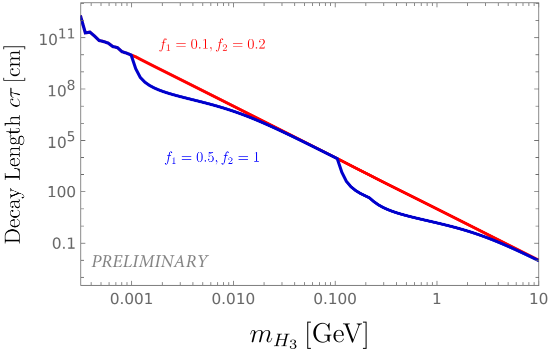
$v_R = 10$ TeV, $g_R = g_L$,

Left: $f_1 = 0.1$, $f_2 = 0.2$.

Right: $f_1 = 0.5$, $f_2 = 1.0$.

Different dependence of dilepton and diphoton channels on m_{H_3}.

The lifetime of H_3



$v_R = 10$ TeV, $g_R = g_L$.

H_3 is very long-lived, in particular for mass below $\mathcal{O}$(GeV).

See the talk by Zeren Wang

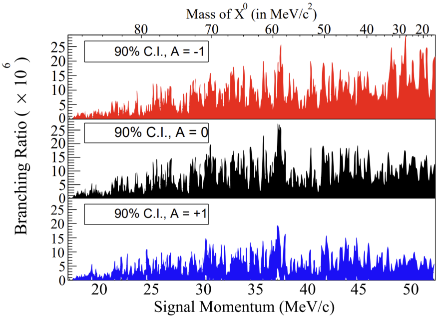
Comparison of scalar & axion constraints

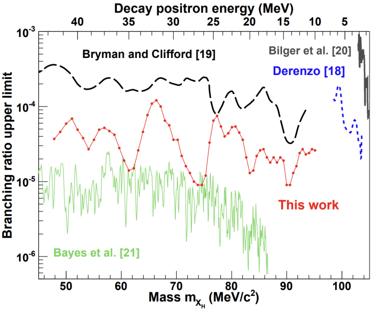
- We "borrow" the rich axion constraints in the literature to set limits on the CP-even scalar H_3 in LRSM.

- Production & decay.
  - Some are very close, e.g. $\ell_\beta \to \ell_\alpha + H_3/a$ and proton & electron beam dump experiments.
  - Some are significantly different, e.g. $H_3/a \to f\bar{f}$.

- We re-interpret the axion constraints, and set limits on H_3.

$$g_{e\mu,\, e\tau,\, \mu\tau}$$

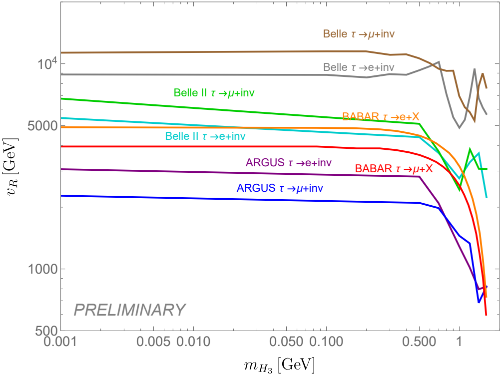




- Precision muon experiment TWIST (left) [1409.0638].
- Precision pion experiment PIENU (right) [2002.09170].
- H_3 very long-lived, decaying outside detectors.
- $\mathrm{BR}(\mu \to e + \mathrm{inv}) \lesssim 10^{-5} \implies v_R \gtrsim 10^6$ GeV, up to $\mathcal{O}(100$ MeV$)$.
- Assuming maximal $N_{1,2}$ mixing: $\theta = 45^\circ$.

Laboratory LFV constraints: $\tau \to e/\mu + \mathrm{inv}$

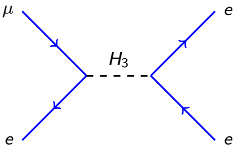
ZPC68(1995)25; 2106.02451; 2503.22195; 2212.03634

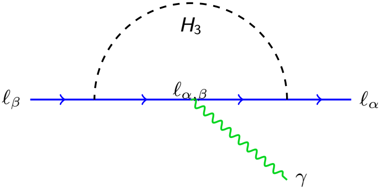


- With $m_{H_3} = 1$ GeV & $v_R = 10$ TeV, the lifetime of H_3 is at the meter order.
- $f_1 = 0.1,\ f_2 = 0.2.$
- Need to re-interpret the limits to constrain m_{H_3} & v_R.
- Assuming maximal $N_{1,2}$ mixing: $\theta = 45^\circ$.

