PROCEEDINGS OF SCIENCE

Searches for rare Higgs boson decays 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

The couplings of the Higgs boson to fermions have been studied with third and second generation quarks and leptons, while no direct measurements of its interactions with the lighter u, d, s quarks have been performed to date. The search for rare decays such as $\mathrm{H} \to \gamma + \phi/\rho/\mathrm{K}^{*0}/\psi(\mathrm{nS})$ can probe these couplings. While the contribution to the rate of these decays from the diagrams involving Yukawa couplings is negligible in the Standard Model (SM), in theories beyond the SM this contribution could be significantly enhanced. Deviations from the SM branching fractions could be observed because of the interference with the dominant diagrams, where the Higgs boson decays to a diphoton state with one off-shell photon. Results from data collected by the CMS experiment at a center-of-mass energy of 13 TeV will be presented.

The International Conference on High Energy Physics (ICHEP2024)
17-24 July 2024
Prague, Czech Republic

*Speaker

PoS(ICHEP2024)051

1. Introduction

The discovery of the Higgs boson in 2012 by the CMS and ATLAS experiments [1–3] marked a significant milestone in understanding the Standard Model (SM) of particle physics. This breakthrough has led to a new phase of research focused on measuring the Higgs boson interactions with other SM particles. While couplings to gauge bosons and third-generation fermions have been observed and align with SM predictions, the couplings to first and second-generation quarks remain experimentally not established. Further data, particularly from the current LHC Run-3 and the upcoming High-Luminosity LHC, are crucial for refining these measurements and potentially uncovering new physics. A promising avenue of research involves studying the rare decays of the Higgs boson, which could reveal new physics through loop processes and anomalous couplings. This contribution presents a summary of the latest results for these searches, 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.

2. Higgs boson decay to a pair of muons

Within the SM, the Higgs boson is predicted to decay into a pair of muons with a branching fraction of $\mathcal{B}(\mathrm{H} \to \mu\mu) = 2.18 \times 10^{-4}$ (±1.7%) for a Higgs boson mass of 125 GeV. The CMS Collaboration has investigated this decay channel using proton-proton collision data collected at $\sqrt{s}$ = 13 TeV during LHC Run-2 [5], which corresponds to an integrated luminosity of 137 fb^{-1}. The analysis strategy relies on the fact that the final state muons are expected to be prompt and isolated.

The expected signal is characterized by a sharp peak near the Higgs boson mass in the $m_{\mu\mu}$ invariant mass distribution. The primary background processes include Drell-Yan, $t\bar{t}$, and diboson production. To enhance sensitivity, the data are categorized into four distinct groups, each targeting a specific Higgs production mechanism: Gluon-Gluon Fusion (GGF), Vector Boson Fusion (VBF), associated production with a W or Z boson (VH), and production alongside a top-quark pair ($t\bar{t}$H). The selected events are modeled using the $m_{\mu\mu}$ distribution. A profile likelihood fit is applied to every category to extract the signal yield, as shown in Figure 1. The results from all categories are then combined.

The observed signal rate, with respect to the SM expectation, is found to be $1.19^{+0.44}_{-0.42}$, interpreted in the κ-framework to a coupling measurement of $\kappa_\mu = 1.07^{+0.22}_{-0.22}$. This result represents the first evidence of the Higgs boson coupling to muons, as the observed significance of the signal, over the background-only hypothesis, amounts to 3.0 standard deviations.

3. Higgs boson decay to Z + γ

The $\mathrm{H} \to \mathrm{Z}\gamma$ decay is a loop-induced process, with the Standard Model (SM) predicting a branching fraction of $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma) = (1.57 \pm 0.09) \times 10^{-3}$ for a Higgs boson mass of 125.38 GeV. The ratio $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma)/\mathcal{B}(\mathrm{H} \to \gamma\gamma)$ is potentially sensitive to physics beyond the SM, whose effects would shift the two branching fractions by a different amount. The CMS Collaboration has conducted a search for the $\mathrm{H} \to \mathrm{Z}\gamma$ decay [6] using data from proton-proton collisions at

$\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}. The search focused on the final state where the Z boson decays into a pair of charged leptons ($\ell = e, \mu$), producing a $\ell\ell\gamma$ signature.

The signal is expected to appear as a narrow peak in the $m_{\ell\ell\gamma}$ invariant mass distribution centered around the Higgs boson mass. The dominant backgrounds arise from Drell-Yan processes with an initial state photon or from events where jets or additional leptons are misidentified as photons. To maximize the sensitivity, the data set is divided into eight distinct categories based on various characteristics: the presence of an additional lepton (to target VH production), the value of a multivariate discriminant based on the kinematics of a candidate dijet system (targeting VBF production), and a separate multivariate discriminant evaluating the kinematics of the $\ell\ell\gamma$ system (GGF production). A maximum likelihood fit to the $m_{\ell\ell\gamma}$ distribution is performed within each category, yielding a best-fit signal strength, i.e. cross section relative to the SM expectation, of $\mu = 2.4 \pm 0.9$.

