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

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arXiv:2406.17040v1

Outline

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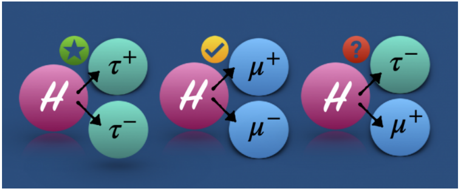
1. Motivation
2. Effective Lagrangian description
3. LFV Higgs decays
   - Decays with χ off-shell
   - Decays with χ on-shell
4. Conclusion

LFV Higgs Decays



LFV Higgs Decays

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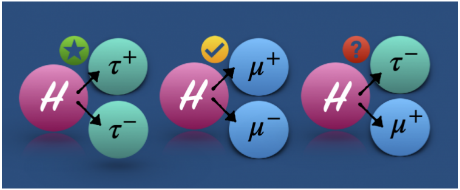

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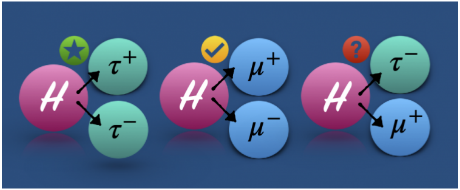

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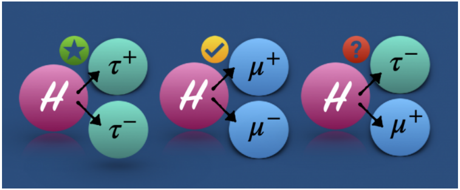

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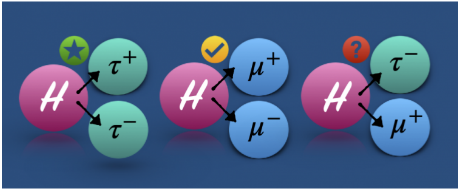

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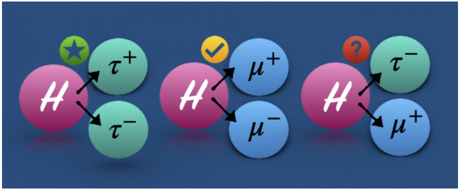

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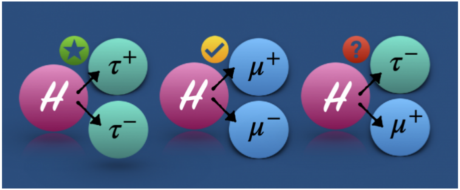

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	BR
$H \to \tau\tau$	$(6.0^{+0.8}_{-0.7})\%$
$H \to \mu\mu$	$(2.6 \pm 1.3) \times 10^{-4}$
$H \to ee$	$\leq 3.6 \times 10^{-4}$ (95%CL)
$H \to \tau\mu$	$\leq 1.5 \times 10^{-3}$ (95%CL)
$H \to \tau e$	$\leq 2.2 \times 10^{-3}$ (95%CL)
$H \to \mu e$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

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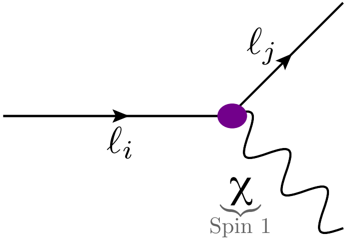
Our Framework



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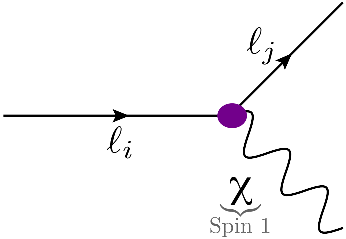

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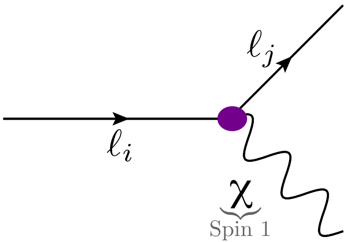

