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Exploring Lepton-Flavor Violation in Higgs Decays via an Ultralight Gauge Boson

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In collaboration with:
Ricardo Gaitán (UNAM), Roberto Martínez (UNAL)

arXiv:2406.17040v1

Outline

1. Motivation
2. Effective Lagrangian description
3. LFV Higgs decays
   - Decays with χ off-shell
   - Decays with χ on-shell
4. Conclusion

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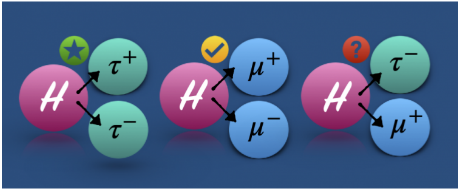

LFV Higgs Decays

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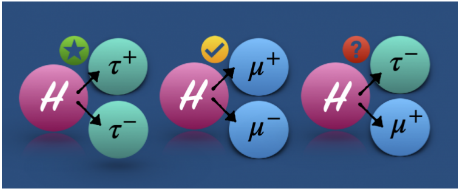

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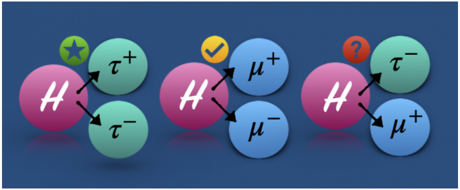

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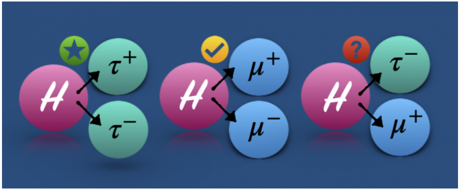

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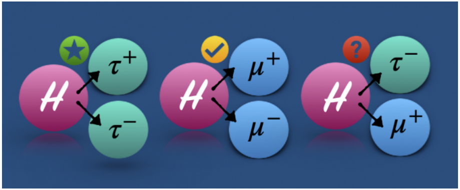

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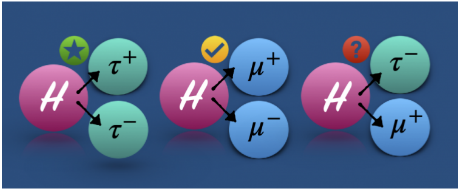

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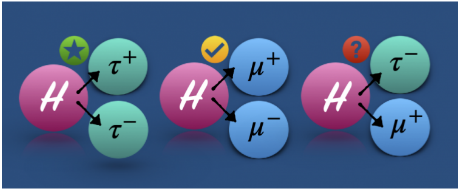

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	BR
$H \to \tau\tau$	$(6.0^{+0.8}_{-0.7})\%$
$H \to \mu\mu$	$(2.6 \pm 1.3) \times 10^{-4}$
$H \to ee$	$\leq 3.6 \times 10^{-4}$ (95%CL)
$H \to \tau\mu$	$\leq 1.5 \times 10^{-3}$ (95%CL)
$H \to \tau e$	$\leq 2.2 \times 10^{-3}$ (95%CL)
$H \to \mu e$	$\leq 6.1 \times 10^{-5}$ (95%CL)

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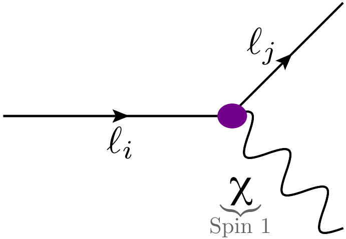
Our Framework



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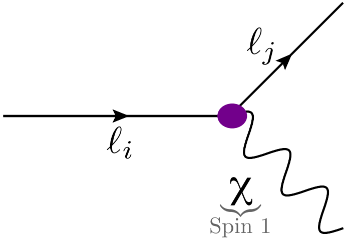

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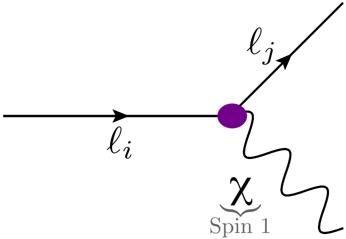

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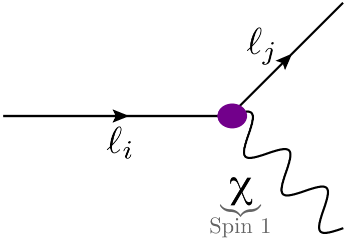

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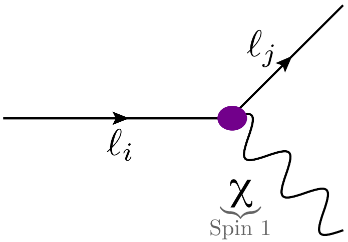

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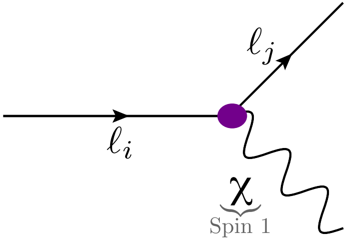

