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Search for dark photons in Higgs boson production via vector boson fusion in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is presented for a Higgs boson that is produced via vector boson fusion and that decays to an undetected particle and an isolated photon. The search is performed by the CMS collaboration at the LHC, using a data set corresponding to an integrated luminosity of $130\,\text{fb}^{-1}$, recorded at a center-of-mass energy of 13 TeV in 2016–2018. No significant excess of events above the expectation from the standard model background is found. The results are interpreted in the context of a theoretical model in which the undetected particle is a massless dark photon. An upper limit is set on the product of the cross section for production via vector boson fusion and the branching fraction for such a Higgs boson decay, as a function of the Higgs boson mass. For a Higgs boson mass of 125 GeV, assuming the standard model production rates, the observed (expected) 95% confidence level upper limit on the branching fraction is 3.5 (2.8)%. This is the first search for such decays in the vector boson fusion channel. Combination with a previous search for Higgs bosons produced in association with a Z boson results in an observed (expected) upper limit on the branching fraction of 2.9 (2.1)% at 95% confidence level.

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*See Appendix A for the list of collaboration members

1 Introduction

Following the observation of a Higgs boson by the ATLAS and CMS collaborations [1–3], an important focus of the CERN LHC physics program has been the study of the properties of this particle. The observation of a sizable branching fraction of the Higgs boson to invisible or almost invisible final states [4–7] would be a strong sign of physics beyond the standard model (BSM). Studies of the new boson at a mass of about 125 GeV [8, 9] show no significant deviation from the standard model (SM) Higgs boson hypothesis, and measurements of its couplings constrain its partial decay width to undetected decay modes [10, 11]. Assuming that the couplings of the Higgs boson to W and Z bosons are not larger than the SM values, an upper limit of 38% has been obtained at 95% confidence level (CL) on the branching fraction of the 125 GeV Higgs boson to BSM particles by the CMS collaboration using data collected in 2016 [11, 12].

This paper presents a search for a scalar Higgs boson H produced via vector boson fusion (VBF) and decaying to an undetected particle and a photon γ. Such Higgs boson decays are predicted by several BSM models [7, 13, 14]. In this search, the target channel is $\mathrm{qqH}(\rightarrow \gamma\gamma_{\mathrm{D}})$, where the final-state quarks (q) arise from the VBF process and γ_{D} is a massless dark photon that couples to the Higgs boson through a dark sector [15–18]. The dark photon escapes undetected. A Feynman diagram for this process is shown in Fig. 1. The branching fraction for a Higgs boson decaying to such an invisible particle and a photon, $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{inv.} + \gamma)$, could be as large as 5% and still be consistent with current experimental constraints [16]. While the main focus of this search is on production via VBF, the additional contribution from gluon fusion production (ggH) is sizable if initial-state gluon radiation mimics the experimental signature of VBF. Thus, the ggH process is also considered for the SM Higgs boson. Additionally, a model-independent search for VBF production is performed for heavy neutral Higgs bosons with masses between 125 and 1000 GeV [19], since similar decays are also possible for potential non-SM scalar bosons.

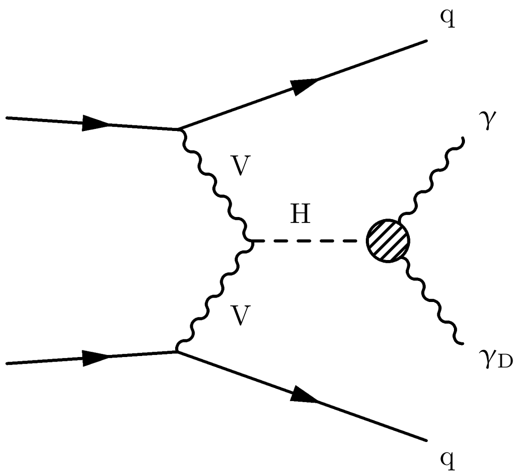

Figure 1: A Feynman diagram for the VBF production of the $\mathrm{qqH}(\gamma\gamma_{\mathrm{D}})$ final state.

In the VBF production mode, a Higgs boson is accompanied by two jets that exhibit a large separation in pseudorapidity ($|\Delta\eta_{\mathrm{jj}}|$) and a large dijet mass (m_{jj}). This characteristic signature allows for the suppression of SM backgrounds, making the VBF channel a very sensitive mode in the search for exotic Higgs boson decays. The invisible particle together with the photon produced in the Higgs boson decay can recoil with high transverse momentum (p_{T}) against the VBF dijet system, resulting in an event with a large missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) which can be used to select signal-enriched samples.

The analysis summarized in this paper uses proton-proton (pp) collision data collected at

$\sqrt{s} = 13$ TeV with the CMS detector in 2016–2018, with a total integrated luminosity of 130 fb^{-1}. Similar searches have previously been performed by the CMS Collaboration using the data collected at $\sqrt{s} = 8$ TeV [20] and $\sqrt{s} = 13$ TeV [21], where the Higgs bosons were produced by ggH or in association with a Z boson, respectively. This analysis presents the first search for Higgs bosons decaying to an undetected particle and a photon using the VBF signature for Higgs boson production.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The tracker system measures the momentum of charged particles in the region up to $|\eta| < 2.5$, where η is the pseudorapidity, while the ECAL and HCAL provide coverage up to $|\eta| < 3.0$. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors to $|\eta| < 5.0$. Muons are detected in gas-ionization chambers embedded in the steel magnetic flux-return yoke outside the solenoid, which cover the region up to $|\eta| < 2.4$.

Events of interest are selected using a two-tiered trigger system [22]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

3 Data samples and event reconstruction

The data used in this search were collected in separate LHC operating periods in 2016–2018. The three data sets are analyzed independently, with calibration constants and correction factors appropriate for the LHC running conditions and CMS detector properties in each year.