When combined with the analogous results from the ATLAS Collaboration [7], as shown in Figure 1 (right), the measured signal strength relative to the SM prediction is $\mu = 2.2 \pm 0.7$, with an observed significance of 3.4 standard deviations. This result marks the first evidence of the $\mathrm{H} \to \mathrm{Z}\gamma$ decay and the measured branching fraction of $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma) = (3.4 \pm 1.1) \times 10^{-3}$ is within 1.9 standard deviations of the SM expectation.

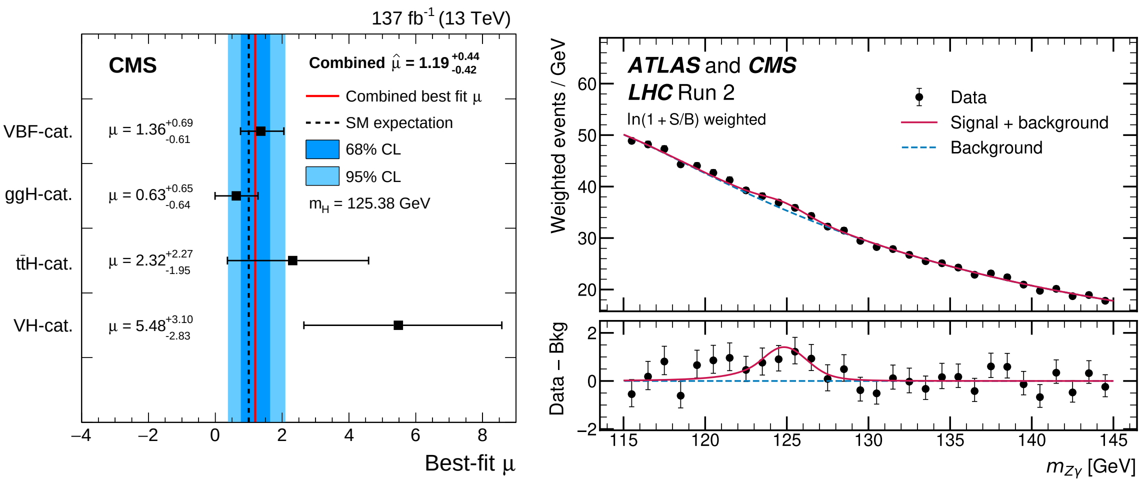

Figure 1: Best-fit signal strengths $\mu_{\mathrm{H}\to\mu\mu}$ for different categories and combined result (left) [5]. Combination of CMS and ATLAS Collaborations results for $\mathrm{H} \to \mathrm{Z}\gamma$ search, with signal-plus-background model after the simultaneous fit to each $m_{\ell\ell\gamma}$ distribution (right) [7].

4. Higgs boson decay to ρ, ϕ or K^{*0} and a photon

The SM predicts rare Higgs boson decays to a meson and a photon, occurring via two main processes: an indirect decay through $\mathrm{H} \to \gamma\gamma^*$ and a direct decay involving a loop of quarks with the same flavour of the meson. Specifically, Higgs boson decays to $\rho\gamma$ or $\phi\gamma$, with predicted branching fractions of $\mathcal{B}(\mathrm{H} \to \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$ and $\mathcal{B}(\mathrm{H} \to \phi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$, offer a probe to light flavour quarks u, d and s. Decays to a $\mathrm{K}^{*0}\gamma$ are sensitive to flavour violating couplings of the s and d quarks, and are predicted to be suppressed in the SM, with a branching fraction of $\mathcal{B}(\mathrm{H} \to \mathrm{K}^{*0}\gamma) \sim 1.0 \times 10^{-19}$.

The CMS Collaboration conducted a search for these rare decays using proton-proton collision data collected during LHC Run-2 [8]. Events are selected to target the subsequent decays of the mesons $\rho \to \pi^+\pi^-$, $\phi \to \mathrm{K}^+\mathrm{K}^-$, $\mathrm{K}^{*0} \to \mathrm{K}^\pm\pi^\mp$. The integrated luminosity of the data set varies between 39.5 and 138 fb^{-1}, depending on the targeted Higgs boson production mode. Different triggers were employed to enhance sensitivity on each production mode: lepton triggers for VH production, single photon plus jet pair triggers for VBF production, and a single photon plus a τ-like jet trigger for GGF production, developed specifically for this analysis. To improve the signal selection and discriminate against γ+jets and multijet backgrounds in the GGF and VBF categories, an MVA classifier is developed. The signal is expected to appear as a resonance in the invariant mass distributions of both the meson candidate and the meson-photon final state. The meson candidate is reconstructed from charged particle tracks using a kinematic vertex-constrained fit and combined with the photon candidate to reconstruct the invariant mass distribution $m_{Q\gamma}$. Figure 2 shows the invariant mass distribution of the candidate meson and of the final state for the $\mathrm{H} \to \phi\gamma$ search.