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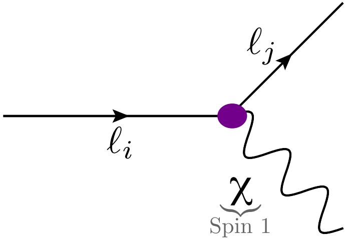

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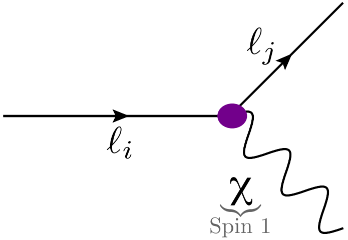

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In *Phys.Lett.B 827 (2022) 136933* in collaboration with A. Ibarra and P. Roig showed that in a renormalizable and gauge invariant theory, the rate does not diverge when $\boldsymbol{m_\chi \to 0}$. We presented two explicit models that generated LFV interaction at the tree level and the one-loop level.

Tree Level Model

The particle content and the corresponding spins and charges under $SU(2)_L \times U(1)_Y \times U(1)_\chi$ are

	L_1	L_2	e_{R_1}	e_{R_2}	ϕ_{11}	ϕ_{12}	ϕ_{21}	ϕ_{22}
spin	$1/2$	$1/2$	$1/2$	$1/2$	0	0	0	0
$SU(2)_L$	2	2	1	1	2	2	2	2
$U(1)_Y$	$-1/2$	$-1/2$	-1	-1	Y_{11}	Y_{11}	Y_{21}	Y_{21}
$U(1)_\chi$	q_{L_1}	q_{L_2}	q_{e_1}	q_{e_2}	$q_{\phi_{11}}$	$q_{\phi_{12}}$	$q_{\phi_{21}}$	$q_{\phi_{22}}$

$L_i = (\nu_{L_i}, e_{L_i})$ and e_{R_i}, $i = 1, 2$.

- ϕ_{jk} complex scalar fields and doublets under $SU(2)_L$. We assume that the hypercharge $Y_{jk} = 1/2$ and charge under $U(1)_\chi$ $q_{\phi_{jk}} = q_{L_j} - q_{e_k}$.
- We also assume that ϕ_{jk} acquire a vacuum expectation value $\Rightarrow \langle \phi_{jk} \rangle = v_{jk}$
- We need to allow for generation dependent charges under $U(1)_\chi$.

Lagrangian and LFV Interactions

- **Kinetic and Yukawa Lagrangians:**

$$\mathcal{L}_{\rm kin} = \sum_{j=1}^{2} i(\overline{L}_j \not{D} L_j + \overline{e}_{R_j} \not{D} e_{R_j}) + \sum_{j,k=1}^{2} (D_\mu \phi_{jk})^\dagger (D^\mu \phi_{jk})$$

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- We recast the kinetic Lagrangian in terms of the mass eigenstates, and we find flavor violating terms of the form

$$\mathcal{L}_{\rm kin} \supset \sum_{j=1}^{2} (i\overline{L}_j \not{D} L_j + i\overline{e}_{R_j} \not{D} e_{R_j})$$

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$$D_\mu \supset i g_\chi q \chi_\mu$$

$\Downarrow$ After basis change to the mass eigenstate basis

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$$g^{RR}_{e\mu} = g_\chi (q_{e_1} - q_{e_2}) \sin\theta_R \cos\theta_R\,, \quad \text{and} \quad g^{LL}_{e\mu} = g_\chi (q_{L_1} - q_{L_2}) \sin\theta_L \cos\theta_L\,.$$

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Effective Lagrangian description

The model that induces LFV transitions at the tree level is included in the low-energy effective Lagrangian with Monopole operators, as follows:

$$\mathcal{L}_{\mathrm{eff}} = f_{ij}\bar{\ell}_i\gamma^{\alpha}\chi_{\alpha}\ell_j + g_{ij}\bar{\ell}_i\gamma^{\alpha}\gamma_5\chi_{\alpha}\ell_j + \mathrm{h.c.}$$

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- $\ell_i\,,\ell_j = e\,,\mu\,,\tau$, with $\ell_i = \ell_j$ and $\ell_i \neq \ell_j$.
- $f_{ij} = c^v_{ij}\frac{m_\chi}{m_{\ell_i^j}}$ and $g_{ij} = c^a_{ij}\frac{m_\chi}{m_{\ell_i^j}}$, where $m_{\ell_i^j}$, represents the mass of the highest-generation lepton between ℓ_i and ℓ_j, and c^v_{ij} and c^a_{ij} are dimensionless independent coefficients.
- With this effective Lagrangian we can describe different LFV decays, but in this work we focus on LFV Higgs decays.

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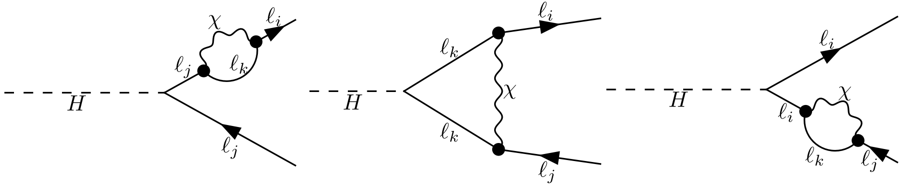
Decays with χ off-shell: $H \to \ell_i \ell_j$

The Effective Lagrangian induces one-loop level two-body LFV decays of $H \to \ell_i \bar{\ell}_j$.