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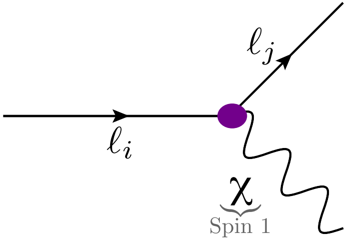

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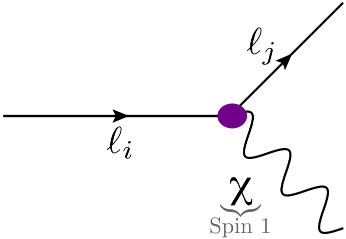

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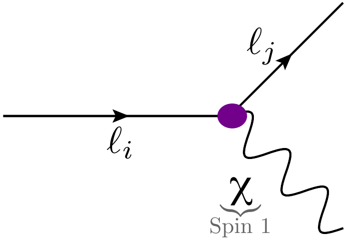

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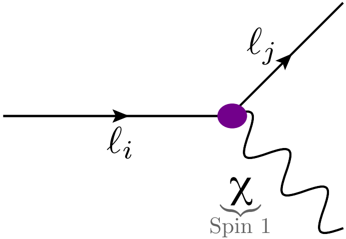

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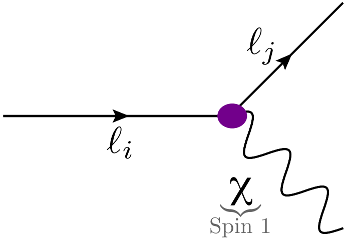

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In *Phys.Lett.B 827 (2022) 136933* in collaboration with A. Ibarra and P. Roig showed that in a renormalizable and gauge invariant theory, the rate does not diverge when $\boldsymbol{m_\chi \to 0}$. We presented two explicit models that generated LFV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

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

$$-\mathcal{L}_{\text{Yuk}} = \sum_{j,k=1}^{2} y_{jk} \overline{L}_j \phi_{jk} e_{R_k} + \text{h.c.}$$

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

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

$$\Downarrow$$

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

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

$$\Downarrow$$

$$-\mathcal{L}_{\rm kin} \supset \overline{e_R} i g_{e\mu}^{RR} \gamma^\rho \chi_\rho \mu_R + \overline{e_L} i g_{e\mu}^{LL} \gamma^\rho \chi_\rho \mu_L + \text{h.c.}\,, \quad \text{with}$$

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

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:

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

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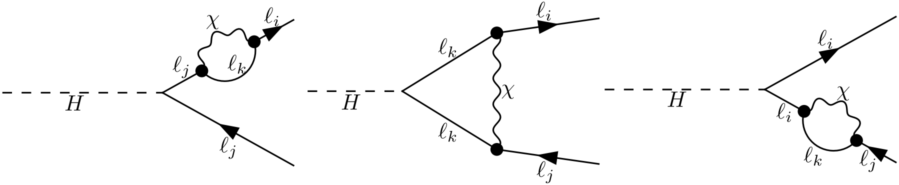
The Effective Lagrangian induces one-loop level two-body LFV decays of $H \to \ell_i \bar{\ell}_j$.



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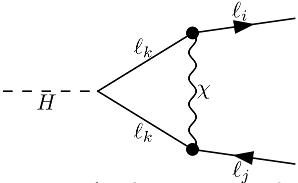


The contribution from the triangle diagram to the branching ratio of $H \to \ell_i \ell_j$, with ℓ_k into the loop, is given by:

