PROCEEDINGS OF SCIENCE

# Higgs boson rare decay and production at CMS

---

**Rocco Ardino**[a,b,c,*] **on behalf of the CMS Collaboration**

[a] *Department of Physics and Astronomy "Galileo Galilei", Padova University, Via Marzolo 8, 35131 Padova, Italy*

[b] *National Institute for Nuclear Physics, Padova Division, Via Marzolo 8, 35131 Padova, Italy*

[c] *CERN, Esplanade des Particules 1, Meyrin, 1211, Switzerland*

*E-mail:* `rocco.ardino@cern.ch`

Higgs boson rare decay and production channel searches are presented in this overview. The results are based on proton-proton collision data recorded by the CMS experiment during LHC Run-2 at a center-of-mass energy of $\sqrt{s} = 13$ TeV. A particular focus is dedicated to the processes providing a probe for the measurement of the Yukawa coupling between the Higgs boson and the first and second generation of fermions. A probe to new physics beyond the Standard Model, such the $\mathrm{H} \to \mathrm{Z}\gamma$ decay, is presented as well to highlight the pivotal role of rare decay searches during LHC Run-3 and for the future High-Luminosity LHC.

*The European Physical Society Conference on High Energy Physics (EPS-HEP2023)*
*21-25 August 2023*
*Hamburg, Germany*

PoS(EPS-HEP2023)394

---

[*] Speaker

## 1. Introduction

The discovery of the Higgs boson in 2012 [1–3], achieved by the CMS and ATLAS experiments, stands as a significant milestone in the understanding of the electroweak sector within the standard model (SM) of elementary particles. As consequence, a new era of measurements has started aiming to determine the couplings between the Higgs boson and the other SM bosons and fermions. After LHC Run-1 and Run-2, the couplings to the gauge bosons and the fermions of the third generation are now observed and consistent with the SM prediction. The couplings with the fermions of the first and second generation, however, are not yet experimentally established. A discrepancy between a measurement and the theoretical expectation from the SM would hint to "new physics" interactions or particles yet to be discovered. These hypothetical entities may potentially exert their influence through quantum loop processes, thereby impacting the branching fractions of rare decay events involving first and second generation fermions. Consequently, the study of such rare decays serves as a critical avenue for probing physics beyond the SM and it represents a pivotal goal for the current LHC Run-3 and the future High-Luminosity LHC. In this context, a summary of the latest results achieved through the analysis of data recorded by the CMS experiment [4] during Run-2 at a center-of-mass energy of $\sqrt{s}$ =13 TeV is presented.

## 2. Higgs decay to a pair of muons

In the SM framework, a branching fraction $\mathcal{B}(\mathrm{H} \to \mu\mu) = 2.18 \cdot 10^{-4}$ (±1.7%) is predicted for a Higgs boson mass of 125 GeV. The final state muons are expected to be prompt, isolated and oppositely charged. The CMS Collaboration has conducted extensive searches targeting this Higgs boson decay mode using proton-proton collision events collected at $\sqrt{s} = 13$ TeV during LHC Run-2 [5]. The data set corresponds to an integrated luminosity of 137 $\mathrm{fb}^{-1}$.

The expected signal features a narrow peak around the Higgs boson mass in the $m_{\mu\mu}$ invariant mass spectrum. The main background contributions include processes such as Drell-Yan, $t\bar{t}$, and diboson production. The data set is divided into four mutually exclusive categories targeting the main Higgs boson production modes, in order Gluon-Gluon Fusion (GGF), Vector Boson Fusion (VBF), VH associated production with a W (WH) or a Z boson (ZH) and associated production with a pair of top quarks ($tt$H). The events passing the selections are modelled using the $m_{\mu\mu}$ feature and a profile likelihood fit is applied to every category for the results extraction, as shown in Figure 1.

After combination, the observed signal rate of the process, with respect to the SM expectation, is found to be $1.19^{+0.44}_{-0.42}$, which translates to the coupling constraint $\kappa_\mu = 1.13^{+0.21}_{-0.22}$ in the $\kappa$-framework. The observed significance of the signal, over the background-only hypothesis, amounts to 3.0 standard deviations, leading to the first evidence of the Higgs boson coupling to muons.