Monte Carlo (MC) simulated events are used to model the expected signal and background yields. The dominant background processes are from $\mathrm{W}+\text{jets}$ and $\gamma+\text{jets}$ production, in addition to smaller contributions from $\mathrm{W}(\ell\nu)+\gamma$, $\mathrm{Z}+\gamma$, and $\mathrm{Z}+\text{jets}$ processes. For each process, three sets of simulated events are needed to match the different data-taking conditions in each of the three years. The next-to-leading order (NLO) POWHEG v2 [24–28] generator is used to simulate the VBF and ggH Higgs boson production processes at NLO in quantum chromodynamics (QCD), as well as the $\mathrm{t\bar{t}}$, tW, $\mathrm{t\bar{t}}\gamma$, triple vector boson (VVV), and WW, WZ, and ZZ (VV) processes. For the VBF signal process, the Higgs boson production cross section as a function of m_{H}, incorporating the inclusive next-to-NLO QCD and NLO electroweak corrections, is taken from Refs. [19, 29], where an SM-like Higgs boson is assumed. Monte Carlo events with SM-like Higgs boson masses of $m_{\mathrm{H}} = 125$, 150, 200, 300, 500, 800, and 1000 GeV are simulated. The semi-visible decay of the Higgs boson $\mathrm{H} \to \gamma\gamma_{\mathrm{D}}$ is simulated with PYTHIA 8.226 (8.230) for the 2016 (2017–18) sample [30]. The same versions of PYTHIA are used to simulate the parton showering and hadronization for all processes. The $\mathrm{W}+\text{jets}$, $\mathrm{Z}+\text{jets}$, and $\gamma+\text{jets}$ background processes are generated using MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) at leading order (LO) accuracy in QCD with up to four partons for 2016 (2017–18) [31]. The different jet multiplicities of these samples are merged using the MLM scheme [32] to match matrix element and parton shower jets. The LO simulations for these processes are corrected using boson p_{T}-dependent NLO QCD K-factors derived using MADGRAPH5_aMC@NLO. They are also corrected using p_{T}-dependent higher-order electroweak corrections extracted from theoretical calculations [33]. Production of $\mathrm{W}(\ell\nu)+\gamma$ and $\mathrm{Z}+\gamma$ events with up to one additional parton is simulated at NLO accuracy in QCD using the MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) generator with the FxFx scheme [34] for 2016 (2017 and 2018) samples. The same generator without the FxFx scheme is used to model the electroweak production of $\mathrm{W}(\ell\nu)+\gamma$, $\mathrm{W}+\mathrm{jets}$, $\mathrm{Z}+\gamma$, and $\mathrm{Z}+\mathrm{jets}$ events with two partons at LO precision in QCD. The NNPDF 3.0 NLO [35] (NNPDF 3.1 next-to-next-to-leading order [36]) parton distribution functions (PDFs) are used for simulating all 2016 (2017–18) samples. The modeling of the underlying event is generated using the CUETP8M1 [37, 38] and CP5 tunes [39] for simulated samples corresponding to the 2016 and 2017–18 data sets, respectively.

All MC generated events are processed through a simulation of the CMS detector based on GEANT4 [40] and are reconstructed with the same algorithms used for data. Additional pp interactions in the same and nearby bunch crossings, referred to as pileup, are also simulated. The distribution of the number of pileup interactions in the simulation is adjusted to match the one observed in the data. The average number of pileup interactions was 23 (32) in 2016 (2017–18).

The CMS particle-flow (PF) algorithm [41] is used to combine the information from all subdetectors for particle reconstruction and identification. Jets are reconstructed by clustering PF candidates using the anti-k_{T} algorithm [42] with a distance parameter of 0.4. Jets are calibrated in the simulation, and separately in data, accounting for energy deposits of neutral particles from pileup and any nonlinear detector response [43, 44]. Jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 4.7$ are considered in the analysis. The effect of pileup is mitigated through a charged-hadron subtraction technique, which removes the energy of charged hadrons not originating from the primary interaction vertex (PV) [45]. The PV is defined as the vertex with the largest value of summed physics-object p_{T}^{2}. Here, the physics objects are the jets clustered using the jet finding algorithm [42, 46] with the tracks assigned to the candidate vertex as inputs, and the associated $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is calculated as the negative vector p_{T} sum of those jets.

For further analysis the vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is defined as the negative vector p_{T} sum of all PF particle candidates and its magnitude is defined as $p_{\mathrm{T}}^{\mathrm{miss}}$. Corrections to jet energies due to detector response are propagated to $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ [47]. Events with possible contributions from beam halo processes or anomalous signals in the calorimeters are rejected using dedicated filters [47].

Electrons and muons are reconstructed by associating a track reconstructed in the tracking detectors with either a cluster of energy in the ECAL [48, 49] or a track in the muon system [50]. Events are rejected from the signal region (SR) if any electron (muon) with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$ (2.4) passing the "loose" identification criteria is found [48, 50]. Several leptonic control regions are defined, where muons must pass the "medium" identification and "tight" isolation working points [48], while electrons must pass the "tight" identification and isolation working points [50]. Section 5 provides more details about the control regions used in the analysis.

Finally, photon candidates are reconstructed from energy deposits in the ECAL [51] with $|\eta| < 1.47$ (barrel region) and $p_{\mathrm{T}} > 80\,\mathrm{GeV}$. The identification of the candidates is based on shower shape and isolation variables, and the medium working point, as described in Ref. [51], is chosen to select those candidates. For a photon candidate to be considered as isolated, scalar sums of the transverse momenta of PF charged hadrons, neutral hadrons, and photons within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the candidate photon must fall below certain bounds [51]. Only the PF candidates that do not overlap with the candidate photon are included in the isolation sums. In addition, a standard "pixel-seed electron veto" [51] is applied to reject electrons misidentified as photons. The electron to photon misidentification rate is measured in $Z \to ee$ events by comparing the ratio of $e\gamma$ to ee pairs consistent with the Z boson mass. The average misidentification rate is 2–3%. If a jet overlaps with a reconstructed photon fulfilling loose identification criteria [51], the jet is removed.

4 Event selection

Collision events were collected using a dedicated VBF+γ trigger in 2016, while in 2017–18, a combination of single-photon and p_T^{miss} triggers was used. The HLT algorithm in 2016 is seeded by an e/γ L1 object with a p_T threshold of 40 GeV and comprises two parts. In the first part, a photon is reconstructed in the barrel region around the L1 object, imposing initial requirements on shower shapes and isolation. The photon p_T must be greater than 75 GeV. In the second part, calorimeter towers in the event are clustered into anti-k_T jets [42] with a distance parameter of 0.4. The event is recorded if it contains a pair of jets with $p_T > 50$ GeV, with $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 3$. This trigger was available for most of the data recorded throughout 2016, and provided an effective integrated luminosity of 28.5 fb^{-1}. This dedicated trigger made possible the offline selection of events with much lower photon p_T and p_T^{miss} than could be achieved with the single-photon and p_T^{miss} triggers used in 2017 and 2018 [52, 53]. These triggers required a photon at the HLT with $p_T > 200$ GeV and $|\eta| < 1.47$, or $p_T^{miss} > 120$ GeV, respectively. The single-photon trigger path is used if an event satisfies both triggers and a photon with $p_T > 230$ GeV is identified in the offline analysis. If no such photon is identified, the event may be selected by the p_T^{miss} trigger path.