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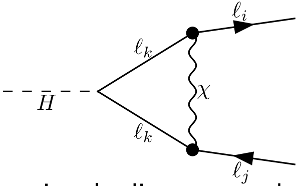


The contribution from the triangle diagram to the branching ratio of $H \to \ell_i \ell_j$, with ℓ_k into the loop, is given by:

$$\mathrm{BR}(H \to \ell_i \ell_j) = \frac{\Gamma(H \to \ell_i \bar{\ell}_j) + \Gamma(H \to \bar{\ell}_i \ell_j)}{\Gamma_H} \quad (1)$$
$$\simeq \frac{m_\chi^4}{m^2_{\ell_i^k} m^2_{\ell_j^k}} \frac{M_H m^2_{\ell_k}}{4\pi\, \Gamma_H\, v^2} \left[\left| c^v_{jk} c^a_{ik} - c^v_{ik} c^a_{jk} \right|^2 + \left| c^v_{jk} c^v_{ik} - c^a_{ik} c^a_{jk} \right|^2 \right] \left| \mathcal{F}_{\mathrm{ren}}(m_{\ell_i}, m_{\ell_j}, m_{\ell_k}) \right|^2 ,$$

where we have conveniently neglected the masses of the leptons in the kinematic expression, Γ_H represents the total Higgs decay width, and the loop function $\mathcal{F}(m_{\ell_i}, m_{\ell_j}, m_{\ell_k})$

$\mathrm{BR}(H \to \ell_i \ell_j)$ as a function of m_χ

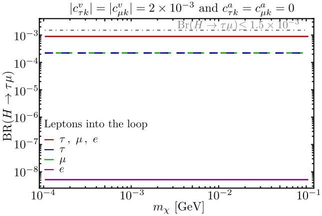


Figure: $H \to \tau\mu$

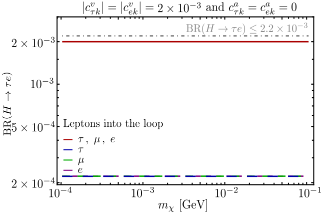


Figure: $H \to \tau e$

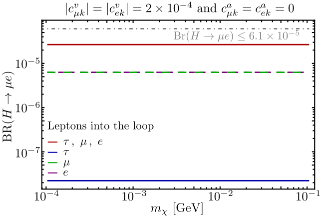
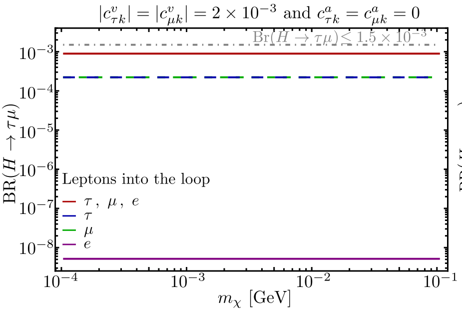
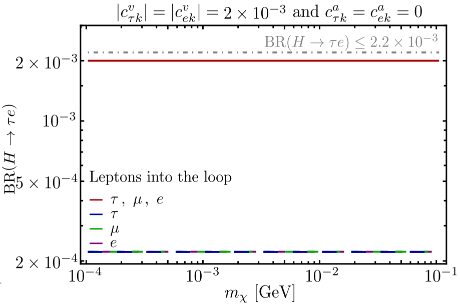


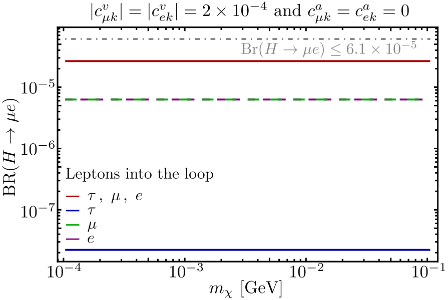
Figure: $H \to \mu e$

Assuming $c^a_{ij} = 0$ and suitable values for c^v_{ij}. The red line corresponds to the scenario where all three lepton contributions are active within the loop, *i.e.*, τ, μ, and e. Conversely, when only a single lepton contribution is activated in the loop, we represent it with violet, green, and blue lines for e, μ, and τ, respectively. The grey line denotes the current upper limit.