## 3. Higgs decay to a pair of charm quarks

The Higgs boson is expected to decay to a pair of charm quarks with a branching fraction of 2.9%. Studying this decay is of paramount importance as it represents a direct probe of the coupling between the Higgs boson and $c$ quarks. However, it is also challenging due to a large amount of multijet background events to model and the need of $c$-jet tagging techniques. The CMS

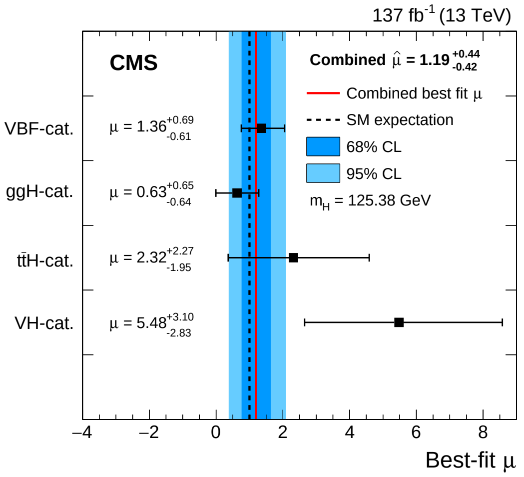

**Figure 1:** Best-fit signal strengths $\mu_{\mathrm{H}\to\mu\mu}$ for different categories and combined result [5].

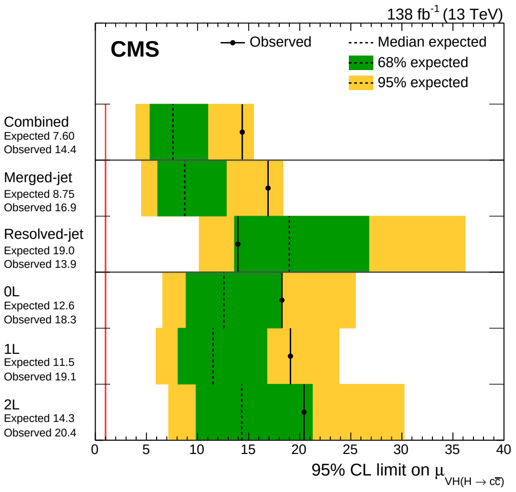

**Figure 2:** 95% C.L. upper limits on $\mu_{\mathrm{VH}(\mathrm{H}\to c\bar{c})}$ for different categories and combined result [6].

Collaboration has studied this decay process with the Run-2 data set [6, 7], targeting a VH production mode for the Higgs boson. Two event topologies are considered: a "resolved" topology, where the two $c$-tagged jets are reconstructed separately, and a "merged" one, with a Higgs boson candidate with $p_{\mathrm{T}} > 300$ GeV decaying into two $c$-tagged jets reconstructed as a single one. Independently from the topology, the signal is expected to peak in the $c$-tagged jet pair invariant mass distribution, which can be used as discriminating feature.

The data set is divided into mutually exclusive categories depending on the number of additional leptons. Upper limits at 95% C.L. are set on the signal rate of the process and the results across all the categories are combined, as shown in Figure 2. The observed (expected) upper limits are 14 ($7.4^{+3.4}_{-2.3}$) times the SM expectation. These limits are translated into the coupling constraints $1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$), namely the most stringent to date.

The analysis strategy is validated by searching for the analogous Z boson decay to a $c$-jet pair, where the Z boson is produced in VZ production mode. The reported signal rate, with respect to the SM expectation, is $\mu = 1.01^{+0.23}_{-0.21}$. The observed significance is 5.7 standard deviations, resulting in the first observation of this decay mode.

## 4. Higgs decay to Z + J/Ψ and a pair of J/Ψ or ϒ

Rare exclusive decays of the Higgs boson to mesons provide experimentally clean final states to study Yukawa couplings to second generation quarks. An example of such processes is the Higgs boson decay into a Z boson and a J/Ψ vector meson or the analogous decay to a pair of J/Ψ or ϒ mesons. The SM predicts a direct and an indirect process for these decays, depending on the presence of $c$ or $b$ quark loops in the Feynman diagrams of the decay. The branching fractions $\mathcal{B}(\mathrm{H} \to \mathrm{ZJ}/\Psi) = 2.3 \cdot 10^{-6}$ and $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\Psi(2\mathrm{S})) = 1.7 \cdot 10^{-6}$ are predicted for the ZJ/Ψ channel. For the decay to a quarkonium pair, $\mathcal{B}(\mathrm{H} \to \mathrm{J}/\Psi\mathrm{J}/\Psi) = 1.5 \cdot 10^{-10}$ and $\mathcal{B}(\mathrm{H} \to \Upsilon\Upsilon) = 2 \cdot 10^{-9}$ are calculated assuming dominance of indirect amplitudes, while earlier predictions report $\mathcal{B}(\mathrm{H} \to \Upsilon\Upsilon) \sim 10^{-5}$.