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

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

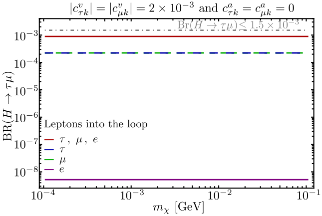


Figure: $H \to \tau\mu$

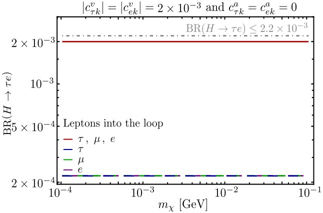


Figure: $H \to \tau e$

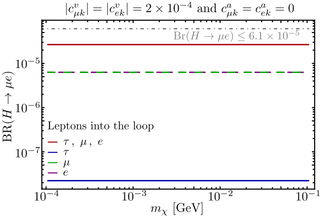
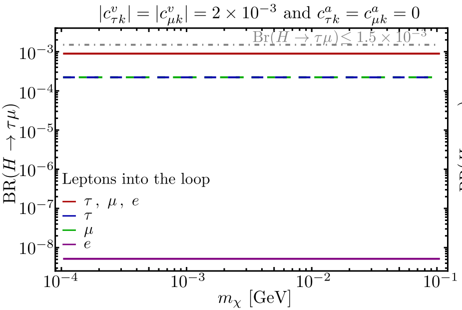
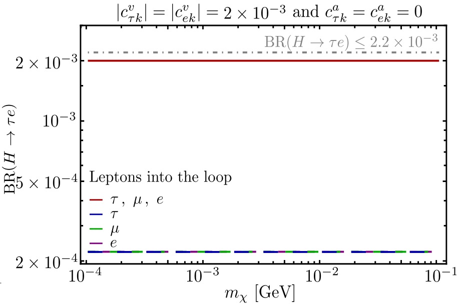


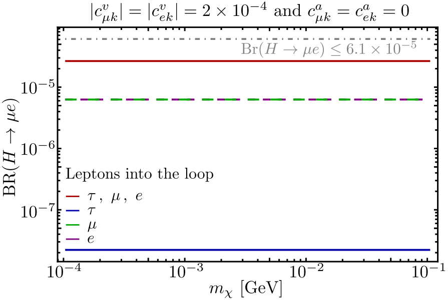
Figure: $H \to \mu e$

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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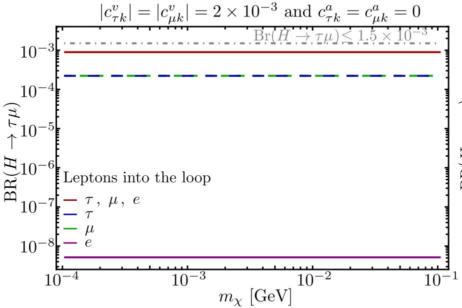
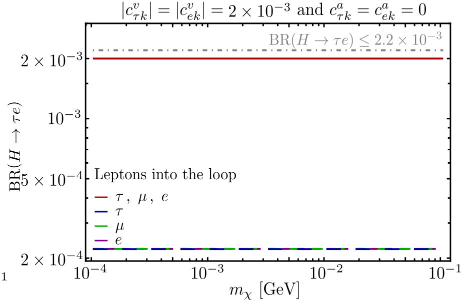
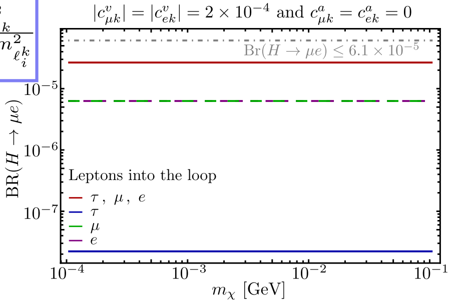




$$\boxed{\mathrm{BR}(H\to\ell_i\ell_j) \propto \frac{m^2_{\ell_k}}{m^2_{\ell^k_j} m^2_{\ell^k_i}}}$$



Constraint Regions on $|c^v_{ij}|$

- 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 $|c^v_{ik}|$.
- Assuming $|c^v_{ik}| \neq 0$ and $|c^a_{ik}| = 0$, 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 $m_{\ell_k} = m_{\ell_i}$.

