Rare Higgs Decays in the Standard Model

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Based on:
https://arxiv.org/abs/2103.03050
https://arxiv.org/abs/2203.00514

Motivations

After the discovery of Higgs boson by the ATLAS and CMS Collaborations, a new era of the precise determination of the properties of this new particle has begun. In recent years, experimental searches for rare Higgs decays, like $h \to V\gamma$ (V denotes vector mesons $\rho, \phi, J/\psi$ and Υ etc.) and $h \to VV (V = J/\psi, \Upsilon)$ have been performed at the LHC.

Motivated by the above experimental studies, we have presented the theoretical analysis of rare processes, including Higgs decays into lepton pair plus one light hadron and decays into a pair of heavy vector quarkonia, in the standard model (SM).

Feynman diagrams for $h \to V\ell\bar{\ell}$

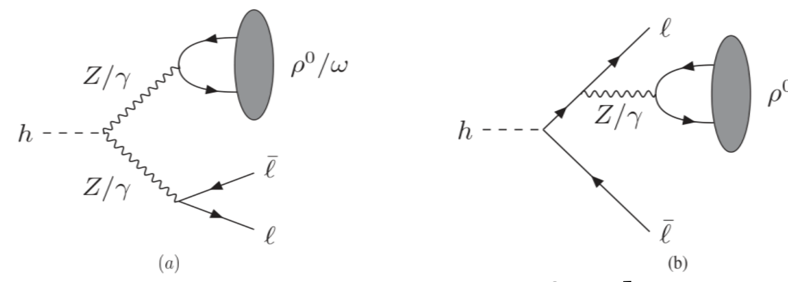


Figure 1: Lowest-order diagrams for $h \to V\ell\bar{\ell}$ ($V = \rho^0, \omega$) decays in the SM. After some adjustment, by omitting some terms, it also gives the decay amplitudes for $h \to \pi^0\ell\bar{\ell}$, $h \to \pi^+(K^+)\ell^-\bar{\nu}_\ell$, and $h \to \rho^+(K^{*+})\ell^-\bar{\nu}_\ell$.

Branching ratios

$h \to V\ell^+\ell^-$. Branching ratio differs with the flavor of the charged leptons. ρ^0 final state has the branching ratio about 10 times as that of ω.

$$\mathcal{B}(h \to \rho^0 e^+e^-) = (4.61 \pm 0.06) \times 10^{-7},$$
$$\mathcal{B}(h \to \rho^0 \mu^+\mu^-) = (3.97 \pm 0.05) \times 10^{-7},$$
$$\mathcal{B}(h \to \rho^0 \tau^+\tau^-) = (1.80 \pm 0.02) \times 10^{-5},$$
$$\mathcal{B}(h \to \omega e^+e^-) = (4.17 \pm 0.09) \times 10^{-8},$$
$$\mathcal{B}(h \to \omega \mu^+\mu^-) = (3.61 \pm 0.08) \times 10^{-8},$$
$$\mathcal{B}(h \to \omega \tau^+\tau^-) = (1.58 \pm 0.03) \times 10^{-6}$$