The CMS Collaboration has studied these processes using the Run-2 data set, with an integrated luminosity of 138 $\text{fb}^{-1}$ in the $\text{ZJ}/\Psi$ channel and 133 $\text{fb}^{-1}$ in the quarkonium pair channel [8]. The $4\mu$ or $2\mu 2e$ final states are exploited for the search, considering the subsequent leptonic decay of the Z boson and the quarkonia. The feed-down decays of the $\Psi(2\text{S})$ or $\Upsilon(n = 2, 3)$ to a $\text{J}/\Psi$ or $\Upsilon(1\text{S})$ and hadrons is taken into account to enhance the sensitivity to the decay. The signal is expected to peak in the four-lepton final state invariant mass distribution, over a background mainly due to a Z boson production in association with a genuine or a misidentified meson candidate. The $m_{4\ell}$ invariant mass distribution, shown in Figure 3 for $\text{ZJ}/\Psi \to 4\mu$ and $\text{J}/\Psi\text{J}/\Psi \to 4\mu$ candidates, is used as discriminating feature and for the extraction of 95% C.L. upper limits on the signal rate of the decay processes, with respect to the SM prediction. No significant discrepancies are found between observed and expected upper limits. The upper limit is 826 times higher than the SM prediction for $\text{H} \to \text{ZJ}/\Psi$. The observed upper limit is found to be 5.8 times higher than the value from earlier SM predictions for $\text{H} \to \Upsilon(\text{nS})\Upsilon(\text{mS})$.

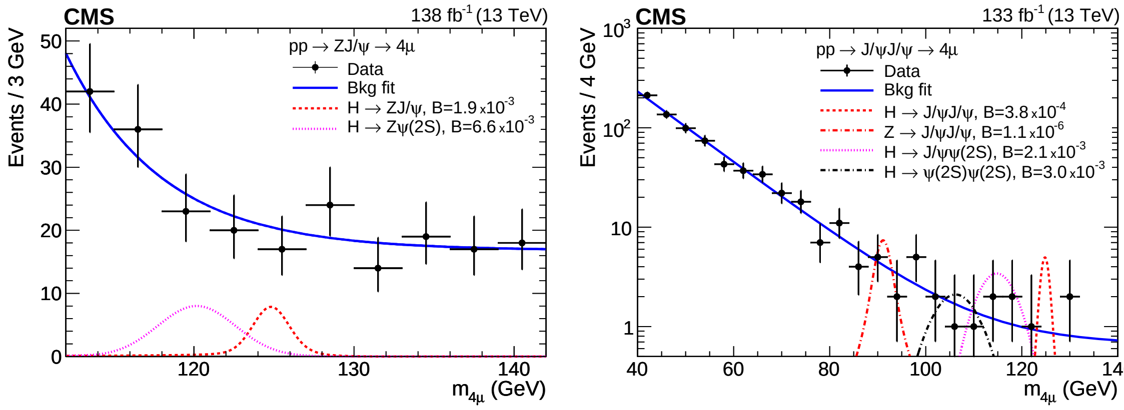

**Figure 3:** Four-lepton invariant mass distributions, (left) for $\text{H} \to \text{ZJ}/\Psi \to 4\mu$ candidates and (right) for $\text{H} \to \text{J}/\Psi\text{J}/\Psi \to 4\mu$ candidates [8].