The signal topology consists of two forward high-p_T jets consistent with VBF production, large p_T^{miss}, and an isolated high-p_T photon. The signal cross section is several orders of magnitude lower than that of the major reducible background processes, and therefore a stringent selection is required to obtain a sample of sufficient purity to define the SR. To be consistent with the expected topology, the selection requires leading and subleading jets with $p_T > 50$ GeV, and at least one photon in the barrel region with $p_T^{\gamma} > 80\,(230)$ GeV for the VBF+γ and p_T^{miss} (single-photon) trigger paths. In addition, events are required to have between two and five jets in total, where each jet has $p_T > 30$ GeV and $|\eta| < 4.7$. For the purpose of rejecting the bulk of the γ+jets background, as well as the signal process with small Lorentz boost of the Higgs boson, a p_T^{miss} greater than 100 (140) GeV in 2016 (2017–18) is required, and the azimuthal angle between all jets with $p_T > 30$ GeV and $\vec{p}_T^{miss}$ ($\Delta\phi_{\text{jet},\vec{p}_T^{miss}}$) must be >1.0. To reduce the background from leptonic events, a veto is applied rejecting events with any loosely identified electron or muon, as described in Section 3.

To select the VBF topology, the two leading jets must be in opposite hemispheres, with $|\Delta\eta_{jj}| > 3$ and $m_{jj} > 500$ GeV, and the so-called Zeppenfeld (z_γ^*) variable [54] must be <0.6, where

$$z_\gamma^* \equiv \left| \Big(\eta_\gamma - (\eta_{j_1} + \eta_{j_2})/2\Big) \,/\, |\Delta\eta_{jj}| \right|, \tag{1}$$

where η_γ is the pseudorapidity of the photon, and η_{j_1} and η_{j_2} are the pseudorapidities of the two candidate VBF jets. Since the total p_T in the event should be consistent with zero, the modulus of the vector sum (p_T^{tot}) of the p_T of the two leading jets, the p_T of the photon, and p_T^{miss} is required to be <150 GeV to reject events with jet p_T mismeasurement or with additional hard jets. A summary of the SR selection for the analysis is shown in Table 1. The different $p_{\mathrm{T}}^{\mathrm{miss}}$ requirements on the three data sets are due to different data-taking conditions.

Table 1: Summary of the selection criteria in the SR, depending on the trigger path and data-taking year. Rows with a single entry indicate that the same requirement is applied for all data-taking years and trigger paths.

Data-taking year	2016	2017/2018	
Trigger	VBF+γ	Single-photon	$p_{\mathrm{T}}^{\mathrm{miss}}$
Number of photons		$\geq$1 photon	
p_{T}^{γ}	>80 GeV	>230 GeV	>80 GeV
Number of leptons		0	
$p_{\mathrm{T}}^{\mathrm{j_1}}$, $p_{\mathrm{T}}^{\mathrm{j_2}}$		>50 GeV	
$p_{\mathrm{T}}^{\mathrm{miss}}$	>100 GeV	>140 GeV	>140 GeV
Jet counting		2–5	
m_{jj}		>500 GeV	
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$		>3.0	
$\eta_{\mathrm{j_1}}\eta_{\mathrm{j_2}}$		<0	
$\Delta\phi_{\mathrm{jet},\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}$		>1.0 radians	
z_{γ}^{*}		<0.6	
$p_{\mathrm{T}}^{\mathrm{tot}}$		<150 GeV	

5 Background estimation

There are multiple sources of SM background to the analysis. The most significant background arises from $\mathrm{W(e\nu)}+\text{jets}$ production, where the photon candidate is a misidentified electron. For larger values of $p_{\mathrm{T}}^{\mathrm{miss}}$, the most important processes are the production of a photon with a Z boson, where the Z boson decays into a neutrino-antineutrino pair ($\mathrm{Z}(\nu\overline{\nu})+\gamma$), and the production of a photon with a W boson, where the W boson decays to a lepton-neutrino pair ($\mathrm{W}(\ell\nu)+\gamma$). For these processes, a VBF-like two-jet signature can be produced by initial-state QCD radiation. The $\mathrm{W}(\ell\nu)+\gamma$ process becomes an irreducible background if the charged lepton falls outside of the detector acceptance. Another significant background process is $\gamma+\text{jets}$ production with a mismeasured $p_{\mathrm{T}}^{\mathrm{miss}}$. Less significant background processes are $\mathrm{Z}(\nu\overline{\nu})+\text{jets}$ and QCD multijet production, which can contribute to the SR when a jet is misidentified as a photon. For the $\mathrm{W(e\nu)}+\text{jets}$, $\mathrm{W}(\ell\nu)+\gamma$, $\mathrm{Z}(\nu\overline{\nu})+\gamma$, and $\mathrm{Z}(\nu\overline{\nu})+\text{jets}$ backgrounds, production via purely electroweak interactions, which is also considered, becomes more relevant at higher m_{jj}.

The main background processes described above are normalized by comparing the predicted yields to data in several control regions (CRs) defined to be as close as possible to the SR [53]. These regions are considered in the final discriminant maximum-likelihood fit, as described in Section 6. In particular, four CRs are defined:

- $\mathrm{W(e\nu)}+\text{jets}$ region: the full SR selection is applied, except that an electron must be selected and no photons found, and the electron is then used in place of the signal photon to build all kinematic variables.
- $\mathrm{Z}(\mu^{+}\mu^{-})+\gamma$ region: the full SR selection is applied, except that two muons must be selected together with a photon, and the $\Delta\phi_{\mathrm{jet},\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}$ requirement is not considered. The muons are added to $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ to emulate the signal topology.

- $W(\mu\nu) + \gamma$ region: the full SR selection is applied, but a muon must be selected together with a photon, and the muon is added to $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ to emulate the signal topology.
- $\gamma +$ jets region: the full SR selection is applied, but $\Delta\phi_{\mathrm{jet},\vec{p}_{\mathrm{T}}^{\mathrm{miss}}}$ must be <0.5.