Upper limits at 95% C.L. are set on the signal rate of the decay processes, with respect to the SM prediction. No significant deviations are found between observed and expected upper limits. The observed upper limits from the combination of all the categories are $\mathcal{B}(\mathrm{H} \to \rho\gamma) = 3.74 \times 10^{-4}$, $\mathcal{B}(\mathrm{H} \to \phi\gamma) = 2.97 \times 10^{-4}$, and $\mathcal{B}(\mathrm{H} \to \mathrm{K}^{*0}\gamma) = 1.71 \times 10^{-4}$, which are the most stringent experimental limits to date.

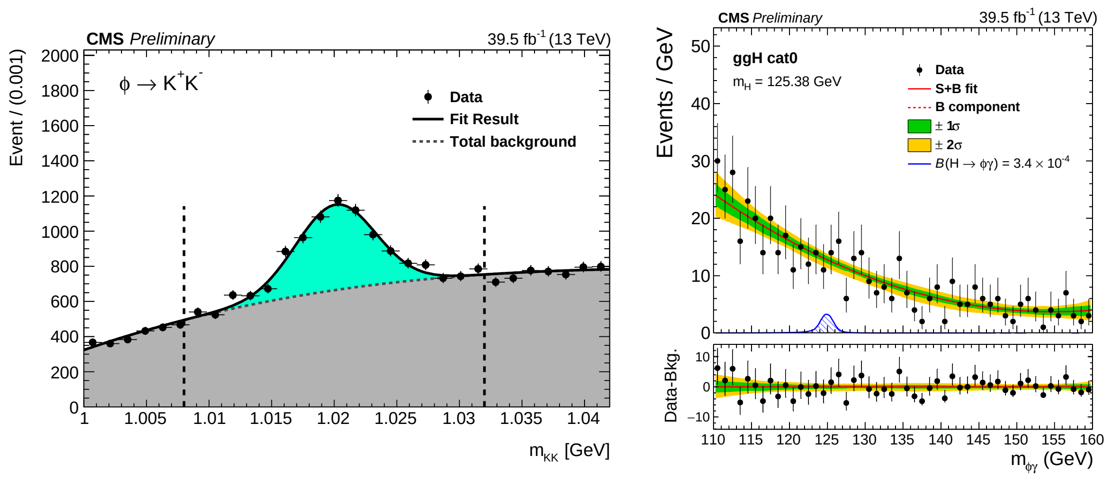

Figure 2: $\mathrm{H} \to \phi\gamma$ search results [8]: candidate $\phi \to \mathrm{K}^+\mathrm{K}^-$ meson invariant mass distribution (left) and $m_{\phi\gamma}$ distribution for GGF category, with MVA selection for signal-enriched region (right).

5. Higgs and Z boson decays to J/ψ or ψ' and a photon

The SM also predicts the rare Higgs boson decay into a J/ψ or ψ' meson and a photon, with branching fractions estimated to be $\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\gamma) = (3.01 \pm 0.15) \times 10^{-6}$ and $\mathcal{B}(\mathrm{H} \to \psi'\gamma) = (1.03 \pm 0.06) \times 10^{-6}$. The direct decay goes through a charm quark loop, making this process a probe to the coupling to the c quark with reduced SM backgrounds.

The CMS Collaboration has conducted a search for these rare decays, as well as for the analogous decays of the Z boson, using proton-proton collision data collected during LHC Run-2 [9]. The events selected for this analysis target the subsequent decay of the charmed meson into a pair of muons, which are expected to be prompt and isolated from hadronic activity. The analyzed data set was collected by the CMS experiment using single muon plus photon triggers and corresponds to an integrated luminosity of 123 fb^{-1}. Events are categorized based on the Higgs boson production mode and key angular variables of the decay. For the Z boson decay search, the categorization is based on an angular likelihood discriminator. The signal is expected to appear as a resonance in the invariant mass distributions of both the meson candidate and the combined meson-photon final state. The meson candidate is reconstructed from the pair of muons in the final state and is combined with the photon candidate to form the invariant mass distribution $m_{Q\gamma}$. Figure 3 shows the invariant mass distributions for the final state in signal-enriched categories for the $\mathrm{Z}, \mathrm{H} \to \mathrm{J}/\psi\gamma$ searches.

