Higgs decays into lepton pairs and a photon

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Based on [2001.06516, 2109.04426 (with Kachanovich, Nierste), 2405.16239 (with Kachanovich)]

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Portrait of $H \to \ell^- \ell^+ \gamma$, $\ell = e, \mu$

- We studied $H \to \ell^- \ell^+ \gamma$ process, with $\ell = e, \mu$, including a new one-loop calculation of the amplitude and decay rates

Dominated by electroweak loops, nonvanishing even for $m_\ell = 0$

- Probing chirality-conserving Higgs couplings to leptons

Consequently:

$$\Gamma(H \to e^- e^+ \gamma) \gg \Gamma(H \to e^- e^+), \quad \text{while}$$

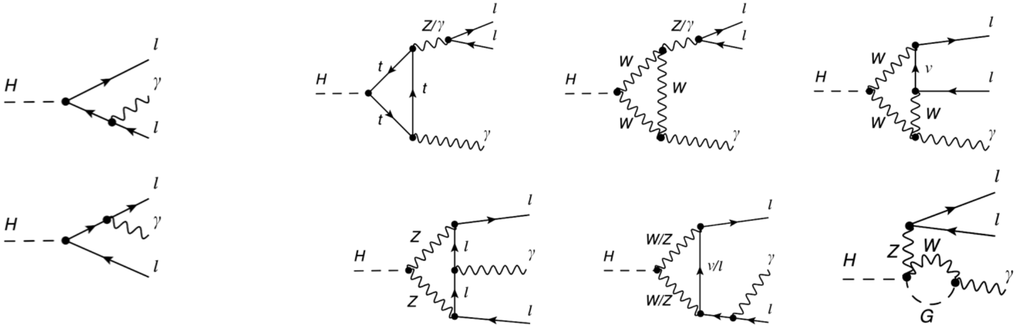
$$\Gamma(H \to \mu^- \mu^+ \gamma) \simeq 1/3\, \Gamma(H \to \mu^- \mu^+)$$

Branching fractions:

$$B(H \to e^- e^+ \gamma) = 5.8 \cdot 10^{-5}, \qquad B(H \to \mu^- \mu^+ \gamma) = 6.4 \cdot 10^{-5}$$

with minimal cuts: $s, t, u > (0.1\, m_H)^2$, $E_\gamma > 5$ GeV, $(E_1 > 7$ GeV, $E_2 > 25$ GeV$)$ or $(E_1 > 25$ GeV, $E_2 > 7$ GeV$)$

Sample set of diagrams:



- Tree-level contribution is negligible for $H \to e^- e^+ \gamma$, but notable for $H \to \mu^- \mu^+ \gamma$

$$\frac{d^2\Gamma}{ds\,dt} = \begin{cases} \frac{d^2\Gamma_{\text{loop}}}{ds\,dt}, & \text{for } \ell = e, \\ \frac{d^2\Gamma_{\text{loop}}}{ds\,dt} + \frac{d^2\Gamma_{\text{tree}}}{ds\,dt}, & \text{for } \ell = \mu. \end{cases}$$

(negligible tree-loop interference)

What makes this process interesting?

We identify three milestones expected from measurements of $H \to \ell^- \ell^+ \gamma$:

- Discovery of $H \to Z\gamma$
- Observation of $H \to \mu^- \mu^+ \gamma$ at tree level driven by muon's Yukawa coupling
- Search for deviations from SM both in H-Z-γ and nonresonant H-$\ell^- \ell^+ \gamma$

Why perform a new calculation?

- Previous calculations:
  - Analytic expressions derived in:

    [1] Abbasabadi, Bowser-Chao, Dicus, Repko (9611209)

    [2] Sun, Chang, Gao (1303.2230)
  - New calculations:

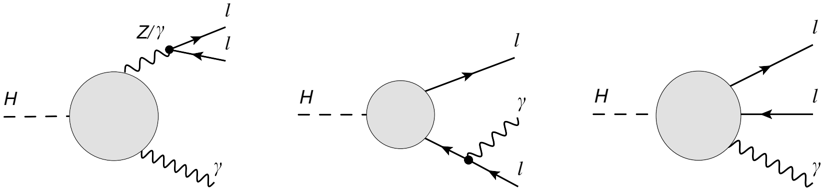
    [4] Passarino (1308.0422)

    [5] Han, Wang (1705.00790)
- Significant discrepancies between previous results for $d\Gamma(H \to \ell^- \ell^+ \gamma)/dm_{\ell\ell}$ prompted our independent calculation.
- To provide expressions that could prove useful in experimental studies

