Search for rare decays of the Higgs and Z bosons to $\phi\gamma$ and $\rho\gamma$ at the CMS experiment

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Summary. — Higgs and Z boson decays into a photon and a $\rho(770)$ and $\phi(1020)$ meson are searched for using proton-proton collision data collected by the CMS experiment at the LHC at CERN, at $\sqrt{s} = 13$ TeV. Events are selected in which the mesons decay into pairs of charged pions and pairs of charged kaons respectively. The analysed data sets correspond to an integrated luminosity of 40 fb^{-1}. No significant excess above the background expectations is observed in any search channel. Upper limits at the 95% confidence level on the Higgs boson branching fractions into $\rho(770)$ and $\phi(1020)$ are determined to be 3.74×10^{-4} and 2.97×10^{-4} respectively. These results constitute the most stringent experimental limits to date on the aforementioned decay channels. Expected upper limits on the Z boson branching ratios are 6.56×10^{-6} and 2.21×10^{-6} for the $\rho(770)$ and $\phi(1020)$ channels respectively.

1. – Introduction

The ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC) discovered a new scalar boson in 2012, and performed numerous studies in order to assess its compatibility with the standard model (SM) Higgs boson [1]. In the SM, the Higgs boson interacts with fermion fields via Yukawa-type couplings, which are proportional to the fermion masses. Experimentally, the top-Higgs coupling strength is indirectly confirmed by the large gluon-gluon fusion production cross section, as well as by direct measurements in the $t\bar{t}H$ production mode. Couplings to the τ lepton and b quark are well established thanks to detailed cross-section measurements in the respective Higgs-boson decay channels. Interactions with c quarks can be searched for via direct identification of c-flavoured jets or final states involving charmonium. Evidences of Higgs bosons coupling with muons have also been found.
However, no direct measurements of the Higgs interaction with u, d, and s quarks have been performed to date, since light quark couplings with the Higgs boson (H) are suppressed by the small masses and the overwhelming QCD-induced backgrounds to related signals hamper direct searches. A class of decays suggested for probing these couplings is that of the Higgs boson into a light meson and a photon or Z boson: within this class,

the CMS Collaboration searched for the decays $H \to Z\phi$ and $H \to Z\rho$, while the ATLAS Collaboration reported upper limits for the decays $H \to \rho\gamma$ and $H \to \phi\gamma$.
Specifically, the observation of the Higgs boson decay to a ϕ or ρ meson and a photon would provide sensitivity to Higgs couplings to the strange-quark, and the up- and down-quarks, respectively. The decay amplitude receives two main contributions that interfere destructively. The first is referred to as "direct" and proceeds through the $H \to q\bar{q}$ coupling, where subsequently a photon is emitted before the $q\bar{q}$ hadronises exclusively to the meson M. The second is referred to as "indirect" and proceeds via the $H \to \gamma\gamma$ coupling followed by the fragmentation $\gamma^* \to M$. In the SM, owing to the smallness of the light-quark Yukawa couplings, the latter amplitude dominates, despite being loop induced. As a result, the expected branching fraction predominantly arises from the "indirect" process, while the Higgs boson couplings to the light quarks are probed by searching for modifications of this branching fraction due to changes in the "direct" amplitude. The expected SM branching fractions are $\mathcal{B}(H \to \phi\gamma) = (2.31 \pm 0.11) \times 10^{-6}$ and $\mathcal{B}(H \to \rho\gamma) = (1.68 \pm 0.08) \times 10^{-5}$ [2].
The decay $\phi \to K^+K^-$ is used to reconstruct the ϕ meson, and the decay $\rho \to \pi^+\pi^-$ is used to reconstruct the ρ meson.
The searches for the analogous decays of the Z boson into a meson and a photon are also presented here. These have been theoretically studied as a unique precision test of the SM and the factorisation approach in quantum chromodynamics (QCD), and they can be valid control channels for the Higgs decays. The SM branching fraction predictions for the decays are $\mathcal{B}(Z \to \phi\gamma) = (1.04 \pm 0.12) \times 10^{-8}$ and $\mathcal{B}(Z \to \rho\gamma) = (4.19 \pm 0.12) \times 10^{-8}$ [3].