## 5. Higgs decay to Z + $\gamma$

The $\text{H} \to \text{Z}\gamma$ process is purely loop induced, with a branching fraction predicted by the SM of $\mathcal{B}(\text{H} \to \text{Z}\gamma) = (1.57 \pm 0.09) \cdot 10^{-3}$ for a Higgs boson of mass $m_\text{H} = 125.38$ GeV. It is comparable to $\mathcal{B}(\text{H} \to \gamma\gamma) = (2.27 \pm 0.04) \cdot 10^{-3}$ and the ratio $\mathcal{B}(\text{H} \to \text{Z}\gamma)/\mathcal{B}(\text{H} \to \gamma\gamma)$ is potentially sensitive to physics beyond the SM, whose effects would shift the two branching fractions by a different amount. Thus, the CMS Collaboration has performed a search for the $\text{H} \to \text{Z}\gamma$ decay [9] with collision events collected at $\sqrt{s} = 13$ TeV and from a recorded integrated luminosity of 138 $\text{fb}^{-1}$. The final state considered is $\ell\ell\gamma$, given the subsequent decay of the Z boson to a pair of leptons.

The signal features a narrow resonant peak in the $m_{\mu\mu\gamma}$ invariant mass distribution around the Higgs boson mass. The main background sources come from Drell Yan with an initial state photon or with jets, where a jet or additional lepton is misidentified as a photon. To improve the sensitivity to the process, the data sample is divided into 8 mutually exclusive categories according to: the presence of an additional lepton, targeting VH production, the value of a multivariate discriminant

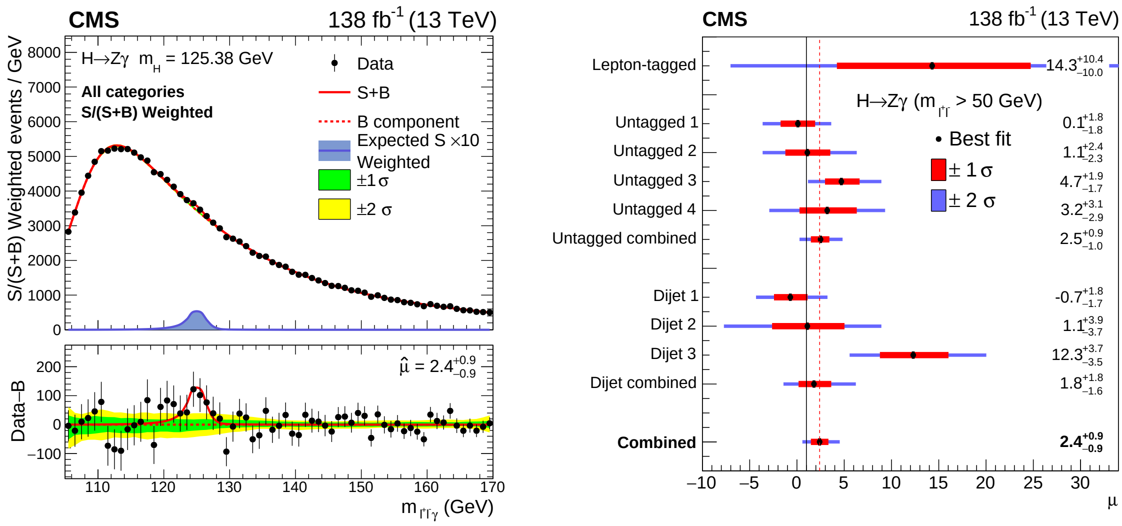

**Figure 4:** (Left) Sum over all categories of the data points and signal-plus-background model after the simultaneous fit to each $m_{\ell\ell\gamma}$ distribution. (Right) Observed signal strength $\mu$ for a SM Higgs boson with $m_{\mathrm{H}} = 125.38$ GeV [9].

characterizing the kinematic properties of a dijet system together with the $\ell\ell\gamma$ candidate, targeting VBF production, and the value of a multivariate discriminant characterizing the kinematic properties of the $\ell\ell\gamma$ system. A maximum likelihood fit is performed on $m_{\ell\ell\gamma}$ in each category and the best fit value for the signal rate with respect to the SM expectation is $\mu = 2.4 \pm 0.9$, as shown in Figure 4 (left).

The analogous result from the ATLAS Collaboration has been combined with the one from the CMS Collaboration [10]. The measured signal rate, relative to the SM prediction, from the combination is $\mu = 2.2 \pm 0.7$ and the observed significance amounts to 3.4 standard deviations. The result is the first evidence of the H → Z$\gamma$ decay and the observed branching fraction, $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma) = (3.4 \pm 1.1) \cdot 10^{-3}$, is within the SM expectation of 1.9 standard deviations.