Our calculation

- We used linear R_ξ gauge, resulting with $\mathcal{O}(10^2)$ loop diagrams
- Analytic check of gauge invariance and UV/IR finiteness

Classes of one-loop diagrams:



(a) (b) (c)

- $H \to Z^*[\to \ell^+\ell^-]\gamma$ (a)
- $H \to \gamma^*[\to \ell^+\ell^-]\gamma$ (a)
- Others, including nonresonant box diagrams (b,c)

- Individual classes of diagrams exhibit ξ-dependence in the linear R_ξ gauge.
- Specifically, the ξ-dependence in the $H \to Z^*(\ell\ell)\gamma$ class cancels with contributions from other diagrams, including box diagrams.
- Multiplying this contribution by the Breit-Wigner distribution to study $H \to Z\gamma$ yields an unphysical result [Passarino, 1308.0422].

$H \to Z\gamma$ is well-defined only for on-shell Z boson

Achieving the three goals requires a clear separation of contributions performed in a gauge-invariant manner.

Loop amplitude:

$$\mathcal{A}_{\text{loop}} = \Big[(k_\mu\, p_{1\nu} - g_{\mu\nu}\, k\cdot p_1)\bar{u}(p_1)\big(a_1\gamma^\mu P_R + b_1\gamma^\mu P_L\big)v(p_2) \\ + (k_\mu\, p_{2\nu} - g_{\mu\nu}\, k\cdot p_2)\bar{u}(p_1)\big(a_2\gamma^\mu P_R + b_2\gamma^\mu P_L\big)v(p_2)\Big]\varepsilon^{\nu\,*}(k)\,,$$

determined in terms of two loop coefficients a_1, b_1, due to

$$a_2(t,u) = a_1(u,t)\,, \qquad b_2(t,u) = b_1(u,t)$$

with $s=(p_1+p_2)^2$, $t=(p_1+k)^2$, $u=(p_2+k)^2$

- We provide compact expressions for $a_1(u,t)$ and $b_1(u,t)$, reduced to scalar one-loop functions

Tools: `Feynarts`, `Feyncalc`, `Feynhelpers`, `PackageX`, `Collier`

Separation of resonant and nonresonant contributions

- Loop coefficients take the form:

$$a_1(s,t) = \widetilde{a}_1(s,t) + \frac{\alpha(s)}{s - m_Z^2 + i m_Z \Gamma_Z}$$

Setting $s = m_Z^2$ in $\alpha(s)$, $\beta(s)$ isolates the gauge-invariant resonant contribution from the nonresonant components:

$$a_1(s,t) = a_1^{nr}(s,t) + a_1^{res}(s)\,,$$

where:

$$a_1^{nr}(s,t) = \widetilde{a}_1(s,t) + \frac{\alpha(s) - \alpha(m_Z^2)}{s - m_Z^2 + i m_Z \Gamma_Z}, \quad a_1^{res}(s) = \frac{\alpha(m_Z^2)}{s - m_Z^2 + i m_Z \Gamma_Z}$$

(The residue of the Z-propagator is gauge-invariant.)

Implementing a discovery strategy for $H \to Z\gamma$:

- Using data on the double differential decay width, $\frac{d^2\Gamma}{ds\,dt}$, perform a fit to extract the following three quantities:

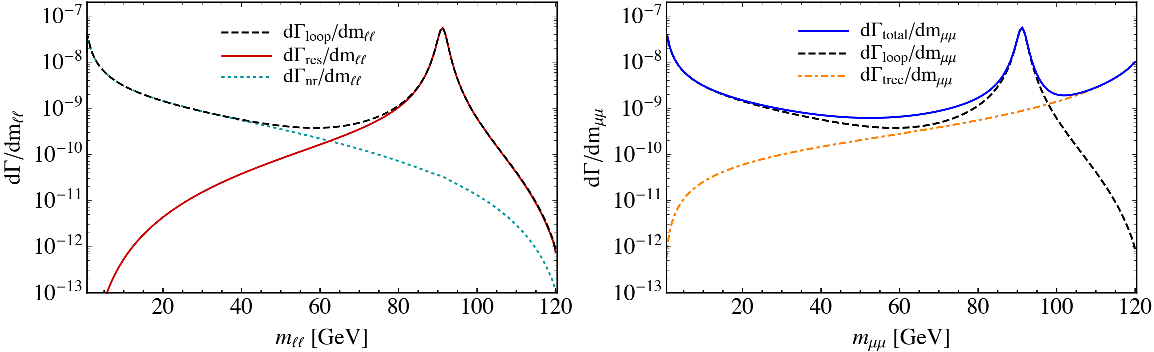
$$\left[\alpha(m_Z^2)\right]^2 + \left[\beta(m_Z^2)\right]^2, \quad |a_1^{nr}|^2 + |b_1^{nr}|^2 \quad \text{and} \quad |a_2^{nr}|^2 + |b_2^{nr}|^2$$

  - targeting $\left[\alpha(m_Z^2)\right]^2 + \left[\beta(m_Z^2)\right]^2 \neq 0$ at $5\,\sigma$ significance.