$\mathrm{BR}(H \to \ell_i \ell_j)$ as a function of m_χ







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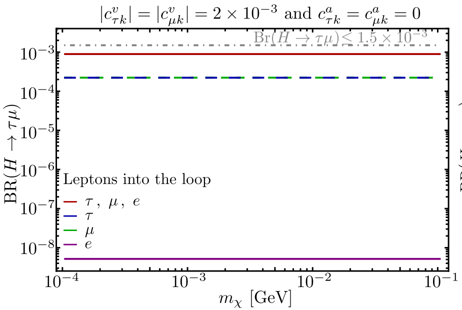
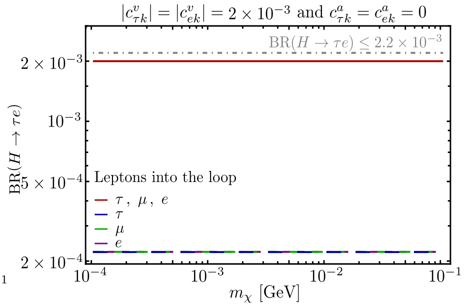
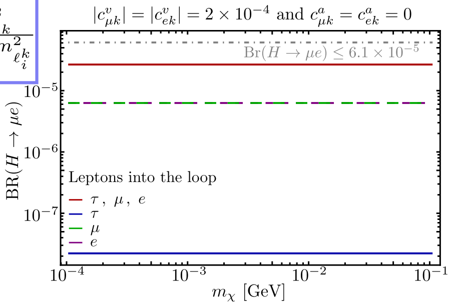




$$\mathrm{BR}(H \to \ell_i \ell_j) \propto \frac{m^2_{\ell_k}}{m^2_{\ell^k_j} m^2_{\ell^k_i}}$$



Constraint Regions on $|c_{ij}^v|$

- We use upper limits for $\mathrm{BR}(H \to e\mu, e\tau, \mu\tau)$ and $\mathrm{BR}(H \to ee, \mu\mu, \tau\tau)$ to constrain $|c_{ik}^v|$.
- Assuming $|c_{ik}^v| \neq 0$ and $|c_{ik}^a| = 0$, with $m_\chi = m_\mu/2$.
- Dominant contributions are shown in Figures for LFV decays. For $\mathrm{BR}(H \to \ell_i \ell_i)$, dominant contributions occur when $m_{\ell_k} = m_{\ell_i}$.

Constraint Regions on $|c_{ij}^v|$

- We use upper limits for $\mathrm{BR}(H \to e\mu, e\tau, \mu\tau)$ and $\mathrm{BR}(H \to ee, \mu\mu, \tau\tau)$ to constrain $|c_{ik}^v|$.
- Assuming $|c_{ik}^v| \neq 0$ and $|c_{ik}^a| = 0$, with $m_\chi = m_\mu/2$.
- Dominant contributions are shown in Figures for LFV decays. For $\mathrm{BR}(H \to \ell_i \ell_i)$, dominant contributions occur when $m_{\ell_k} = m_{\ell_i}$.

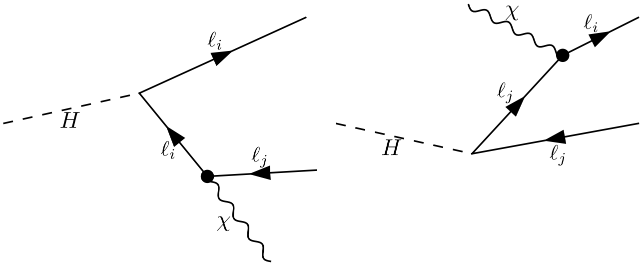
Constraints are:

$$0 < |c_{\mu\mu}^v| \lesssim 5.26 \times 10^{-4}, \quad 0 < |c_{\tau\tau}^v| \lesssim 8.41 \times 10^{-3}, \quad 0 < |c_{ee}^v| \lesssim 3.96 \times 10^{-5},$$

$$0 < |c_{\mu e}^v| \lesssim 5.35 \times 10^{2}\sqrt{\frac{1}{4.41 \times 10^{12} + 1.59 \times 10^{19}|c_{ee}^v|^2}}, \quad 0 < |c_{\tau\mu}^v| \lesssim 1.33 \times 10^{-3}$$

and $$0 < |c_{\tau e}^v| \lesssim 1.76 \times 10^{-3}\sqrt{\frac{4.58 \times 10^{13} - 4.4 \times 10^{17}|c_{\mu e}^v|^2}{5.5 \times 10^{13} + 7.78 \times 10^{17}|c_{ee}^v|^2}}.$$

Decays with χ on-shell: $H \to \ell_i \ell_j \chi$



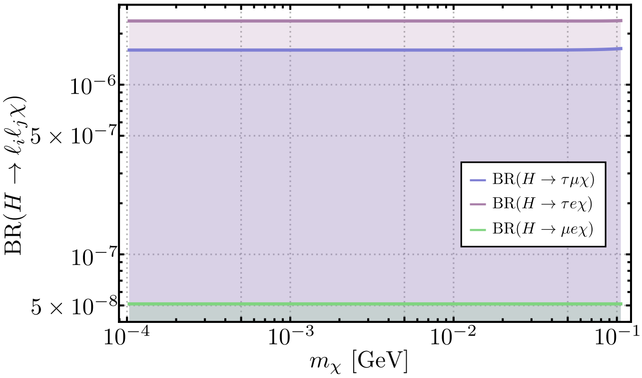
Utilizing the effective Lagrangian, we can induce the decays $H \to \ell_i \bar{\ell}_j \chi$ at the tree level. Here, we introduce the Mandelstam variables $t \equiv (q_{\ell_j} + q_\chi)^2$ and $s \equiv (q_{\ell_i} + q_\chi)^2$. The differential decay rate is then expressed as:

$$\frac{d^2\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{ds\ dt} = \frac{1}{32(2\pi)^3 M_H^3} \overline{|\mathcal{M}_{H\to\ell_i\bar{\ell}_j\chi}(s,t)|^2},$$