LFV processes that are less constraining or not applicable

- Some LFV processes involving two 1-loop effective couplings of H_3: $\ell_\beta \to \ell_\alpha \gamma$, $\ell_\beta \to \ell_\alpha \gamma\gamma$, $\ell_\beta \to \ell_\alpha \ell_\gamma \ell_\delta$, $(g-2)_{e,\,\mu}$.





Low-energy supernova constraints on $g_{e\mu}$

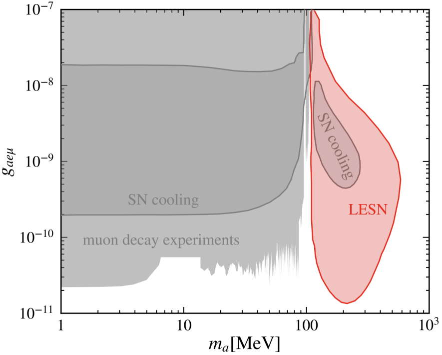
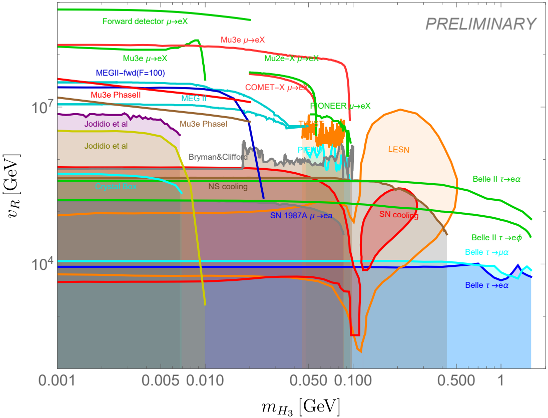


Figure: Figure from Zuowei Liu et al 2506.16922

- Low-energy supernova: explosion energies as low as 0.1 B $= 10^{50}$ erg.
- dominant production channel: $e + \mu \to a$.
- The supernova limits on axion: $g_{ae\mu} \lesssim \times 10^{-11}$ (see the talk by Zuowei Liu).



$g_R = g_L,\ f_1 = 0.1,\ f_2 = 0.2,\ \theta = 45^\circ$

Shaded regions: current limits.

Lines: future prospects.

Only most constraining τ limits in the figure.

Direct LHC limits $m_{W_R} \gtrsim 6.4$ TeV $\Longrightarrow v_R \gtrsim 10$ TeV [2304.09553].

$g_{ee,\,\mu\mu}$

Weak meson limits

- PIENU [2407.12738]:
  $\pi \to \ell + \nu + X$, $\mathrm{BR} \sim 10^{-6}$, limits rather weak.
- NA62 [2101.12304]:
  $K \to \ell + \nu + X$, $\mathrm{BR} \sim 10^{-6}$, limits rather weak.
- BaBar, Belle & LHCb [2211.08343]:
  K, D, $B \to \mu + \nu + a$, $f_a \gtrsim$ GeV, limits rather weak.

- SINDRUM [PLB175(1986)101]:
  $\pi \to e + \nu + a$, $a \to e^+e^-$, not applicable.
- E865 [hep-ex/0204006]:
  $K \to e + \nu + a$, $a \to e^+e^-$, not applicable.
- BaBar [1406.2980]:
  $e^+e^- \to \gamma A'$, $A' \to e^+e^-$, $\mu^+\mu^-$, not applicable.
- BaBar [1606.03501]:
  $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$, not applicable.

supernova constraints on g_{ee}

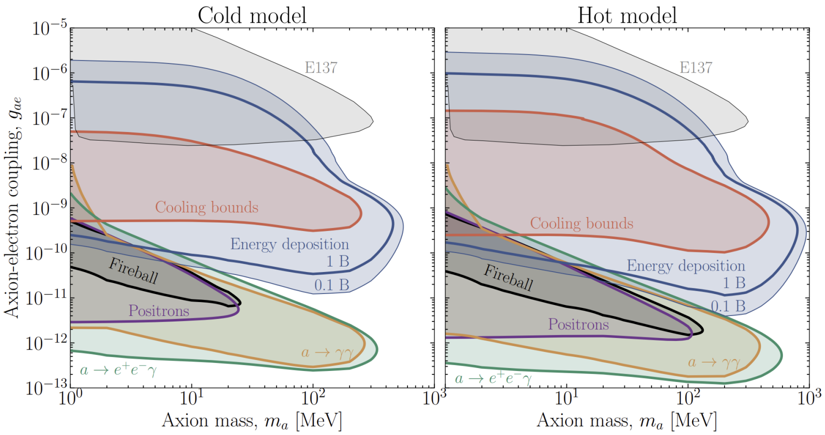


Figure: Figure from 2503.15630

- supernova limits on axion: $g_{aee} \lesssim 3 \times 10^{-12}$ [2503.15630].
- $\Longrightarrow v_R \gtrsim 10^5$ GeV.