(with negligible resonant-nonresonant interference)

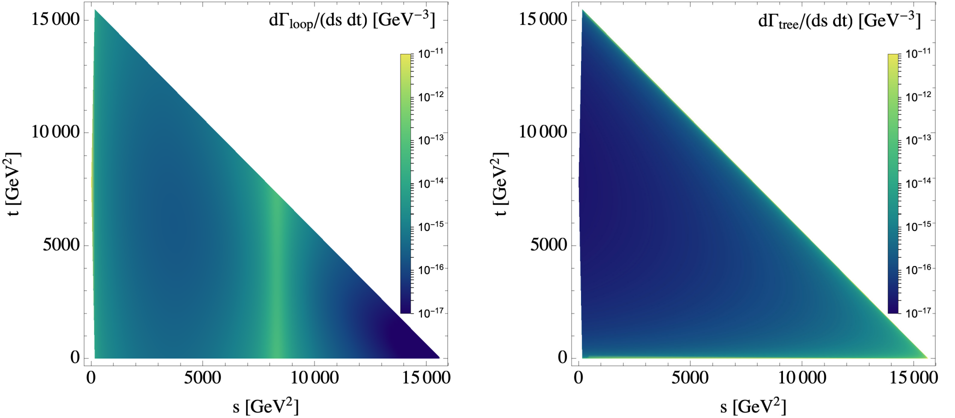
- Using the measured value of this quantity, relate $d\Gamma_{res}/ds$ to $\Gamma(H \to Z\gamma)$ under the narrow width approximation.
- To faciliate this, we provide numerical easy-to-use expressions for $a_{1,2}^{nr}$ and $b_{1,2}^{nr}$.

Differential distributions over dilepton mass:



- Peaks at the Z-pole and photon pole; for muons, the tree-level contribution rises towards the spectrum's endpoint.
- Nonresonant loop contributions are prominent between the photon and Z poles.

To devise kinematic cuts for separating contributions, we examine Dalitz plots



- Loop contributions (resonant and nonresonant) are sensitive to the cuts on s near the peaks, but insensitive to t and u near the edges
- Tree-level contribution peaks at low t and low u

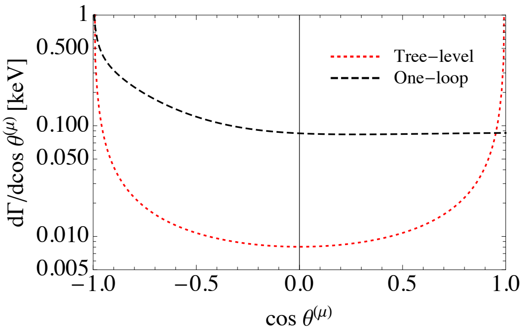
For generic cuts, nonresonant and tree contributions constitute significant fractions of the rate

$\boldsymbol{s_{min}}$	$\boldsymbol{s_{max}}$	$\boldsymbol{\tilde{t}_{min}, \tilde{u}_{min}}$	Γ_{res}(keV)	Γ_{nr}(keV)	Γ_{tree}(keV)	Γ_{tot}(keV)
$(0.1\, m_H)^2$	$(120\, GeV)^2$	$(0.1\, m_H)^2$	0.202	0.042	0.026	0.270
$(0.1\, m_H)^2$	$(120\, GeV)^2$	$(0.2\, m_H)^2$	0.165	0.037	0.013	0.215

Strategy for the separation of contributions:

- **Resonant contribution:** s around the Z-peak, excluding regions with significant tree-level effects; requires tighter cuts on t and u.
- **Nonresonant contribution:** s in the intermediate range between the photon and Z-peaks.
- **Tree-level contribution:** s above the Z-peak, with looser cuts on t and u.