2. – Data and Monte Carlo simulation

During the 2018 data taking period, the CMS experiment recorded in proton-proton collisions at $\sqrt{s} = 13$ TeV a total integrated luminosity of $\mathcal{L}_{int} = 63.67$ fb^{-1}. The data sample used to perform the analysis is lower, as a dedicated trigger for this analysis was not operational during the whole year. The dedicated trigger started to operate when a part of the total integrated luminosity has already been delivered, thus the available data sample corresponds to $\mathcal{L}_{int} = 39.54$ fb^{-1}.
Samples of simulated Higgs boson events, produced via the gluon-gluon fusion ggH mode, are generated at next-to-leading order (NLO) in quantum chromodynamics (QCD) using POWHEG 2.0, with improved MiNLO accuracy where available. Background estimation relies solely on data. All generated samples are interfaced with PYTHIA 8.212 to model parton showering and hadronization. The Higgs and Z boson decays were simulated as a cascade of two-body decays, respecting angular momentum conservation. The same generators are used also for the simulation of the Z boson decays.

3. – Event selection for $\phi\gamma \to K^+K^-\gamma$ and $\rho\gamma \to \pi^+\pi^-\gamma$ final states

The $\phi\gamma$ and $\rho\gamma$ exclusive final states are quite similar, as both involve a pair of oppositely charged reconstructed ID tracks. The distinction lies in the mass of the pair: for the $\phi\gamma$ final state, the mass aligns with the ϕ meson when assuming the tracks are charged kaons. In contrast, for the $\rho\gamma$ final state, the mass matches the ρ meson under the assumption that the tracks are charged pions.
Photon candidates are reconstructed as SuperClusters in the electromagnetic calorimeter. Reconstructed photon candidates are required to have $p_T > 35$ GeV and $|\eta_\gamma| < 2.1$.

Moreover, the energy collected around the calorimeter cluster associated to the photon in a cone of $\Delta R = 0.4$ after subtracting the energy collected within the cluster itself is required to be less than 6 GeV + 1.2% $\times E_T^\gamma$.
Since the mesons from the boson decays have a large momentum, their secondary decay products are expected to be very collimated in the laboratory frame, hence their signature can be identified as a jet by clustering algorithms. As a consequence, jets are used to reduce track combinatorial. Jets are reconstructed from particle-flow candidates from the anti-k_T clustering algorithm with a radius parameter of $\Delta R = 0.4$ and required to pass basic identification criteria. As mentioned, ρ and ϕ are reconstructed from their decay into $\pi^+\pi^-$ and K^+K^-, respectively. The strategy to reconstruct the products of the meson decay consists in exploiting those jets of the event that pass ID and kinematic jet requirements, like: $p_T^{jet} > 40$ GeV, $|\eta_{jet}| < 2.1$ and $m_{jet\gamma} > 100$ GeV for the Higgs boson, while $m_{jet\gamma} > 30$ GeV for the Z boson. The procedure is to select among the constituents of these jets a charged pair whose properties best match with ones of a pair of charged tracks coming from the meson. A dedicated isolation of the candidate based on charged tracks is determined from the meson momentum and other tracks in a cone of radius $\Delta R = 0.3$ around the direction of the di-track system as follows:

$$\text{iso}_{\text{ch}}^{\text{ditrk}} = \frac{p_T^{\text{ditrk}}}{p_T^{\text{ditrk}} + \sum_{\text{trk}} |p_T^{\text{trk}}|} \quad (1a)$$

The isolation is required to be greater than 0.9. Pairs of charged-hadron candidates are selected based on their invariant masses. Those with an invariant mass $m_{K^+K^-}$, under the charged-kaon hypothesis, between 1008 MeV and 1032 MeV are selected as $\phi \to K^+K^-$ candidates. Pairs with an invariant mass $m_{\pi^+\pi^-}$, under the charged-pion hypothesis, between 620 MeV and 920 MeV are selected as $\rho \to \pi^+\pi^-$ candidates. The candidates where $m_{K^+K^-}$ is consistent with the ϕ meson mass are rejected from the $\rho\gamma$ analysis, and viceversa.
From the selection criteria applied, the shape of this background exhibits a turn-on structure in the $m_{M\gamma}$ distribution around 100 GeV, in the region of the Z boson signal, and a smoothly falling background in the region of the Higgs boson signal.