$h \to V\nu\bar{\nu}$

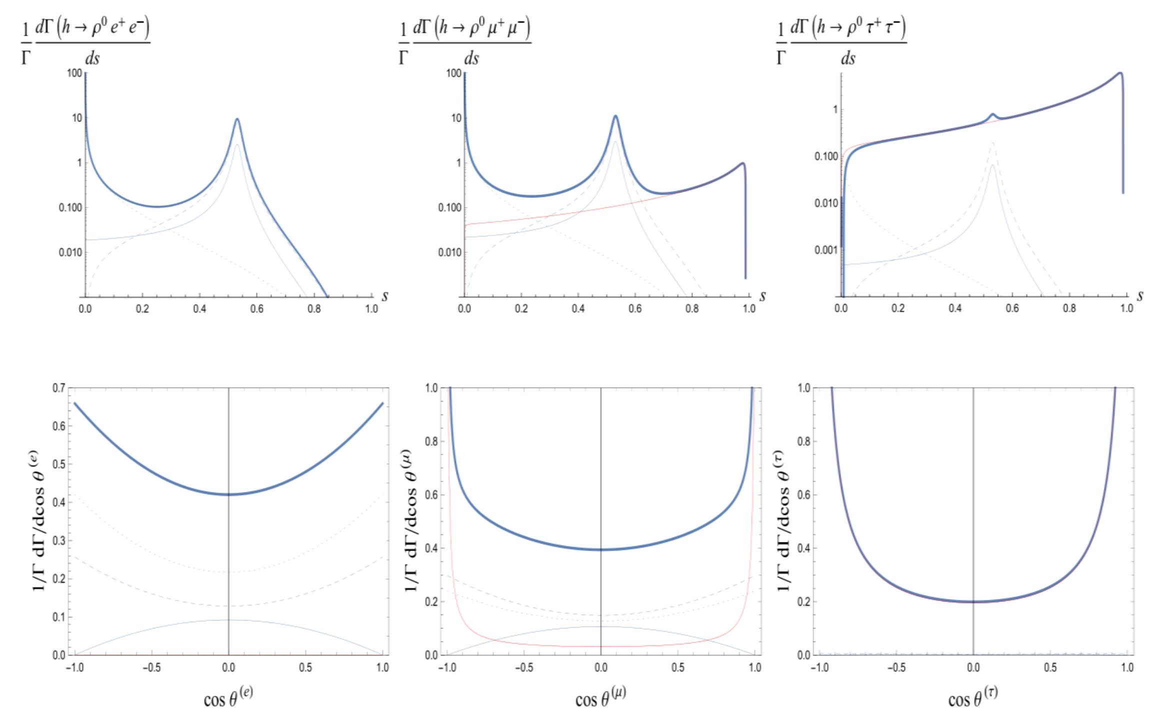
$$\mathcal{B}(h \to \rho^0 \nu\bar{\nu}) = (1.19 \pm 0.01) \times 10^{-6},$$
$$\mathcal{B}(h \to \omega \nu\bar{\nu}) = (1.11 \pm 0.02) \times 10^{-7},$$

$h \to \pi^0\ell\bar{\ell}$. Almost degenerate for the flavor of the charged leptons

$$\mathcal{B}(h \to \pi^0 e^+e^-) = (7.06 \pm 0.02) \times 10^{-8},$$
$$\mathcal{B}(h \to \pi^0 \mu^+\mu^-) = (7.06 \pm 0.02) \times 10^{-8},$$
$$\mathcal{B}(h \to \pi^0 \tau^+\tau^-) = (7.10 \pm 0.02) \times 10^{-8},$$
$$\mathcal{B}(h \to \pi^0 \nu\bar{\nu}) = (4.21 \pm 0.01) \times 10^{-7},$$

$h \to \pi^+(K^+)\ell^-\bar{\nu}_\ell$, and $h \to \rho^+(K^{*+})\ell^-\bar{\nu}_\ell$. Degenerate for flavors of the charged leptons.

$$\mathcal{B}(h \to \pi^+ \ell^-\bar{\nu}_\ell) = (4.05 \pm 0.01) \times 10^{-7},$$
$$\mathcal{B}(h \to \rho^+ \ell^-\bar{\nu}_\ell) = (1.03 \pm 0.01) \times 10^{-6},$$
$$\mathcal{B}(h \to K^+ \ell^-\bar{\nu}_\ell) = (3.14 \pm 0.01) \times 10^{-8},$$
$$\mathcal{B}(h \to K^{*+} \ell^-\bar{\nu}_\ell) = (5.32 \pm 0.02) \times 10^{-8}$$



The normalized invariant mass distribution and angular distribution of $h \to \rho^0\ell^+\ell^-$ decay for $\ell = e, \mu$, and τ, respectively.
red line: contribution from Figure 1(b), thin solid line: contribution from hZZ, dashed line: contribution from $hZ\gamma$, dotted line: contribution from $h\gamma\gamma$, thick solid line: total contribution.

Analysis

1、The contributions from $h\ell\ell$ vertex is negligible for the electron mode, small but non-negligible for muon mode, but dominant for tauon mode.

2、The contributions from hZZ (tree) and $hZ\gamma$ (loop-induced) vertices are of the same importance, which indicates the process may be sensitive to the shot-distance physics.

Feynman diagrams for $h \to VV$

Figure 2: $h \to VV$ decays in the SM: (a) and (b) through the ZZ intermediate state while (c) through the gluon intermediate state. V dominantly longitudinal polarized.