## 6. Rare Higgs production H$\gamma$

The Higgs boson couplings to light quarks can be accessed through the Higgs boson rare production mode in association with a photon. The gluon initiated contribution $gg \to \mathrm{H}\gamma$ vanishes due to Furry's theorem, thus the inclusive H$\gamma$ production at the LHC is directly related to the coupling with the light quarks $u$, $d$, $s$, $c$. The CMS Collaboration has studied this particular production mode in the search for the WW$\gamma$ production using the Run-2 data set [11]. For the experimental search, only W leptonic decays are considered and a final state $e\mu\nu_e\nu_\mu\gamma$. Background contributions arise from Z$\gamma$, $t\bar{t}\gamma$, single top production with a prompt lepton and a prompt photon, as well as from events with nonprompt leptons and photons within jets.

To extract upper limits at 95% C.L. on the $\kappa_q$, a profile likelihood ratio test is built in bins of the angular separation $\Delta R(\ell,\ell)$ between the two leptons, and the transverse mass $m_{\mathrm{T}}^{\mathrm{WW}}$ of the Higgs boson candidate. The observed (expected) upper limits on $\kappa_q$ are: $|\kappa_u| \leq 16000$ (13000), $|\kappa_d| \leq 17000$ (14000), $|\kappa_s| \leq 1700$ (1300), $|\kappa_c| \leq 200$ (110).

## 7. Conclusions

The study of Higgs boson rare decay and production modes is pivotal for the measurement of the Yukawa couplings between the Higgs boson and the first and second generation of fermions and to probe physics beyond the SM. The CMS Collaboration has performed extensive searches in this sense, leading to new results using the data set collected during LHC Run-2. The first evidence has been accomplished for $\mathrm{H} \rightarrow \mu\mu$ and, thanks to combining data with that of the ATLAS Collaboration, for $\mathrm{H} \rightarrow \mathrm{Z}\gamma$, and the most stringent constraints to date have been set on $\kappa_c$. In general, no significant discrepancy with respect to the SM predictions has been observed in the channels discussed in this overview. New results and further improvements are expected for LHC Run-3 and High-Luminosity LHC.

## References

[1] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30 [1207.7235].

[2] CMS Collaboration, “Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s}$ = 7 and 8 TeV”, *JHEP* **2013** (2013) 81 [1303.4571].

[3] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1 [1207.7214].

[4] CMS Collaboration, “The CMS experiment at the CERN LHC. The Compact Muon Solenoid experiment”, *JINST* **3** (2008) S08004.

[5] CMS Collaboration, “Evidence for Higgs boson decay to a pair of muons”, *JHEP* **2021** (2021) 148 [2009.04363].

[6] CMS Collaboration, “Search for Higgs Boson Decay to a Charm Quark-Antiquark Pair in Proton-Proton Collisions at $\sqrt{s}$ = 13 TeV”, *PRL* **131** (2023) 061801 [2205.05550].

[7] CMS Collaboration, “Search for Higgs Boson and Observation of $Z$ Boson through Their Decay into a Charm Quark-Antiquark Pair in Boosted Topologies in Proton-Proton Collisions at $\sqrt{s}$ = 13 TeV”, *PRL* **131** (2023) 041801 [2211.14181].

[8] CMS Collaboration, “Search for Higgs boson decays into Z and J/Ψ and for Higgs and Z boson decays into J/Ψ or Υ pairs in pp collisions at $\sqrt{s}$=13 TeV”, *Physics Letters B* **842** (2023) 137534 [2206.03525].

[9] CMS Collaboration, “Search for Higgs boson decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s}$= 13 TeV”, *JHEP* **2023** (2023) 233 [2204.12945].

[10] ATLAS and CMS Collaborations, “Evidence for the Higgs boson decay to a Z boson and a photon at the LHC”, *sub. to PRL* (2023) [2309.03501].

[11] CMS Collaboration, “Observation of WW$\gamma$ production and constraints on Higgs couplings to light quarks in proton-proton collisions at $\sqrt{s}$ = 13 TeV”, *sub. to PRL* (2023) [2310.05164].