There are other rare SM processes involving a photon and neutrinos or out-of-acceptance leptons, e.g. VV, VVV, $\mathrm{t\bar{t}}\gamma$, $\mathrm{t}\gamma$. The contributions from these minor background processes are very small after the final selection, so they are estimated directly from MC simulation.

We also consider the possibility that a pathological event reconstruction could lead to a significant underestimation of the photon energy (mismeasured γ), leaving an event with large $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ aligned in azimuthal angle with a photon. These events can be selected as part of the SR and a yield estimation is needed. It is possible to model the distribution of such events using the $\gamma +$ jets simulation. Distributions obtained this way can be used in the signal extraction fit, as described below. Since the shapes of the kinematic distributions are sufficiently distinct between this background and the signal, their rates can be determined simultaneously through the fit.

The distribution of this background is obtained by selecting events from $\gamma +$ jets simulation with the signal candidate selection criteria of Section 4, excluding $p_{\mathrm{T}}^{\mathrm{miss}}$-related requirements. The content of these events is modified by setting the photon transverse momentum to a fraction of its original value and adding the difference in p_{T}^{γ} to the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ variable. The nominal value for the new p_{T}^{γ} used to obtain this background template is 50%, and alternative scenarios using 25 and 75% are considered to account for potential variations in the template shape. The overall normalization is assumed to have an uncertainty corresponding to a factor of two.

The rate of hadrons being misidentified as photons (nonprompt) is estimated using two low-$p_{\mathrm{T}}^{\mathrm{miss}}$ $\gamma +$ jets samples [52]. In the first sample, a binned template fit is performed on the distribution of the lateral extension of the ECAL shower of the photon candidate along the η direction [48], $\sigma_{\eta\eta}$, applying the full photon selection, except for the $\sigma_{\eta\eta}$ requirement. Two sets of templates are created: for real photons and misidentified hadrons. The photon template is obtained using $\gamma +$ jets simulated events. The $\sigma_{\eta\eta}$ distribution for the hadron template is derived from data using a sideband in the charged-hadron isolation distribution. The number of misidentified hadrons surviving the $\sigma_{\eta\eta}$ requirement applied to the full photon selection is determined from the template fit. Their relative contribution to the total event yield in this low-$p_{\mathrm{T}}^{\mathrm{miss}}$ sample is referred to as the hadron fake rate in the following. The second low-$p_{\mathrm{T}}^{\mathrm{miss}}$ sample, obtained by inverting the charged-hadron isolation requirement altogether and loosening the $\sigma_{\eta\eta}$ requirement, almost exclusively consists of events with misidentified hadrons. A hadron misidentification transfer factor is calculated as the ratio of the hadron fake rate in the first subsample and the total yield in the second subsample. It is derived as a function of p_{T}^{γ}. The resulting misidentification transfer factors are then used to extrapolate to the SR from a high-$p_{\mathrm{T}}^{\mathrm{miss}}$ control sample with the same photon candidate selection as applied for the second low-$p_{\mathrm{T}}^{\mathrm{miss}}$ sample. An absolute prediction for the nonprompt background is then obtained by multiplying the event yields in the control sample with the transfer factors. An uncertainty of 5 to 15%, depending on the photon p_{T}, is assigned on the nonprompt rates to account for the limited statistical precision of the measurements. An alternative estimate of this background was made by considering events with $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$. An additional systematic uncertainty was assigned based on the observed difference between the two estimates.

6 Signal extraction

After applying the selection, a binned maximum-likelihood fit to the transverse mass of the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and photon system, m_{T}, is performed to discriminate between the signal and the remaining background processes, where m_{T} is defined as

$$m_{\mathrm{T}} \equiv \sqrt{2p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\gamma}[1-\cos(\Delta\phi_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\vec{p}_{\mathrm{T}}^{\gamma}})]}, \tag{2}$$

and $\Delta\phi_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}},\vec{p}_{\mathrm{T}}^{\gamma}}$ is the azimuthal angle between the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and $\vec{p}_{\mathrm{T}}^{\gamma}$ vectors. A profile likelihood technique is used where systematic uncertainties are represented by nuisance parameters [55]. For each individual bin, a Poisson likelihood term is used to describe the fluctuation of the yields around the expected central value, which is given by the sum of the contributions from signal and background processes. The uncertainties affect the overall normalizations of the signal and background yields, as well as the shapes of the predictions across the distributions of the observables. Uncertainties that affect only the normalization within a category are incorporated as nuisance parameters with log-normal probability density functions. Uncertainties affecting the template shapes are treated as nuisance parameters with Gaussian constraints. The normalization of each bin is interpolated smoothly with a sixth-order polynomial between the ± 1 standard deviation variations and extrapolated linearly beyond this. The total likelihood is defined as the product of the likelihoods of the individual bins and the probability density functions for the nuisance parameters, including the product of the likelihood for the individual years.

In addition, events in the SR and in all the CRs are split in two m_{jj} regions, below and above 1500 GeV. This value is chosen to ensure roughly half of the VBF signal events are in each region. The division also makes it possible to account for different relative contributions to the $\mathrm{W}(\mathrm{e}\nu)+\text{jets}$, $\mathrm{W}(\ell\nu)+\gamma$, $\mathrm{Z}(\nu\overline{\nu})+\gamma$, and $\mathrm{Z}(\nu\overline{\nu})+\text{jets}$ templates from strong or purely electroweak production mechanisms as a function of m_{jj}. In the $\mathrm{Z}(\mu^+\mu^-)+\gamma$ and $\mathrm{W}(\mu\nu)+\gamma$ CRs the m_{T} variable emulates the one in the SR by adding the leptons to the $p_{\mathrm{T}}^{\mathrm{miss}}$. The exact m_{T} binning choice in the SRs and CRs is summarized in Table 2. Correlations between systematic uncertainties in different regions of m_{T} and m_{jj} used in the template fit are taken into account. For all major background sources, normalization factors are used that are allowed to float freely in the fit. A single normalization factor for each process is used for the $\mathrm{W}(\ell\nu)+\gamma$ and $\mathrm{Z}+\gamma$ backgrounds, while for the $\mathrm{W}+\text{jets}$ and $\gamma+\text{jets}$ background processes, separate parameters are applied for each kinematic region defined by one bin of the respective CRs, resulting in six (two) separate normalization parameters for the $\mathrm{W}+\text{jets}$ ($\gamma+\text{jets}$) process. The events with mismeasured photons are included in the SRs as described in Section 5.

