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Search for exotic decays of the Higgs boson using photons with the CMS experiment

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In multiple beyond the standard model (SM) scenarios, the 125 GeV Higgs boson (H) can decay to light pseudoscalars (a), each of which decay into two photons, resulting in a four photon final state. We present a search for exotic decays of the SM Higgs boson in the four photon final state using 132 fb^{-1} of proton-proton collision data collected by the CMS experiment at a center-of-mass energy of 13 TeV. This analysis probes pseudoscalars that range in mass from 15 GeV to 60 GeV and decay into photons that are reconstructed as resolved objects in the CMS electromagnetic calorimeter. Although the branching fraction for a→ $\gamma\gamma$ is subdominant, the low backgrounds in the four photon final state make it important to study. These new results, the first in the four photon final state from CMS, set limits on the product of the production cross-section of the SM Higgs boson times the branching ratio of H→ $aa \rightarrow \gamma\gamma\gamma\gamma$, as a function of pseudoscalar mass.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker

PoS(EPS-HEP2021)636

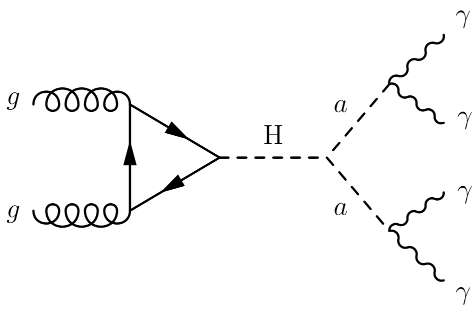

Figure 1: Feynman diagram for BSM decay of the Higgs boson into a pair of light pseudoscalars, which further decay to photons.

1. Introduction

In 2012, the Higgs boson (H) was discovered by the CMS and ATLAS experiments [1–3] at the Large Hadron Collider (LHC) with a mass of 125 GeV. Since then, both CMS and ATLAS experiments have performed precision measurements of the spin, parity, width, and couplings of the Higgs boson in its various production and decay modes, all of which indicate that it is compatible with the standard model (SM). However, various beyond the SM (BSM) theories describe the possibility of exotic decays of the Higgs boson to light bosons and have not been excluded so far.

Multiple searches for exotic decays of the Higgs boson at the LHC have been performed on the 8 and 13 TeV data collected at the LHC. Decays of the type H$\rightarrow$ aa, where a is a light pseudoscalar boson, are well motivated in various BSM scenarios. In many of these scenarios, the branching fraction of the pseudoscalars to a pair of photons is sufficient to be visible at the LHC. The final state with four photons provides an experimental signature that has very low contributions from SM processes and, is therefore an important channel to pursue a search for light pseudoscalars. A Feynman diagram contributing to this process at leading order (LO) is shown in Fig. 1.

2. Analysis strategy

Events considered in this analysis are required to contain at least one diphoton candidate that is constructed from photon candidates that pass identification criteria, which are slightly more stringent than the trigger requirements. Additionally, events must consist of at least four identified photon candidates in the ECAL and tracker fiducial region (η < 2.5), excluding the ECAL barrel-endcap transition region (1.44 < η < 1.57), where the photon reconstruction is sub-optimal. The four photon candidates are also required to pass selections on their p_T. When more than four photon candidates are found, the four candidates with the highest p_T are chosen. Each photon candidate must pass a veto on the presence of geometrically compatible hits in the pixel detector. The photon candidates are also required to pass the criteria: $110 < m_{\gamma\gamma\gamma\gamma} < 180$ GeV, where $m_{\gamma\gamma\gamma\gamma}$ is the invariant mass of the photon candidates. The Higgs boson candidate is constructed from the four photon candidates, which have passed all the previously described selections.

To improve the sensitivity of the search, an classifier, which exploits the identification and kinematic information of the photons and pseudoscalar candidates, is trained to separate the signal from the background. The classifier utilizes the reconstructed pseudoscalar mass as input information, and an optimized selection on the output of the classifier is used to define the final signal regions in the analysis. When all four photons from the decay of the pseudoscalar pair are within the acceptance criteria of the analysis, the $H \to aa \to \gamma\gamma\gamma\gamma$ signal will cause a peak at 125 GeV in the $m_{\gamma\gamma\gamma\gamma}$ distribution. The analysis performs a simultaneous maximum likelihood fit of the signal and background models to the observed $m_{\gamma\gamma\gamma\gamma}$ distribution in data after a selection on the classifier output is applied.

3. Background estimation and event classification

Because of the low signal selection efficiency on the background samples, it is difficult to model the background from simulation. The expected background model, which is used to train an event classifier, is estimated from data. The method, referred to as event mixing, does not rely on a control or sideband region, but instead aims at estimating the background contribution using the original data set as input. This procedure begins with using data events that have passed trigger selections, and replacing three out of the four photons in each event with photons from consecutive events to create a "mixed" data set. The shuffling of photons between the events not only constructs a data set that is similar to the original data, but also insensitive to the possible presence of a resonant signal.

A BDT classifier is trained to separate signal from background. The training sample is parameterized as a function of m_a in order to make the classifier output uniform and sensitive to the full range of signal hypotheses considered in the search [4].

For each signal hypothesis, events that pass selection on the BDT output are further used to obtain final results.