Forward-backward asymmetry:



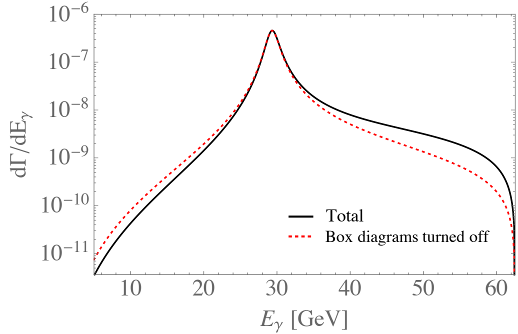
Interesting asymmetry w.r.t. $\cos\theta^{(\mu)}$ - angle between lepton and photon (in Higgs boson RF)

$$\mathcal{A}_{\mathsf{FB}}^{(\ell)} = \frac{\int_{-1}^{0} \frac{d\Gamma}{d\cos\theta^{(\ell)}} - \int_{0}^{1} \frac{d\Gamma}{d\cos\theta^{(\ell)}}}{\int_{-1}^{0} \frac{d\Gamma}{d\cos\theta^{(\ell)}} + \int_{0}^{1} \frac{d\Gamma}{d\cos\theta^{(\ell)}}}$$

$$\mathcal{A}_{\mathsf{FB}}^{(e)} = 0.343, \qquad \mathcal{A}_{\mathsf{FB}}^{(\mu)} = 0.255$$

Brief Overview of $H \to \nu\bar{\nu}\gamma$ [2405.16239]

- Non-resonant box contributions important for high photon energies with off-shell Z bosons.
- Potentially relevant for dark sector searches, especially at future lepton colliders.



Somewhat larger branching fraction:

$$B(H \to \nu\bar{\nu}\gamma) = 3.2 \cdot 10^{-4}$$

Summary

- Performed a new calculation of $H \to \ell^- \ell^+ \gamma$ ($\ell = e, \mu$) with compact expressions fully reduced to scalar one-loop functions, with analytic checks of ξ-independence, UV- and IR finiteness
- Evaluated differential decay rates and branching fractions
- Suggested a gauge-invariant separation of resonant contribution, enabling the determination of $\Gamma(H \to Z\gamma)$
- Separation of resonant, non-resonant, and tree-level contributions can be obtained by using the kinematic cuts
- We use $\alpha^{-1} = \frac{\pi}{\sqrt{2} G_F m_W^2 \sin^2 \theta_W} = 132$, compare to $\alpha^{-1} = 128$. Ambiguity in numerical inputs for α can only be resolved through a NLO calculation
- Performed one-loop calculation of $H \to \nu\bar{\nu}\gamma$ process

Additional Details on the Cuts

Resonant contribution

s_{min}	s_{max}	$\tilde{t}_{min}, \tilde{u}_{min}$	Γ_{res} (keV)	Γ_{nr}(keV)	Γ_{tree}(keV)	Γ_{tot}(keV)
$(70\,GeV)^2$	$(100\,GeV)^2$	$(0.1\,m_H)^2$	**0.195**	0.002	0.007	0.204
$(70\,GeV)^2$	$(100\,GeV)^2$	$(0.2\,m_H)^2$	**0.160**	0.001	0.004	0.165

Nonresonant contribution

s_{min}	s_{max}	$\tilde{t}_{min}, \tilde{u}_{min}$	Γ_{res}(keV)	Γ_{nr}(keV)	Γ_{tree}(keV)	Γ_{tot}(keV)
$(10\,GeV)^2$	$(40\,GeV)^2$	$(0.1\,m_H)^2$	$3.53 \cdot 10^{-4}$	$\mathbf{3.78 \cdot 10^{-2}}$	$1.02 \cdot 10^{-3}$	$3.92 \cdot 10^{-2}$
$(20\,GeV)^2$	$(40\,GeV)^2$	$(0.1\,m_H)^2$	$3.33 \cdot 10^{-4}$	$\mathbf{1.75 \cdot 10^{-2}}$	$8.12 \cdot 10^{-4}$	$1.87 \cdot 10^{-2}$

Tree-level contribution

s_{min}	s_{max}	$\tilde{t}_{min}, \tilde{u}_{min}$	Γ_{res}(keV)	Γ_{nr}(keV)	Γ_{tree}(keV)	Γ_{tot}(keV)
$(100\,GeV)^2$	$(120\,GeV)^2$	$(0.1\,m_H)^2$	$1.93 \cdot 10^{-3}$	$7.51 \cdot 10^{-5}$	$\mathbf{1.5 \cdot 10^{-2}}$	$1.70 \cdot 10^{-2}$
$(100\,GeV)^2$	$(120\,GeV)^2$	$(0.2\,m_H)^2$	$1.40 \cdot 10^{-3}$	$5.28 \cdot 10^{-5}$	$\mathbf{6.06 \cdot 10^{-3}}$	$7.51 \cdot 10^{-3}$