7 Efficiencies and systematic uncertainties

Several sources of systematic uncertainty are taken into account in the maximum-likelihood fit. For each source of uncertainty, the effects on the signal and background distributions are considered correlated.

The integrated luminosities of the 2016, 2017, and 2018 data-taking periods are individually known with uncertainties in the 2.3–2.5% range [56–58], while the total Run 2 (2016–2018) integrated luminosity has an uncertainty of 1.8%. The better precision of the overall luminosity measurement results from an improved understanding of relevant systematic effects.

The simulation of pileup events assumes a total inelastic pp cross section of 69.2 mb, with an associated uncertainty of 4.6% [59, 60], which has an impact on the expected signal and background yields of about 1%.

Table 2: Summary of the m_T binning choice in the SRs and CRs.

Region	Bins	m_T range (GeV)
SR, $m_{jj} < 1500$ GeV	6	$[0, 30, 60, 90, 170, 250, \infty]$
SR, $m_{jj} \geq 1500$ GeV	6	$[0, 30, 60, 90, 170, 250, \infty]$
$W(e\nu) +$ jets CR, $m_{jj} < 1500$ GeV	3	$[0, 90, 250, \infty]$
$W(e\nu) +$ jets CR, $m_{jj} \geq 1500$ GeV	3	$[0, 90, 250, \infty]$
$Z(\mu^+\mu^-) + \gamma$ CR, $m_{jj} < 1500$ GeV	1	$[0, \infty]$
$Z(\mu^+\mu^-) + \gamma$ CR, $m_{jj} \geq 1500$ GeV	1	$[0, \infty]$
$W(\mu\nu) + \gamma$ CR, $m_{jj} < 1500$ GeV	1	$[0, \infty]$
$W(\mu\nu) + \gamma$ CR, $m_{jj} \geq 1500$ GeV	1	$[0, \infty]$
$\gamma +$ jets CR, $m_{jj} < 1500$ GeV	1	$[0, \infty]$
$\gamma +$ jets CR, $m_{jj} \geq 1500$ GeV	1	$[0, \infty]$

Discrepancies in the lepton and photon reconstruction and identification efficiencies between data and simulation are corrected by applying scale factors to all simulated samples. These scale factors are determined using $Z \to \ell\bar{\ell}$ events in the Z boson peak region that were recorded with unbiased triggers [48, 50]. The scale factors depend on the p_T and η of the lepton and have an uncertainty of $\approx$2% for both electrons and muons. The above procedure is applied also to determine the scale factors for photons using $Z \to e^+e^-$ events as a proxy, and the yield uncertainty for photon candidates is $\approx$4%. The photon momentum scale uncertainty is about 0.5%. These uncertainties are treated as correlated across the three years.

The determination of the trigger efficiency leads to an uncertainty of $\approx$1% in the VBF+γ and single-photon triggers, while the uncertainty is $\approx$7% for the p_T^{miss} triggers. These uncertainties are treated as uncorrelated across the three data sets and trigger selections, as data-taking conditions have varied across the three years.

The uncertainty in the calibration of the jet energy scale directly affects the acceptance of the jet multiplicity requirement and the p_T^{miss} measurement. These effects are estimated by shifting the jet energy in the simulation up and down by one standard deviation. The uncertainty in the jet energy scale is 2–5%, depending on p_T and η [43], and the impact on the expected signal and background yields is about 3%. The uncertainties in the jet energy scale are treated as uncorrelated across the three data sets.

The theoretical uncertainties due to the choice of QCD renormalization and factorization scales used in the simulation of the background processes are estimated by varying these scales independently up and down by a factor of two (excluding the two extreme variations) and taking the envelope of the resulting distributions as the uncertainty [61, 62]. The variations of the PDF set and the strong coupling constant are used to estimate the corresponding uncertainties in the yields of the signal and background processes, following Refs. [35, 63]. The uncertainties in the signal predictions due to the choice of the PDF set and the renormalization and factorization scale variations are taken from Ref. [19]. For the ggH contribution, an additional uncertainty of 40% is assigned to take into account the limited knowledge of the ggH cross section in association with two or more jets, as well as the uncertainty in the prediction of the ggH differential cross section for large Higgs boson p_T, following the recipe described in Refs. [61, 64]. Theoretical uncertainties in modeling the parton shower and underlying event primarily affect the jet multiplicity and are evaluated following the recipes from Refs. [19, 29].

The statistical uncertainty associated with the limited number of simulated events is also considered a part of the systematic uncertainty. A summary of the impacts of the systematic uncertainties on the signal cross section for $m_\mathrm{H} = 125\,\mathrm{GeV}$ is presented in Table 3. The impacts are evaluated by fitting to Asimov data sets [55] and are defined as the change in the fitted signal cross section when varying a nuisance parameter by its post-fit uncertainty. By performing the fit to the data simultaneously in the different CRs and SRs, the resultant final background uncertainties are reduced compared to the input uncertainties [53, 64]. The impacts are shown for the case of a signal ($\sigma = 0.05\sigma_\mathrm{SM}$, where σ_SM is the SM Higgs boson cross section for $m_\mathrm{H} = 125\,\mathrm{GeV}$) and for the case of no signal ($\sigma = 0$). The systematic uncertainties are dominated by the limited number of simulated events, the background normalization factors, and the jet energy scale.

Table 3: Summary of the uncertainties in the fitted signal cross section in fb for $m_\mathrm{H} = 125\,\mathrm{GeV}$ assuming the presence of a signal ($\sigma = 0.05\sigma_\mathrm{SM}$) and the absence of a signal ($\sigma = 0$).

Source of uncertainty	Impact for scenario with signal (fb)	Impact for scenario without signal (fb)
Integrated luminosity	3.3	0.6
Lepton and trigger measurements	17	7.7
Jet energy scale and resolution	24	19
Pileup	9.7	8.5
Background normalization	25	18
Theory	6.0	3.0
Simulation sample size	36	36
Total systematic uncertainty	54	46
Statistical uncertainty	58	48
Total uncertainty	79	66

8 Results

The numbers of observed and expected events after applying the full selection requirements are shown in Table 4. Owing to the anticorrelation between the yields of several background processes, the uncertainty in the background sum in the different regions is smaller than the uncertainties in some of the individual contributions. For illustration purposes, the signal shown has $\mathcal{B}(\mathrm{H} \to \mathrm{inv.} + \gamma)$ set to 0.05 and assumes the SM production cross section, as this corresponds roughly to the expected sensitivity level of the analysis.