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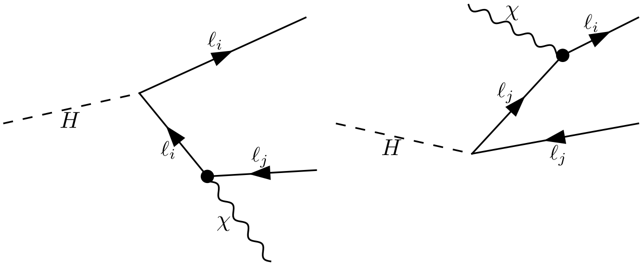
Constraints are:

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

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

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

Decays with χ on-shell



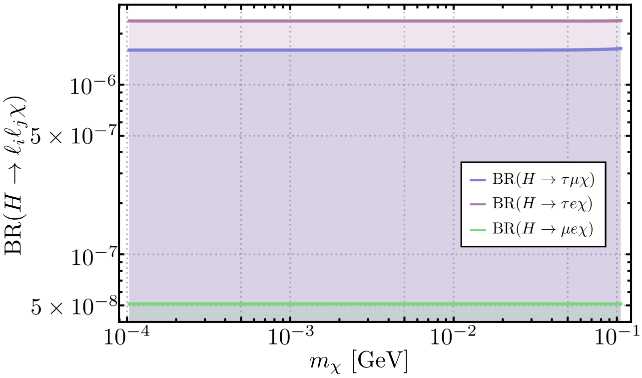
Utilizing the effective Lagrangian, we can induce the decays $H \to \ell_i \bar{\ell}_j \chi$ at the tree level. Here, we introduce the Mandelstam variables $t \equiv (q_{\ell_j} + q_\chi)^2$ and $s \equiv (q_{\ell_i} + q_\chi)^2$. The differential decay rate is then expressed as:

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

$\mathrm{BR}(H \to \ell_i \ell_j \chi)$ 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 $c^a_{ij} = 0$ 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: $H \to \ell_i \ell_j \chi$

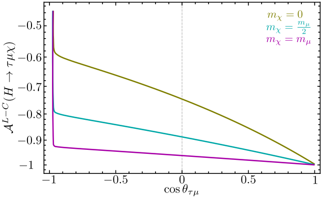


Figure: $H \to \mu\tau\chi$

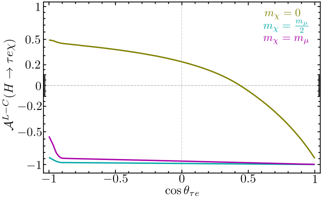


Figure: $H \to e\tau\chi$

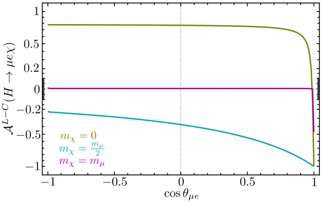


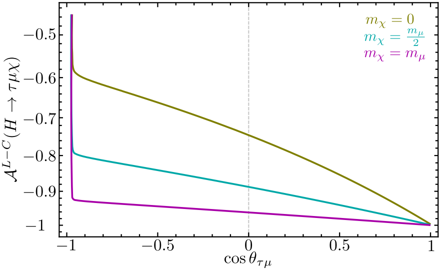
Figure: $H \to e\mu\chi$

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

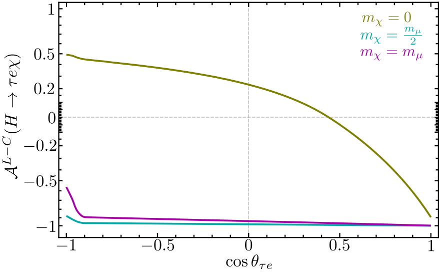
$$\mathcal{A}^{L-C}(H \to \ell_i \ell_j \chi) = \frac{\frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{d\cos\theta_{\ell_i \ell_j}} - \frac{d\Gamma(H \to \bar{\ell}_i \ell_j \chi)}{d\cos\theta_{\ell_i \ell_j}}}{\frac{d\Gamma(H \to \ell_i \bar{\ell}_j \chi)}{d\cos\theta_{\ell_i \ell_j}} + \frac{d\Gamma(H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

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 $m_\chi = m_\mu$.