supernova constraints on $g_{\mu\mu}$

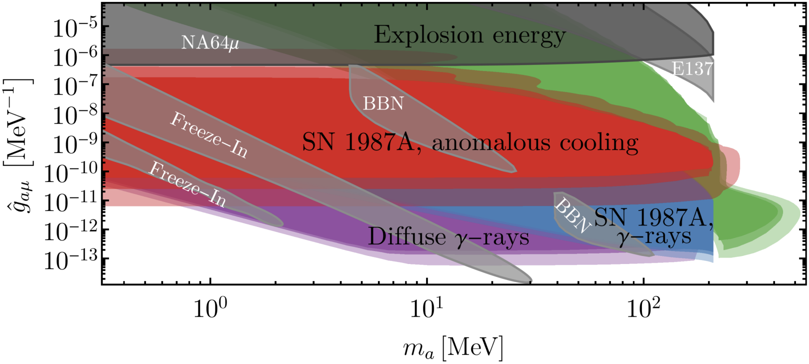
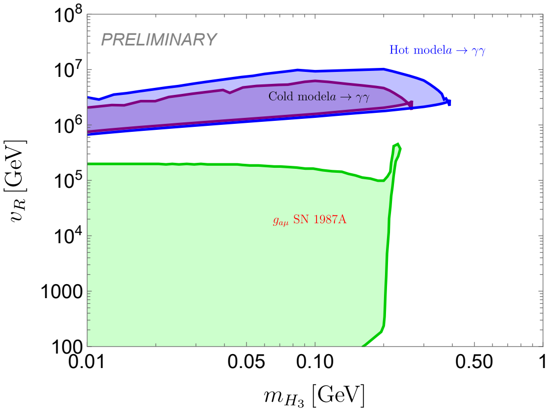


Figure: Figure from 2510.14469

- supernova limits on axion: $g_{a\mu\mu} \lesssim 10^{-11}$.
- $\Longrightarrow v_R \gtrsim 10^6$ GeV.

Limits on m_{H_3} & v_R: LFC case



$f_1 = 0.1,\ f_2 = 0.2.$

blue & purple: coupling g_{ee}.

green: coupling $g_{\mu\mu}$.

$g_{\gamma\gamma}$ & $g_{\gamma Z}$

Electron beam dump limits

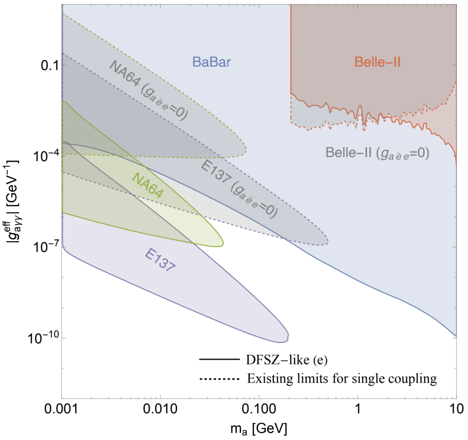


Figure: Figure from 2304.05435

- The E137 limit on $g_{a\gamma\gamma}$ can go down to 10^{-10} GeV^{-1}.
- $\Longrightarrow$ v_R constrained up to 10^5 GeV.