Upper limits at 95% C.L. are set on the signal rate of these decay processes relative to the SM predictions. No significant deviations are observed between the expected and observed upper limits. The results yield the following observed upper limits: $\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\gamma) < 2.6 \times 10^{-4}$, $\mathcal{B}(\mathrm{H} \to \psi'\gamma) < 9.9 \times 10^{-4}$, $\mathcal{B}(\mathrm{Z} \to \mathrm{J}/\psi\gamma) < 0.6 \times 10^{-6}$, and $\mathcal{B}(\mathrm{Z} \to \psi'\gamma) < 1.3 \times 10^{-6}$. The upper limits on $\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\gamma)$ are interpreted in the κ-framework to constrain the ratio of the coupling to the c quark and to γ (κ_c/κ_γ). The ratio κ_c/κ_γ is constrained to be in the interval $(-157, +199)$ at 95% confidence level.

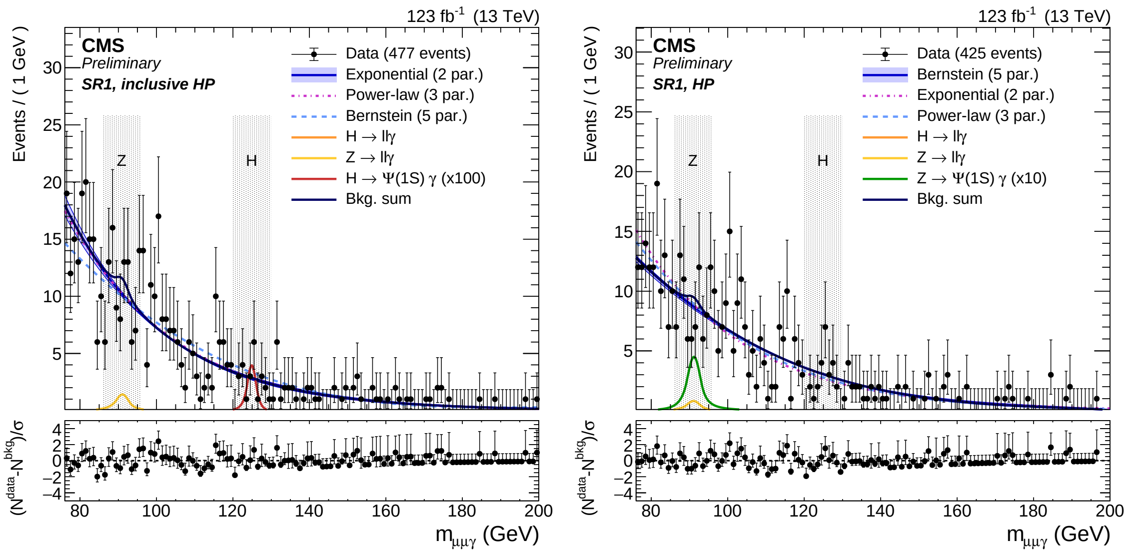

Figure 3: $m_{\mu\mu\gamma}$ invariant mass distribution for signal-enriched categories for $\mathrm{H} \to \mathrm{J}/\psi\gamma$ (left) and $\mathrm{Z} \to \mathrm{J}/\psi\gamma$ (right) searches [9].

6. Conclusions

The study of rare Higgs boson decays is crucial for measuring the Yukawa couplings between the Higgs boson and the first and second generations of fermions, as well as for probing physics beyond the SM. The CMS Collaboration has performed searches for these processes, leading to new results using the data set collected during LHC Run-2. The first evidence for the decay $H \to \mu\mu$ has been achieved, and, in combination with ATLAS data, evidence for the $H \to Z\gamma$ decay has also been accomplished. Searches for rare decays to a meson such as $\rho, \phi, J/\psi, \psi'$in association with a photon have demonstrated the potential of these channels to probe the Yukawa couplings to first and second generation quarks. In particular, the $H \to K^{*0}\gamma$ decay provides a probe for flavour violating couplings of the s and d quarks, offering a window into potential SM anomalies. No significant discrepancies from the SM predictions have been observed in the channels discussed in this overview. Future data from LHC Run-3 and the High-Luminosity LHC are expected to bring new results and further advancements in these searches.

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 decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s}$= 13 TeV", *JHEP* **2023** (2023) 233 [2204.12945].

[7] ATLAS and CMS Collaborations, "Evidence for the Higgs boson decay to a Z boson and a photon at the LHC", *Physical Review Letters* **132** (2024) [2309.03501].

[8] CMS Collaboration, "Search for rare decays of the Higgs boson into a photon and a ρ, ϕ or K^{*0} meson", CMS-PAS-HIG-23-005 (2024) .

[9] CMS Collaboration, "Search for the rare decays of the Z and Higgs bosons to a J/Ψ or Ψ' meson and a photon in proton-proton collisions at $\sqrt{s}$ = 13 TeV", CMS-PAS-SMP-22-012 (2023) .