The VBF signal reconstruction efficiency increases with m_H, with values of 0.2, 2.6, and 8.2% for masses of 125, 300, and 1000 GeV, respectively. The inefficiency is driven by the $p_\mathrm{T}^\mathrm{miss}$ and photon p_T requirements. The m_jj distributions in the $\gamma +$ jets, $\mathrm{Z}(\mu^+\mu^-) + \gamma$, and $\mathrm{W}(\mu\nu) + \gamma$ CRs are shown in Fig. 2, while the m_T distributions in the $\mathrm{W}(\mathrm{e}\nu) +$ jets CRs and in the SRs are shown in Fig. 3. The signal spectrum shows a Jacobian peak with an end-point at $m_\mathrm{T} \sim m_\mathrm{H}$, while the background processes have either a flat distribution or display an increase towards lower values of m_T.

No significant excess of events above the expectation from the SM background is found. The upper limits at 95% CL are calculated using a modified frequentist approach with the $\mathrm{CL_s}$ criterion [65, 66] and an asymptotic method for the test statistic [55, 67]. The statistical compatibility of the observed results, using the test based on a saturated χ^2 model [68], with the expectation under the background-only hypothesis corresponds to a p-value of 0.25. The expected and observed cross section upper limits at 95% CL on the product of the signal cross section σ_VBF for VBF production and $\mathcal{B}(\mathrm{H} \to \mathrm{inv.} + \gamma)$ as a function of m_H are shown in Fig. 4, and range

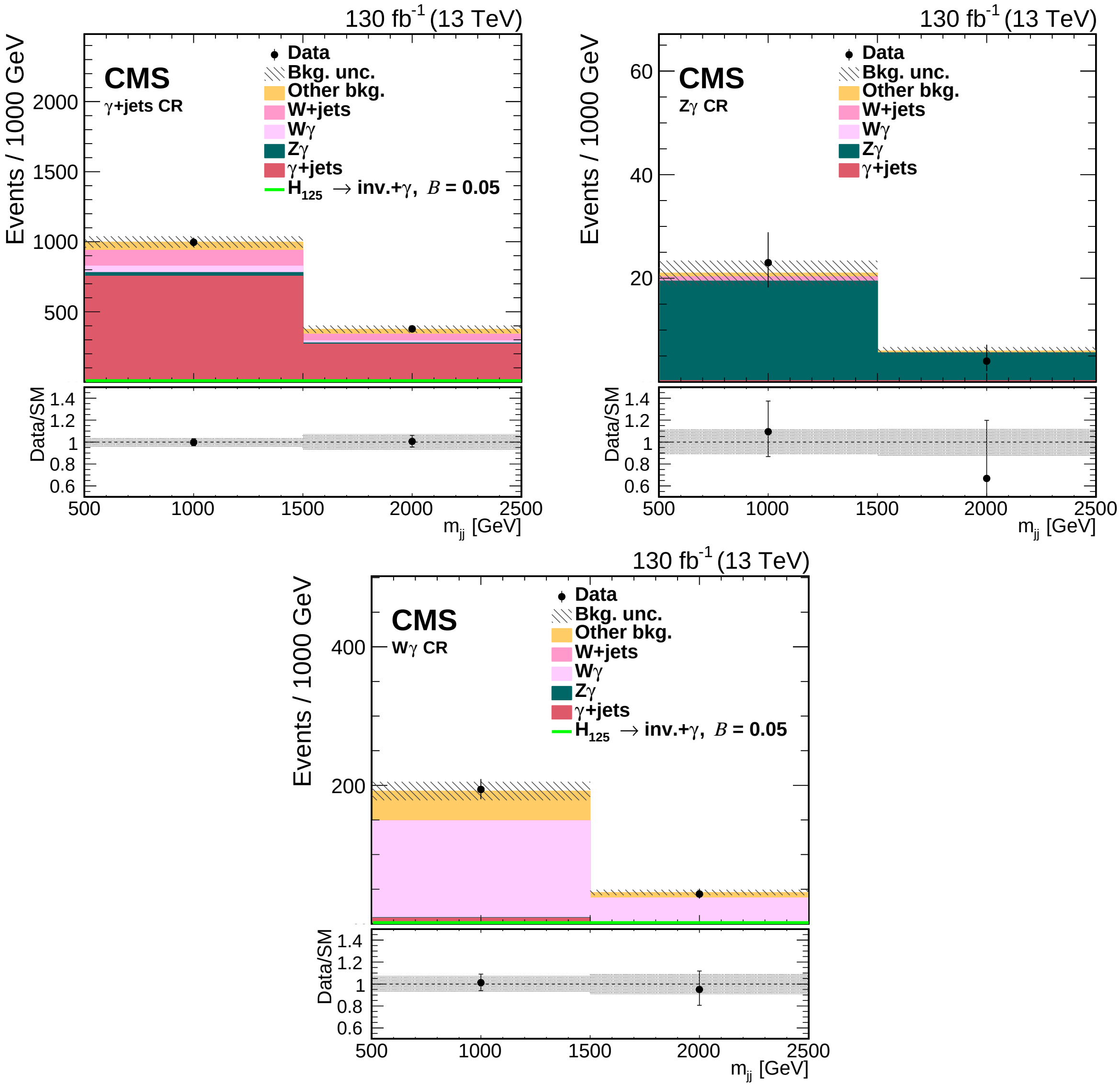

Figure 2: The m_{jj} distributions from the simultaneous fit in the $\gamma +$ jets (upper left), $\mathrm{Z}(\mu^+\mu^-) + \gamma$ (upper right), and $\mathrm{W}(\mu\nu) + \gamma$ (lower) CRs. The category other background includes contributions from Z + jets, nonprompt, top quark, VV, and VVV processes. Overflow events are included in the last bin. The shaded bands represent the combination of the statistical and systematic uncertainties in the predicted yields. The light green line, illustrating the possible contribution expected from inclusive SM Higgs boson production, assumes a branching fraction of 5% for H $\rightarrow$ inv. $+ \gamma$ decays. The lower panel in the figures shows a per-bin ratio of the data yield and the background expectation. The shaded band corresponds to the combined systematic and statistical uncertainty in the background expectation.