4. Signal and background modeling

The signal shape for the $m_{\gamma\gamma\gamma\gamma}$ distribution, for each nominal signal hypothesis, is constructed from simulation. After all of the analysis selections are applied, a unique signal model is built for each nominal signal hypothesis and for each of the three data taking years (2016, 2017, and 2018) by modeling the $m_{\gamma\gamma\gamma\gamma}$ distribution with a double-sided Crystal Ball (CB) function [5], which is a modified version of the standard CB function with two independent exponential tails. These signal models, scaled by the corresponding luminosity, are summed in order to construct the final signal model.

The background model is built to describe the shape of the $m_{\gamma\gamma\gamma\gamma}$ distribution that results from processes other than the decay of the Higgs boson. Since the shape of this distribution is not known, different functional forms must be considered in the construction of the background model. The choice of function can result in different number of estimated events under the signal peak and, as a result, affect the measured signal strength. This inherent uncertainty associated with the choice of function is accounted for by the discrete profiling method [6]. This method treats the choice of the background function as a discrete nuisance parameter in the likelihood fit to data.

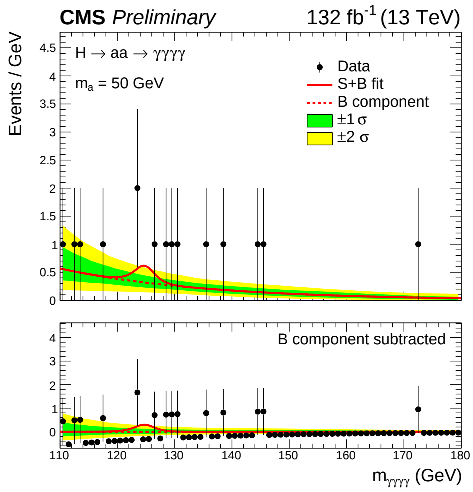

Figure 2: Invariant mass distribution, m$_{\gamma\gamma\gamma\gamma}$, for data (black points) and signal-plus-background model fit is shown for m$_a$ = 50 GeV. The solid red line shows the total signal-plus-background contribution, whereas the dashed red line shows the background component only. The lower panel shows the residuals after subtraction of this background component. The one (green) and two (yellow) standard deviation bands include the uncertainties in the background component of the fit. The lower panel in each plot shows the residual signal yield after the background subtraction.

5. Results

An unbinned maximum-likelihood fit is performed to the m$_{\gamma\gamma\gamma\gamma}$ distribution in the mass range $110 < m_{\gamma\gamma\gamma\gamma} < 180$ for each $m_a$hypothesis, with an m$_a$ granularity of 0.5 GeV up to m$_a$ = 40 GeV and 1 GeV for m$_a$ > 40 GeV. The data collected by the CMS experiment through 2016, 2017, and 2018 are combined for the fit. A unique likelihood function is defined for each m$_a$ hypothesis using analytic models to describe the m$_{\gamma\gamma\gamma\gamma}$ distributions of signal and background events, and nuisance parameters associated with the uncertainties considered in this analysis are included in the likelihood function.

The data and the signal-plus-background model fit to m$_{\gamma\gamma\gamma\gamma}$ is shown in Fig. 2 for m_a= 50 GeV.

No significant deviation from the background-only hypothesis is observed. Upper limits are set at the 95% confidence level (CL) on the product of the production cross section of the Higgs boson and the branching fraction into four photons via a pair of pseudoscalars, $\sigma\times\mathcal{B}(H \to aa \to \gamma\gamma\gamma\gamma)$. This is done using the modified frequentist approach for confidence levels, with the LHC profile likelihood ratio used as the test statistic [7–10]. The observed (expected) limit ranges from 0.80 (1.00) fbfor m$_a$ = 15 GeV to 0.33 (0.30) fb for m$_a$ = 60 GeV, and is shown in Fig. 3 as a function of m$_a$.

6. Summary

The data collected during Run 2 of the LHC is used to search for the exotic decay of the Higgs boson in the four photon final state. In absence of the evidence of any signal, limits are placed on $\sigma\times\mathcal{B}(H \to aa \to \gamma\gamma\gamma\gamma)$.

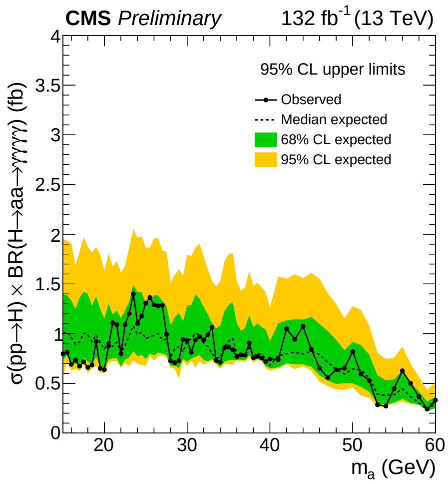

Figure 3: Expected and observed 95 % limits on the product of the production cross section of the Higgs boson and the branching fraction into four photons via a pair of pseudoscalars, $\sigma \times \mathcal{B}(H \to aa \to \gamma\gamma\gamma\gamma)$, is shown as a function of m$_a$. The green (yellow) bands represent the 68% (95%) expected limit intervals.

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