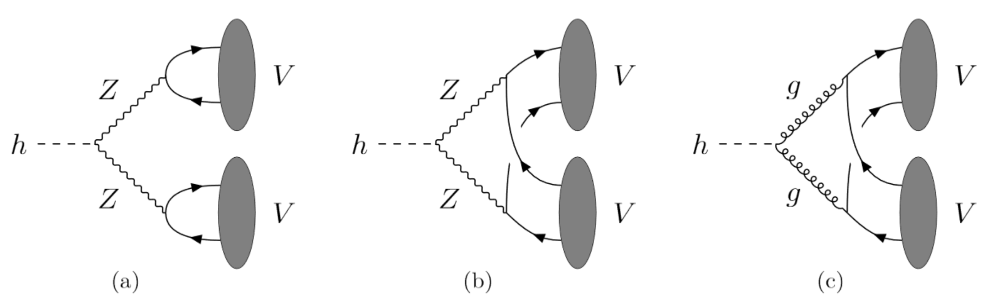
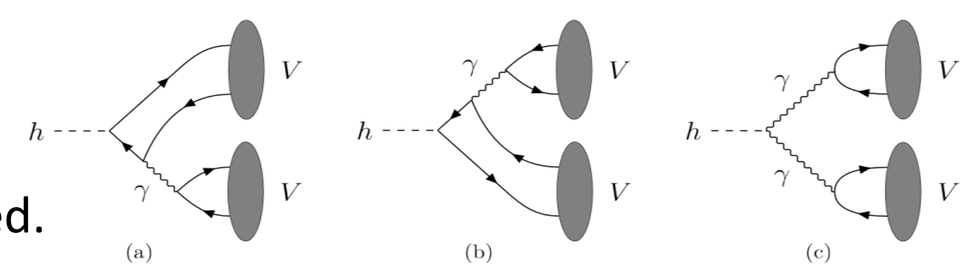


Figure 3: $h \to VV$ decays in the SM through the virtual photon intermediate states. V dominantly transversely polarized.



Branching ratios of $h \to VV$ decays

B_1: Figure 2, B2: Figure 3.

V	m_V(GeV)	$\mathcal{B}_1(h \to VV)$	$\mathcal{B}_2(h \to VV)$	$\mathcal{B}(h \to VV)$
$J/\Psi(1S)$	3.097	1.6×10^{-11}	5.8×10^{-10}	5.9×10^{-10}
$\Psi(2S)$	3.686	3.9×10^{-12}	4.7×10^{-11}	5.1×10^{-11}
$\Upsilon(1S)$	9.460	4.1×10^{-10}	2.4×10^{-11}	4.3×10^{-10}
$\Upsilon(2S)$	10.02	9.6×10^{-11}	6.4×10^{-12}	1.0×10^{-10}
$\Upsilon(3S)$	10.36	5.4×10^{-11}	3.8×10^{-12}	5.7×10^{-11}

Analysis

Compared to the process of longitudinally polarized final states(Figure 2), the transversely polarized final states(Figure 3) have a $\epsilon^*(p) \cdot \epsilon^*(q) \sim m_V^2/m_h^2$ suppression, but the photon propagator can give a $1/m_V^2$ factor to counteract the above suppression. For charmonium case, transversely polarized final states give dominant contributions; while for bottomonium modes, the longitudinally polarized ones are more important.

Summary

Exclusive rare Higgs decays into lepton pair plus one light hadron, such as $h \to \rho^0(\omega)\ell\bar{\ell}$, $h \to \pi^0\ell\bar{\ell}$, $h \to \pi^+(K^+)\ell^-\bar{\nu}_\ell$, and $h \to \rho^+(K^{*+})\ell^-\bar{\nu}_\ell$, have been explored in the standard model. Decay amplitudes are dominantly from the Higgs couplings to gauge bosons and to charged leptons, and their branching ratios are predicted in the range of $10^{-8} \sim 10^{-5}$. We have also analyzed the differential dilepton invariant mass and angular distributions of $h \to \rho^0\ell^+\ell^-$ decays.

Higgs decays into pair of heavy quarkonia, $h \to VV$, has also been explored in the SM. The total decay rates of $h \to VV$ in the SM have also been calculated, and our predictions for their branching fractions are around 10^{-10}. The transversely polarized final states can also give important contributions.

It will be challenging to search for these rare processes. Nevertheless, experimental studies of them, might be interesting both to help deepen our understanding of the standard model and to probe new physics beyond the standard model in the future high-precision experiments.