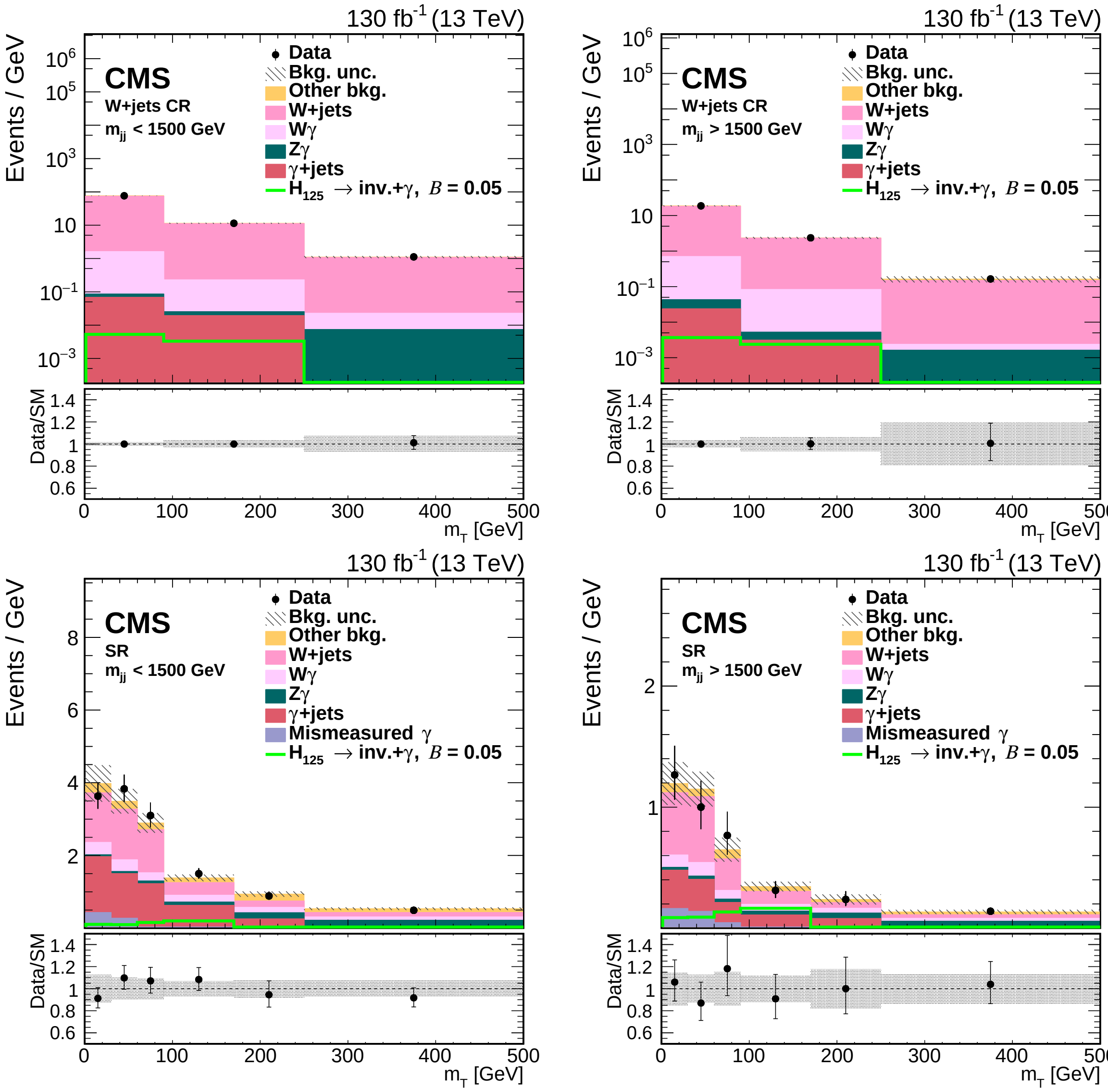

Figure 3: The m_{T} distributions from the simultaneous fit for events with $m_{\mathrm{jj}} < 1500\,\mathrm{GeV}$ in the $\mathrm{W}(\mathrm{e}\nu) + \mathrm{jets}$ CRs (upper left), for events with $m_{\mathrm{jj}} \geq 1500\,\mathrm{GeV}$ in the $\mathrm{W}(\mathrm{e}\nu) + \mathrm{jets}$ CRs (upper right), for events with $m_{\mathrm{jj}} < 1500\,\mathrm{GeV}$ in the SRs (lower left), and for events with $m_{\mathrm{jj}} \geq 1500\,\mathrm{GeV}$ in the SRs (lower right). The category other background includes contributions from $\mathrm{Z} + \mathrm{jets}$, nonprompt, top quark, VV, and VVV processes. Overflow events are included in the last bin. The shaded bands represent the combination of the statistical and systematic uncertainties in the predicted yields. The light green line, illustrating the possible contribution expected from inclusive SM Higgs boson production, assumes a branching fraction of 5% for $\mathrm{H} \rightarrow \mathrm{inv.} + \gamma$ decays. The lower panel in the figures shows a per-bin ratio of the data yield and the background expectation. The shaded band corresponds to the combined systematic and statistical uncertainty in the background expectation.

Table 4: Data, expected backgrounds, and estimated signal in the different regions. The expected background yields are shown with their best-fit normalizations from the simultaneous fit assuming background-only in the different regions. The combination of the statistical and systematic uncertainties is shown. The illustrative signal yield assumes a production cross section of $0.05\sigma_{SM}$. All data-taking periods and trigger paths are combined together for each region.