$\mathrm{BR}(H \to \ell_i \ell_j \chi)$ is defined as:

$$\mathrm{BR}(H \to \ell_i \ell_j \chi) = \frac{\Gamma(H \to \ell_i \bar{\ell}_j \chi) + \Gamma(H \to \bar{\ell}_i \ell_j \chi)}{\Gamma_H}.$$

Upper bound on $\mathrm{BR}(H \to \ell_i \ell_j \chi)$ as a function of m_χ



These bounds are derived from constraints established by the upper limits of $H \to \ell_i \ell_j$ decays while assuming $c^a_{ik} = 0$. Notably, similar to the $\mathrm{BR}(H \to \ell_i \ell_j)$ decays, the 3-body Higgs decay $\mathrm{BR}(H \to \ell_i \ell_j \chi)$ displays minimal dependence on the χ-boson mass.

Angular Observables

- We examined the decays $H \to \ell_i \bar{\ell}_j \chi$ as functions of lepton energy E_{ℓ_i} and angle $\cos\theta_{\ell_i \ell_j}$.
- Here, $\theta_{\ell_i \ell_j}$ is the angle between the momenta of the two leptons in the $\ell_i - \chi$ rest frame, where $\vec{q}_{\ell_i} + \vec{q}_\chi = \vec{0}$. Consequently, we have $|\vec{p}_H| = |\vec{q}_{\ell_j}| = \sqrt{E_H^2 - M_H^2}$ and $|\vec{q}_{\ell_i}| = |\vec{q}_\chi| = \sqrt{E_{\ell_i}^2 - m_{\ell_i}^2}$, with

$$E_H = \frac{(E_{\ell_i} + E_\chi)^2 + M_H^2 - m_{\ell_j}^2}{2(E_{\ell_i} + E_\chi)} .$$

- Then $s = (E_{\ell_i} + E_\chi)^2$ and $t = m_{\ell_j}^2 + m_\chi^2 + 2(E_{\ell_j} E_\chi + |\vec{q}_{\ell_i}||\vec{q}_{\ell_j}| \cos\theta_{\ell_i \ell_j})$. The partial decay rate is:

$$\frac{d^2\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i}\, d\cos\theta_{\ell_i \ell_j}} = \frac{(E_\chi + E_{\ell_i})^2 |\vec{q}_{\ell_i}||\vec{q}_{\ell_j}|}{(2\pi)^3\ 8 M_H^3 E_\chi} |\mathcal{M}_{H \to \ell_i \bar{\ell}_j \chi}(\cos\theta_{\ell_i \ell_j}, E_{\ell_i})|^2 .$$

Lepton Charge Asymmetry: $H \to \ell_i \ell_j \chi$

$\mathcal{A}^{L-C}(H \to \ell_i \ell_j \chi)$ as a function of $\cos\theta_{\ell_i \ell_j}$

$$\mathcal{A}^{L-C}(H \to \ell_i \ell_j \chi) = \frac{\frac{d\Gamma(H\to \ell_i \bar{\ell}_j \chi)}{d\cos\theta_{\ell_i\ell_j}} - \frac{d\Gamma(H\to \bar{\ell}_i \ell_j \chi)}{d\cos\theta_{\ell_i\ell_j}}}{\frac{d\Gamma(H\to \ell_i \bar{\ell}_j \chi)}{d\cos\theta_{\ell_i\ell_j}} + \frac{d\Gamma(H\to \bar{\ell}_i \ell_j \chi)}{d\cos\theta_{\ell_i\ell_j}}}.$$

We assume $c_{ij}^a = 0$ while $|c_{ij}^v|$ follows the constraints derived. We consider three options for the χ-boson mass: $m_\chi = 0$, $m_\chi = m_\mu/2$, and $m_\chi = m_\mu$.

Lepton Charge Asymmetry: $H \to \ell_i \ell_j \chi$

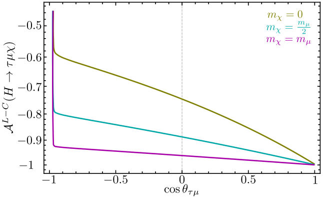


Figure: $H \to \mu\tau\chi$

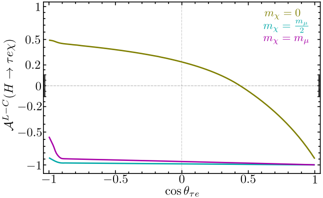


Figure: $H \to e\tau\chi$

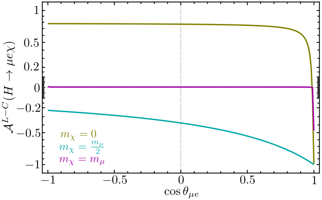


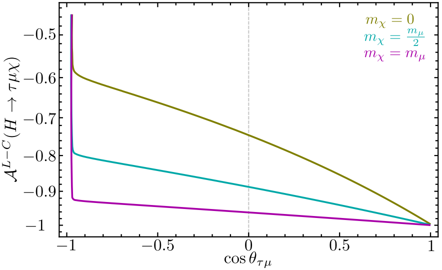
Figure: $H \to e\mu\chi$

$\mathcal{A}^{L-C}(H \to \ell_i \ell_j \chi)$ as a function of $\cos\theta_{\ell_i \ell_j}$