4. – Background evaluation and Multivariate Analysis

An accurate modeling of the background is essential to distinguish the signature of the signal events to the background events, and to perform a more refined selection based on a multivariate analysis (MVA). Since MC background samples do not adequately describe the data behaviour in the gluon fusion category, a fully data driven background estimation is used in this case. For all the decay channels, the background is estimated by data events in the sidebands of the meson invariant mass distribution, exploiting the narrow peaks centered on the resonance mass of the mesons. The sidebands range has been defined aiming to the best agreement between data and background estimation. For the $\phi\gamma$ analysis the sidebands region is defined by 1.000 GeV $< m_{K^+K^-} <$ 1.008 GeV and 1.032 GeV $< m_{K^+K^-} <$ 1.040 GeV. For the $\rho\gamma$ analysis the sidebands region is defined by 550 MeV $< m_{\pi^+\pi^-} <$ 620 MeV and 920 MeV $< m_{\pi^+\pi^-} <$ 1000 MeV. For both the $\phi\gamma$ and $\rho\gamma$ final states, the main sources of background in the searches are events involving inclusive photon + jet or multijet processes where a meson candidate is reconstructed from ID tracks originating from a jet.
Since the selection performed until here involves minimal thresholds on the kinematic

variables of the final states, a further event selection is required to enhance background and signal discrimination. This is performed through a multivariate analysis technique, namely a boosted decision tree (BDT). This BDT classifier based on the root library TMVA [4] is trained using half of the signal and background events, and validated through the other half. The BDT used in this analysis exploits the Gradient Boost algorithm, which takes as input several variables that capture the distinctive kinematic features of the signal and the background. Those variables are: the charged isolation of the first (more energetic) track coming from the decay of the meson $\mathrm{iso}_{\mathrm{ch}}^{\mathrm{trk1}}$, the transverse momentum of the pair p_T^{ditrk}, the transverse energy of the photon E_T^{γ}, and the pseudorapidity of the pair η_{ditrk}. It is chosen as the BDT discriminant threshold the one which maximizes the significance Z, which is calculated as

$$\mathrm{Z} = \frac{\mathrm{S}\epsilon_{\mathrm{S}}^{\mathrm{BDT}}}{\sqrt{\mathrm{B}\epsilon_{\mathrm{B}}^{\mathrm{BDT}}}}, \tag{2a}$$

where S and B are the expected number of signal events with a branching ratio of 10^{-5} and background events after the first event selection, and $\epsilon_{\mathrm{S}}^{\mathrm{BDT}}$ and $\epsilon_{\mathrm{B}}^{\mathrm{BDT}}$ are the signal and background efficiencies as a function of the BDT discriminant.

For the $\phi\gamma$ final state, the total signal efficiencies (kinematic acceptance, trigger and reconstruction efficiencies) are 3% for both the Higgs and Z boson decays. The corresponding efficiencies for the $\rho\gamma$ final state are 3% and 2%, respectively.

The Higgs boson MC signal distribution is modelled with a double-side Crystal-Ball pdf, while the Z boson MC signal distribution is modelled with a Voigtian pdf (a convolution of relativistic Breit–Wigner and Gaussian pdfs). The background distribution, *i.e.* the $m_{M\gamma}$ distribution obtained with data coming from the sidebands of the meson mass distribution, is fitted with a Chebychev polynomial.

5. – Systematic uncertainties

Several sources of systematic uncertainties have been considered. The most important are reported in this section. Theoretical uncertainties in the gluon fusion Higgs boson and Z boson production cross sections amount to 3.9% and 2.9% respectively. The uncertainty on the integrated luminosity is 2.5%. The systematic uncertainty in the expected signal yield associated with the trigger efficiency is estimated to be 4.5%. The tracking efficiency uncertainty per track amount to 2.3%. Uncertainties in the photon ID efficiency corrections amounts to 1.5 % for both H and Z boson.

6. – Results

The data are analyzed by comparing them to background and signal predictions using a maximum-likelihood fit of the $m_{M\gamma}$ distribution. The parameters of interest are the Higgs and Z boson signal normalisations. Table I presents the expected and observed numbers of background events within the $m_{M\gamma}$ ranges relevant to these signals.

The observed yields align with the expected number of events from the background-only prediction, considering both systematic and statistical uncertainties. 95% confidence level upper limits on the $\mathcal{B}(H \to \phi\gamma)$, $\mathcal{B}(H \to \rho\gamma)$, $\mathcal{B}(Z \to \phi\gamma)$, and $\mathcal{B}(Z \to \rho\gamma)$ are then set using the $\mathrm{CL_S}$ modified frequentist formalism. For the Higgs boson analysis, both