	SR	$W(e\nu)+$jets CR	$Z(\mu^+\mu^-)+\gamma$ CR	$W(\mu\nu)+\gamma$ CR	$\gamma+$jets CR
W + jets	250 ± 17	10500 ± 100	—	—	180 ± 37
$W(\ell\nu)+\gamma$	98 ± 11	240 ± 36	—	190 ± 18	76 ± 8
$Z+\gamma$	98 ± 18	6.8 ± 1.5	25 ± 4	1.7 ± 0.4	46 ± 8
γ + jets	230 ± 22	12 ± 4	—	9.5 ± 2.3	1400 ± 58
Mism. γ	34 ± 15	—	—	—	—
Z + jets	41 ± 6	100 ± 10	—	6.3 ± 0.6	26 ± 3
Nonprompt	20 ± 4	1.1 ± 0.2	1.2 ± 0.2	4.4 ± 0.9	62 ± 13
Top quark	18 ± 5	16 ± 4	0.3 ± 0.1	30 ± 7	22 ± 5
VV	6.9 ± 1.0	200 ± 9	0.3 ± 0.3	4.4 ± 0.9	5.7 ± 0.5
VVV	3.1 ± 0.5	7.6 ± 1.0	—	8.1 ± 1.1	3.6 ± 0.5
Total background	800 ± 25	11100 ± 100	27 ± 4	250 ± 16	1800 ± 43
Data	801	11091	27	253	1830
$qqH_{125}(\gamma\gamma_D)$	50.5 ± 7.4	1.7 ± 0.3	—	—	4.5 ± 0.4
$ggH_{125}(\gamma\gamma_D)$	30.6 ± 14.3	1.2 ± 0.6	—	—	6.9 ± 2.9

from $\approx$160 to $\approx$2 fb as m_H increases from 125 to 1000 GeV. For the years 2017 and 2018, the p_T^{miss} trigger path is the most sensitive one for signal models with $m_H \lesssim 400$ GeV; above this value, the single-photon trigger path dominates. These limits also apply to other models where a scalar particle decays to a photon and light invisible particles. For $m_H = 125$ GeV, the result is interpreted as an upper limit on $\mathcal{B}(H \to \text{inv.} + \gamma)$ assuming the production rate for an SM Higgs boson [19]. In this case, the additional contribution from the ggH production in the VBF category is considered, accounting for an increase in the signal yields of about 60%, and mainly contributing to the region with $m_{jj} < 1500$ GeV. The observed (expected) 95% CL upper limit at $m_H = 125$ GeV on $\mathcal{B}(H \to \text{inv.} + \gamma)$ is 3.5 ($2.8^{+1.3}_{-0.8}$)%.

The results of this analysis are combined with a complementary search for the same Higgs boson decay where the Higgs boson is produced in association with a Z boson (ZH) [21]. The combination is performed assuming the production rates for an SM-like 125 GeV Higgs boson [19]. For the combination, all the experimental uncertainties are treated as correlated between the two analyses, while all others are treated as uncorrelated. The observed and expected 95% CL limits at $m_H = 125$ GeV on $\mathcal{B}(H \to \text{inv.} + \gamma)$ for the VBF category, ZH category, and their combination are shown in Table 5. The combined observed (expected) upper limit at 95% CL at $m_H = 125$ GeV on $\mathcal{B}(H \to \text{inv.} + \gamma)$ is 2.9 (2.1)%.

Table 5: Observed and expected 95% CL limits at $m_H = 125$ GeV on $\mathcal{B}(H \to \text{inv.} + \gamma)$ for the VBF category, ZH category, and their combination.

VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.5	$2.8^{+1.3}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+1.0}_{-0.7}$

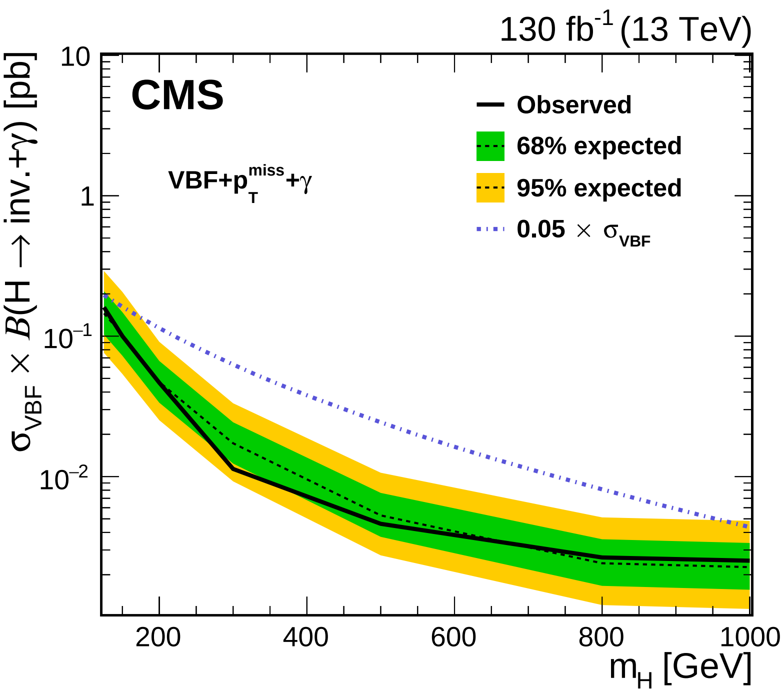

Figure 4: Expected and observed upper limits at 95% CL on the product of σ_{VBF} and $\mathcal{B}(\mathrm{H} \to \mathrm{inv.} + \gamma)$ as a function of m_{H}. The dot-dashed line shows the predicted signal corresponding to $0.05\sigma_{\mathrm{VBF}}$, assuming SM couplings. A linear interpolation is performed between the values obtained for the probed m_{H} values.

9 Summary

A search has been presented for a Higgs boson that is produced via vector boson fusion (VBF) and that decays to an undetected particle and a photon. This is the first analysis for such decays in the VBF channel. The search has been performed by the CMS Collaboration using a data set corresponding to an integrated luminosity of 130 fb^{-1} recorded at a center-of-mass energy of 13 TeV in 2016-2018. No significant excess of events above the expectation from the standard model background is found. The results are used to place limits on the product of the signal cross section σ_{VBF} for VBF production and the branching fraction for such decays of the Higgs boson, in the context of a theoretical model where the undetected particle is a massless dark photon. Allowing for deviations from standard model VBF production, the upper limit on the product of σ_{VBF} and $\mathcal{B}(\mathrm{H} \to \mathrm{inv.} + \gamma)$ ranges from $\approx$160 to $\approx$2 fb, for m_{H} from 125 GeV to 1000 GeV. The observed (expected) upper limit at 95% confidence level at $m_{\mathrm{H}} = 125$ GeV assuming standard model production rates on $\mathcal{B}(\mathrm{H} \to \mathrm{inv.} + \gamma)$ is 3.5 (2.8)% for this channel. Combining with an existing analysis targeting associated Z boson production, and assuming the standard model rates, the observed (expected) upper limit at 95% confidence level at $m_{\mathrm{H}} = 125$ GeV on $\mathcal{B}(\mathrm{H} \to \mathrm{inv.} + \gamma)$ is 2.9 (2.1)%.

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