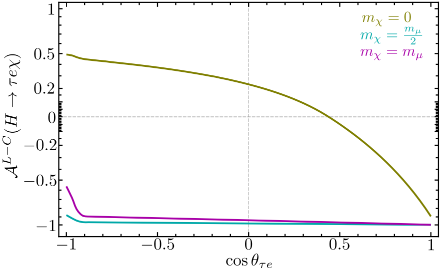
$$\mathcal{A}^{L-C}(H \to \ell_i \ell_j \chi) = \frac{\frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{d\cos\theta_{\ell_i \ell_j}} - \frac{d\Gamma(H \to \bar{\ell}_i \ell_j \chi)}{d\cos\theta_{\ell_i \ell_j}}}{\frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{d\cos\theta_{\ell_i \ell_j}} + \frac{d\Gamma(H \to \bar{\ell}_i \ell_j \chi)}{d\cos\theta_{\ell_i \ell_j}}} .$$

We assume $c^a_{ij} = 0$ while $|c^v_{ij}|$ follows the constraints derived. We consider three options for the χ-boson mass: $m_\chi = 0$, $m_\chi = m_\mu/2$, and $m_\chi = m_\mu$.

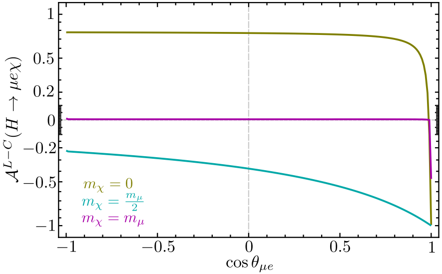
Lepton Charge Asymmetry: $H \to \ell_i \ell_j \chi$



(a) $H \to \tau\mu\chi$



(b) $H \to \tau e\chi$



(c) $H \to \mu e\chi$

Forward-Backward Asymmetry: $H \to \ell_i \bar{\ell}_j \chi$

$\mathcal{A}^{F-b}(H \to \ell_i \bar{\ell}_j \chi)$ as a function of E_{ℓ_i} [GeV]

$$\mathcal{A}^{F-b}(H \to \ell_i \bar{\ell}_j \chi) = \frac{\int_{-1}^{0} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i} d\cos\theta_{\ell_i \ell_j}} - \int_{0}^{1} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i} d\cos\theta_{\ell_i \ell_j}}}{\int_{-1}^{0} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i} d\cos\theta_{\ell_i \ell_j}} + \int_{0}^{1} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i} d\cos\theta_{\ell_i \ell_j}}}$$

We assume $c^a_{ij} = 0$ while $|c^v_{ij}|$ follows the constraints derived. We consider three options for the χ-boson mass: $m_\chi = 0$, $m_\chi = m_\mu/2$, and $m_\chi = m_\mu$.

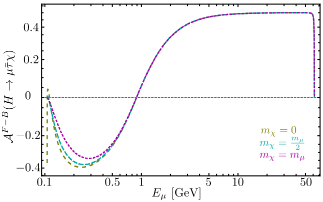


Figure: $H \to \mu\bar{\tau}\chi$

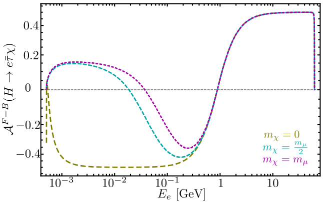


Figure: $H \to e\bar{\tau}\chi$

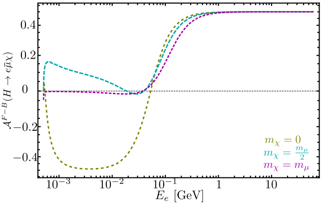


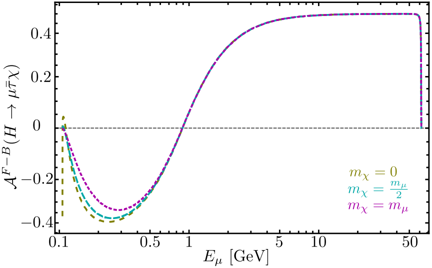
Figure: $H \to e\bar{\mu}\chi$

$\mathcal{A}^{F-b}(H \to \ell_i \bar{\ell}_j \chi)$ as a function of E_{ℓ_i} [GeV]