Beam dump limits on LRSM

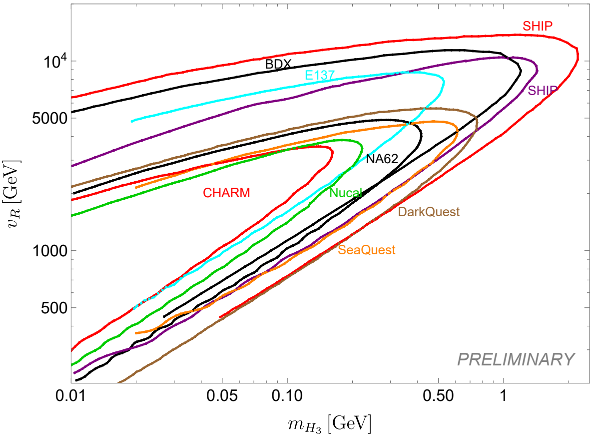


Figure: $f_1 = 0.1,\ f_2 = 0.2$

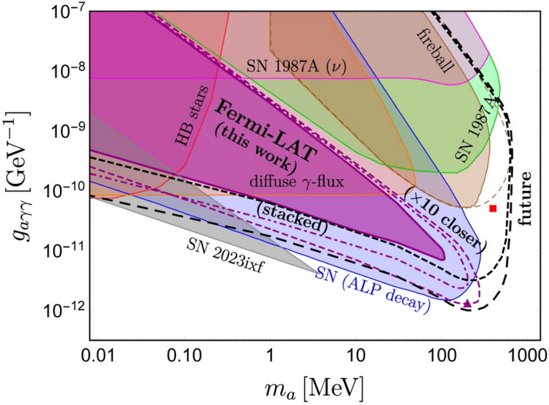
Weak limits on $g_{\gamma\gamma}$

- BESIII [2211.12699]:
  $J/\psi \to a + \gamma$, $a \to \gamma\gamma$, not applicable or weak limit.
- Belle II [2007.13071]:
  The searches of $\Upsilon(4S) \to a + \gamma$, $a \to \gamma\gamma$, not applicable or weak limit.
- BESIII, Belle, BaBar [2003.05594, 1809.05222, 1007.4646, 0808.0017]:
  J/ψ, $\Upsilon(1S)$, $\Upsilon(3S) \to \gamma + A^0$, $A^0 \to \mathrm{inv}$, $g_{X_{\gamma\gamma}} \lesssim 10^{-3}$ GeV^{-1}, weak limits.
- GlueX [2308.06339]:
  $\gamma + N \to N + a$, $a \to \gamma\gamma$, $f_a \gtrsim$ TeV, not applicable or weak limit.
- CMS [2202.03450]:
  vector boson scattering
  $\gamma\gamma \to a^* \to \gamma\gamma$, $g_{a\gamma\gamma} < 4.99$ TeV^{-1}, weak limit.
- ATLAS and CMS [2008.05355, 1810.04602]:
  ultra-peripheral heavy-ion collisions
  $\gamma\gamma \to a \to \gamma\gamma$, $f_a \gtrsim 10$ TeV, weak limit.

Weak limits on $g_{\gamma Z}$

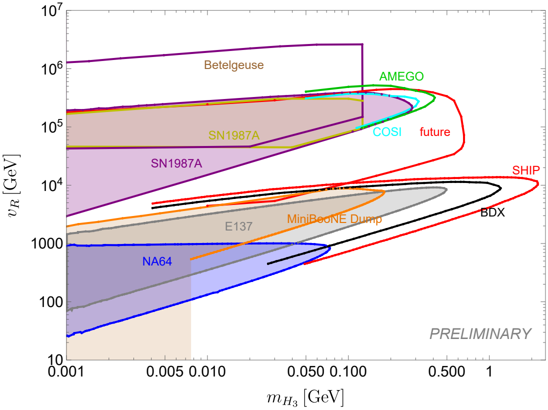
- L3 [PLB345(1995)609]:
  $Z \to \gamma + X$, $X \to \gamma\gamma$, $\mathrm{BR}(Z \to \gamma X)\mathrm{BR}(X \to \gamma\gamma) \lesssim 10^{-5}$,
  applies to the case of relatively heavy H_3 with $m_{H_3} \gtrsim 10$ GeV, with lifetime shorter than $\mathcal{O}(0.1$ cm), weak limit.
- CDF [1311.3282]:
  $Z \to \pi^0\gamma$, $\mathrm{BR} < 2.01 \times 10^{-5}$, weak limit.
- ATLAS [1509.05051]:
  $Z \to 3\gamma$, $\mathrm{BR} < 2.2 \times 10^{-6}$, weak limit.

Astrophysical limits



- SN1987A limits [2212.09764, 2304.01060].
- NS merger limits [2305.01002]
- $\Longrightarrow$ v_R up to $10^{5.5}$ GeV.

Limits & prospects of m_{H_3} & v_R: diphoton case



- $f_1 = 0.1,\ f_2 = 0.2.$
- shaded regions: excluded by current limits.
- lines: future prospects:
  Betelgeuse: future supernova observations;
  "future": future neutron star observations.

For larger Yukawa coupling case of $f_1 = 0.5$, $f_2 = 1.0$, the LFV & LFC prospects can be further improved by a factor of $\mathcal{O}(10)$.

more figures will be added...

Conclusion

- The phenomenologies of FCNC & LFV are very rich in the minimal LRSM, at the tree & 1-loop level.
- The light H_3 induced LFV, LFC and diphoton signals are very rich, depending on its mass and the v_R scale.
- The most stringent limits are from the high-precision measurements, e.g. muon and tauon decays, and astrophysical limits, e.g. those from supernovae and neutron stars.
- v_R is constrained up to the 10^7 GeV scale, well above the direct LHC constraints (direct W_R & Z_R searches).
- The right-handed scale v_R can be probed up to $\sim 10^9$ GeV at the future high-intensity frontier experiments.

Thank you for your attention!