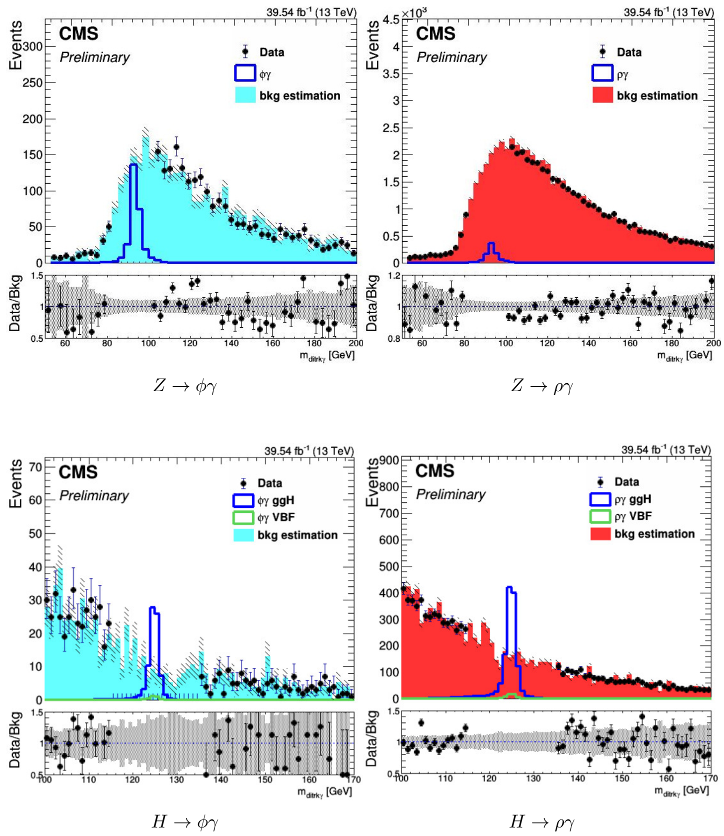

Fig. 1.: Invariant mass distributions of the ditrack and the photon

TABLE I.: Number of observed events and the mean expected background, estimated from the maximum-likelihood fit. The expected Higgs and Z boson signal yields are also shown.

	$H \to \phi\gamma$	$H \to \rho\gamma$	$Z \to \phi\gamma$	$Z \to \rho\gamma$
Obs yield (Mean exp bkg)	493 (492 ± 22)	6714 (6745 ± 78)	2508 (2485 ± 56)	34278 (34169 ± 211)
Exp signal yield	$(9.0 \pm 0.1) \times 10^{-4}$	$(4.6 \pm 0.1) \times 10^{-4}$	$(32 \pm 1) \times 10^{-6}$	$(60 \pm 1) \times 10^{-6}$

the expected and the observed limits are reported. For the Z boson analysis, only the expected limits are reported.

7. – Summary

A search has been conducted for Higgs and Z boson decays into $\phi\gamma$ and $\rho\gamma$ using $\sqrt{s} =$ 13 TeV proton-proton collision data collected by the CMS detector at the LHC, with

integrated luminosities reaching up to 39.56 fb^{-1}. The ϕ and ρ mesons are reconstructed through their primary decay channels into K^+K^- and $\pi^+\pi^-$ final states, respectively. The background model is derived using a fully data driven approach.
No significant excess of events above the background expectations is observed, as expected from the SM. The observed 95% upper limits for the Higgs analysis are $\mathcal{B}(H \to \phi\gamma) < 2.97 \times 10^{-4}$, $\mathcal{B}(H \to \rho\gamma) < 3.74 \times 10^{-4}$, in costintency with the expected ones [5]. The expected 95% CL upper limits for the Z analysis are $\mathcal{B}(Z \to \phi\gamma) < 2.21 \times 10^{-9}$, and $\mathcal{B}(Z \to \rho\gamma) < 6.56 \times 10^{-6}$. The observed upper limits for the Z boson are not reported, because the analysis is still at a preliminary phase.

TABLE II.: Expected and observed branching ratio upper limits at 95% CL. The $\pm 1\sigma$ intervals of the expected limits are also given.

Branching ratio limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)$ $[10^{-4}]$	$2.88^{+1.33}_{-0.83}$	2.97
$\mathcal{B}(Z \to \phi\gamma)$ $[10^{-6}]$	$2.21^{+1.37}_{-0.75}$	/
$\mathcal{B}(H \to \rho\gamma)$ $[10^{-4}]$	$5.71^{+2.37}_{-1.63}$	3.74
$\mathcal{B}(Z \to \rho\gamma)$ $[10^{-6}]$	$6.56^{+4.03}_{-2.22}$	/

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