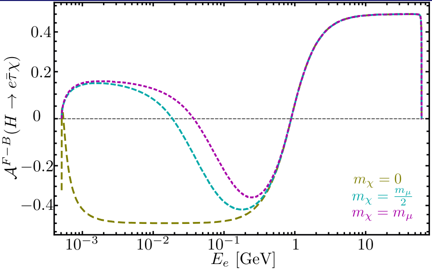
$$\mathcal{A}^{F-b}(H \to \ell_i \bar{\ell}_j \chi) = \frac{\int_{-1}^{0} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i}\, d\cos\theta_{\ell_i \ell_j}} - \int_{0}^{1} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i}\, d\cos\theta_{\ell_i \ell_j}}}{\int_{-1}^{0} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i}\, d\cos\theta_{\ell_i \ell_j}} + \int_{0}^{1} \frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{dE_{\ell_i}\, d\cos\theta_{\ell_i \ell_j}}}$$

We assume $c^a_{ij} = 0$ while $|c^v_{ij}|$ follows the constraints derived. We consider three options for the χ-boson mass: $m_\chi = 0$, $m_\chi = m_\mu/2$, and $m_\chi = m_\mu$.

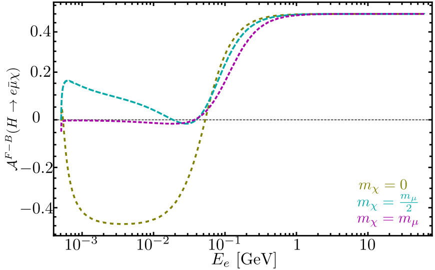
Forward-Backward Asymmetry: $H \to \ell_i \bar{\ell}_j \chi$



(a) $H \to \mu\bar{\tau}\chi$



(b) $H \to e\bar{\tau}\chi$



(c) $H \to e\bar{\mu}\chi$

Outline

1 Motivation

2 Effective Lagrangian description

3 LFV Higgs decays
- Decays with χ off-shell
- Decays with χ on-shell

4 Conclusion

Conclusions

- We studied the role of an ultralight gauge boson, χ, in mediating LFV Higgs decays.
- Our model matched tree-level $\bar{\ell}_i \ell_j \chi$ interactions with an EFT, preserving χ-boson mass as it approaches zero.
- We analyzed LFV Higgs decay for both on-shell and off-shell χ conditions.
- We derived indirect limits on $H \to \ell_i \ell_j \chi$ decays using bounds on $H \to \ell_i \ell_j$.
- Results show minimal dependence on χ-boson mass, except for Asymmetry: Lepton Charge and Forward-Backward, which is slightly sensitive.
- These constraints offer insights into LFV in Higgs decays via an ultralight gauge boson.

Questions?

Thank you!

Backup

Mixing angles and masses in the tree level model

After the SSB of the symmetry $U(1)_\chi$, the non-zero expectation values for ϕ_{jk} generate a mass for the χ boson: $m_\chi^2 = g_\chi^2(q_{\phi_{11}}^2 v_{11}^2 + q_{\phi_{12}}^2 v_{12}^2 + q_{\phi_{21}}^2 v_{21}^2 + q_{\phi_{22}}^2 v_{22}^2)$. The expectation value of the doublet scalars generates a mass term for the charged leptons, $-\mathcal{L}_{\rm mass} \supset \overline{e_{L_j}} M_{jk} e_{R_k} + \rm{h.c.}$, with

$$M = \begin{pmatrix} y_{11} v_{11} & y_{12} v_{12} \\ y_{21} v_{21} & y_{22} v_{22} \end{pmatrix} .$$

We now rotate the fields to express the Lagrangian on the mass eigenstate basis:

$$\begin{pmatrix} e_L \\ \mu_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & \sin\theta_L \\ -\sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} e_{L_1} \\ e_{L_2} \end{pmatrix} , \qquad \begin{pmatrix} e_R \\ \mu_R \end{pmatrix} = \begin{pmatrix} \cos\theta_R & \sin\theta_R \\ -\sin\theta_R & \cos\theta_R \end{pmatrix} \begin{pmatrix} e_{R_1} \\ e_{R_2} \end{pmatrix}$$

so that $-\mathcal{L}_{mass} \supset \overline{e_L} m_e e_R + \overline{\mu_L} m_\mu \mu_R + \text{h.c.}$, with

$$m_\mu^2 \simeq y_{11}^2 v_{11}^2 + y_{12}^2 v_{12}^2 + y_{21}^2 v_{21}^2 + y_{22}^2 v_{22}^2 ,$$

$$m_e^2 \simeq \frac{(y_{11} v_{11} y_{22} v_{22} - y_{12} v_{12} y_{21} v_{21})^2}{y_{11}^2 v_{11}^2 + y_{12}^2 v_{12}^2 + y_{21}^2 v_{21}^2 + y_{22}^2 v_{22}^2} ,$$

$$\sin 2\theta_L \simeq -2 \frac{y_{11} v_{11} y_{21} v_{21} + y_{12} v_{12} y_{22} v_{22}}{y_{11}^2 v_{11}^2 + y_{12}^2 v_{12}^2 + y_{21}^2 v_{21}^2 + y_{22}^2 v_{22}^2} ,$$

$$\sin 2\theta_R \simeq -2 \frac{y_{11} v_{11} y_{12} v_{12} + y_{21} v_{21} y_{22} v_{22}}{y_{11}^2 v_{11}^2 + y_{12}^2 v_{12}^2 + y_{21}^2 v_{21}^2 + y_{22}^2 v_{22}^2} ,$$

where we have used that empirically $m_\mu \gg m_e$.