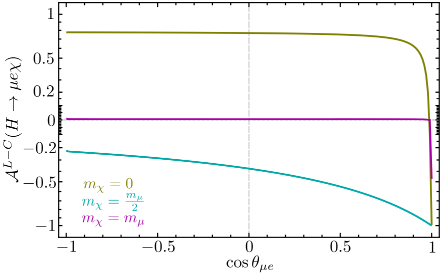
Lepton Charge Asymmetry: $H \to \ell_i \ell_j \chi$



(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 $c_{ij}^a = 0$ 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 $m_\chi = m_\mu$.

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

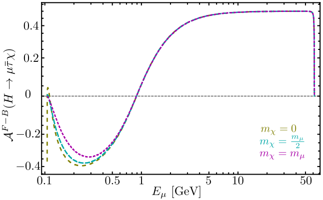


Figure: $H \to \mu\bar{\tau}\chi$

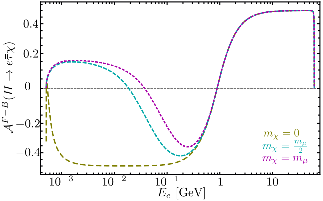


Figure: $H \to e\bar{\tau}\chi$

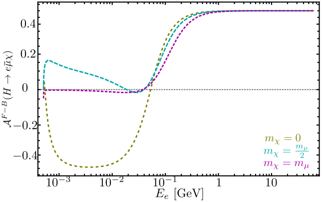


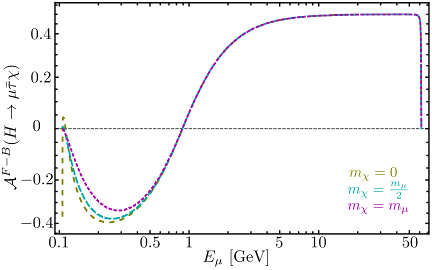
Figure: $H \to e\bar{\mu}\chi$

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

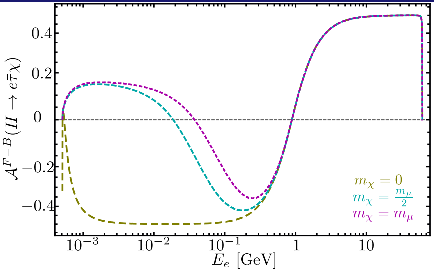
$$\mathcal{A}^{F-b}(H \to \ell_i\bar{\ell}_j\chi) = \frac{\int_{-1}^{0} \frac{d\Gamma(H\to\ell_i\bar{\ell}_j\chi)}{dE_{\ell_i}\, d\cos\theta_{\ell_i\ell_j}} - \int_{0}^{1} \frac{d\Gamma(H\to\ell_i\bar{\ell}_j\chi)}{dE_{\ell_i}\, d\cos\theta_{\ell_i\ell_j}}}{\int_{-1}^{0} \frac{d\Gamma(H\to\ell_i\bar{\ell}_j\chi)}{dE_{\ell_i}\,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

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 $m_\chi = m_\mu$.

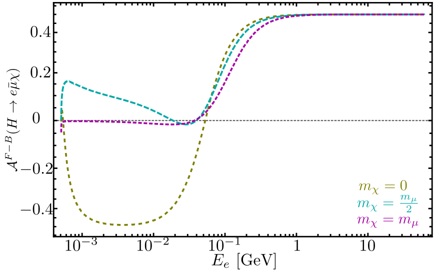
Forward-Backward Asymmetry: $H \to \ell_i \bar{\ell}_j \chi$



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



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



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

Outline

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.
- Results show minimal dependence on χ-boson mass, except for Asymmetry: Lepton Charge and Forward-Backward, which is slightly sensitive.
- We derived indirect limits on $H \to \ell_i \ell_j \chi$ decays using bounds on $H \to \ell_i \ell_j$.
- These constraints offer insights into LFV in Higgs decays via an ultralight gauge boson.

Questions?

Thank you!