Loop function $\mathcal{F}(m_{\ell_i}, m_{\ell_j}, m_{\ell_k})$

$$
\begin{aligned}
\mathcal{F}(m_{\ell_i}, m_{\ell_j}, m_{\ell_k}) = & \frac{\mathrm{A}_0\left[m_{\ell_k}^2\right]}{m_\chi^2} - \left(\frac{M_H^2}{2m_\chi^2} - \frac{2m_{\ell_k}^2}{m_\chi^2} - 3\right)\mathrm{B}_0\left[M_H^2, m_{\ell_k}^2, m_{\ell_k}^2\right] - \\
& 3\Big(\mathrm{B}_0\left[m_{\ell_i}^2, m_{\ell_k}^2, m_\chi^2\right] + \mathrm{B}_0\left[m_{\ell_j}^2, m_{\ell_k}^2, m_\chi^2\right] - \left(M_H^2 + m_\chi^2\right) \\
& \mathrm{C}_0\left[M_H^2, m_{\ell_i}^2, m_{\ell_j}^2, m_{\ell_k}^2, m_{\ell_k}^2, m_\chi^2\right]\Big) + 2\,.
\end{aligned}
$$

The associated counterterm Lagrangian is given by

$$
\mathcal{L}_{\mathrm{CT}} = C_{f_{ij}}\bar{\ell}_i\ell_j H + C_{g_{ij}}\bar{\ell}_i\gamma_5\ell_j H + \mathrm{h.c.}\,,
$$

where the coefficients of the scalar and pseudoscalar operators are specified as:

$$
\begin{aligned}
C_{f_{ij}} &= \frac{m_{\ell_k}}{2m_\chi^2 v\bar{\epsilon}_{\mathrm{uv}}}\left(M_H^2 - 6m_{\ell_k}^2 + 6m_\chi^2\right)\left(f_{ik}f_{jk} - g_{ik}g_{jk}\right), \\
C_{g_{ij}} &= \frac{m_{\ell_k}}{2m_\chi^2 v\bar{\epsilon}_{\mathrm{uv}}}\left(M_H^2 - 6m_{\ell_k}^2 + 6m_\chi^2\right)\left(f_{ik}g_{jk} - f_{jk}g_{ik}\right),
\end{aligned}
$$

with $\frac{1}{\bar{\epsilon}_{\mathrm{uv}}} \equiv \frac{1}{\epsilon_{\mathrm{uv}}} - \gamma_E + \ln 4\pi$. The amplitude is renormalized using the $\overline{\mathrm{MS}}$-scheme, ensuring that only finite contributions remain in the final calculation.

Squared Amplitude $H \to \ell_i \bar{\ell}_j \chi$

$$\overline{|\mathcal{M}_{H\to\ell_i\bar{\ell}_j\chi}(s,t)|^2} \simeq \frac{2}{m_{\ell_i^j}^2 v^2}\Bigg[\frac{m_{\ell_j}^2}{\Gamma_{\ell_j}^2 m_{\ell_j}^2 + (m_{\ell_j}^2 - s)^2}\Bigg[\left(\left|c_{ij}^a\right|^2 + \left|c_{ij}^v\right|^2\right)\Big(M_H^2(m_{\ell_i}^4 + m_{\ell_i}^2(m_\chi^2 - 2s)$$

$$+ m_{\ell_j}^2 m_\chi^2 - 2m_\chi^4 + s^2) - m_{\ell_i}^4(3m_{\ell_j}^2 + s) + m_{\ell_i}^2(m_{\ell_j}^4 - m_{\ell_j}^2(2m_\chi^2 - 5s + t)$$

$$+s(-2m_\chi^2 + 2s + t)) + t(m_{\ell_j}^2 - s)(s - 2m_\chi^2) + (m_\chi^2 - s)((m_{\ell_j}^2 + s)^2 + 8m_{\ell_j}^2 m_\chi^2)\Big)$$

$$+ 6m_{\ell_i} m_{\ell_j} m_\chi^2\left(\left|c_{ij}^a\right|^2 - \left|c_{ij}^v\right|^2\right)(M_h^2 - 2(m_{\ell_j}^2 + s))\Bigg] + \left\{\begin{array}{c} s \leftrightarrow t \\ m_{\ell_i} \leftrightarrow m_{\ell_j} \\ \Gamma_{\ell_j} \to \Gamma_{\ell_i} \end{array}\right\}\Bigg]$$

In this expression, the interference terms are subdominant and have been neglected. Here, Γ_{ℓ_k} denotes the total decay width of the lepton ℓ_k. It is important to note that the squared amplitude does not exhibit divergences for m_χ, ensuring the finiteness of the decay rate in the massless limit.