Search for dark photons in Higgs boson production via vector boson fusion in proton-proton collisions at 13 TeV (Review)

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Motivation

Investigation of the ability of the LHC to find dark matter (DM) using vector boson fusion (VBF).

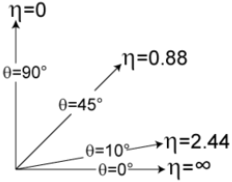
Motivation for VBF searches:

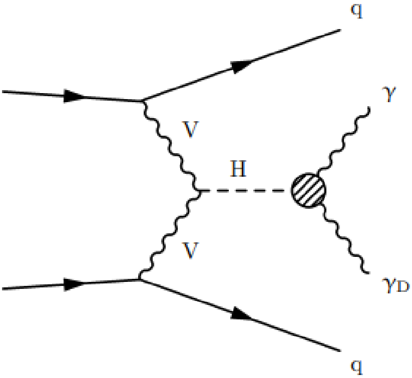
- High number of techniques existing for the identification of the Higgs boson and backgrounds.,
  ⇒ Missing energy signal a clear sign of BSM;
- VBF production is relatively common.
- Demanding two jets with large separation combined with missing energy allows a trigger threshold lower than monojet.
- The only requirement is that DM interacts with visible particles via the Higgs. No need for model-dependent assumptions.

Target Channel

Target channel combines multiple ingredients:

- γ_D is a massless dark photon that couples to the Higggs boson through a dark sector. Large missing transverse momentum (p_T^{miss}).
- Two jets with large separation in pseudorapidity ($|\Delta\eta_{jj}|$) and large dijet mass (m_{jj}).
- Photon γ produced with high transverse momentum p_T.

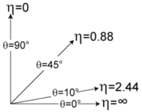




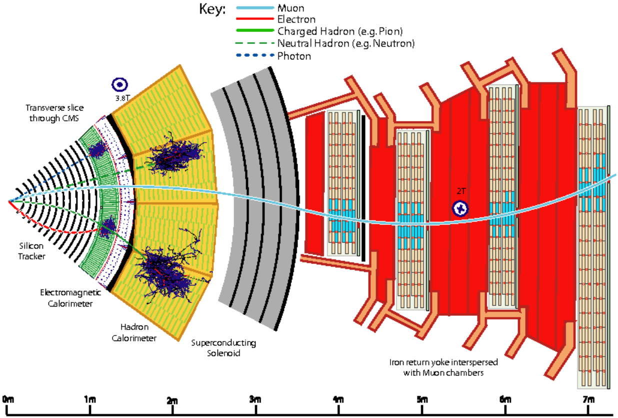
Feynman diagram for the VBF production of the $qqH(\gamma\gamma_D)$ final state.

CMS detector

Silicon tracker measures the momentum $|\eta| < 2.5$, the ECAL and HCAL cover $|\eta| < 3.0$. Forward calorimeters extend to $|\eta| < 5.0$.



Events of interest are selected using a two-tiered (L1 and HLT) trigger system optimized for fast processing and reducing the event rate before data storage.



Sketch of the particle interactions in a slice of the CMS detector [CMS, 2003]. Data collected in 2016-2018.

Event reconstruction

The dominant background processes are from $W+$jets and $\gamma+$jets production, with smaller contributions from $W(l\nu)+\gamma$, $Z+\gamma$, and $Z+$jets processes. The matrix elements for the processes with jets are obtained using the public program *MadGraph5_aMC@NLO 2.2.2* at LO accuracy in QCD. The obtained values are then corrected with factors coming from theoretical calculations and runs of the program at NLO. The $W(l\nu)+\gamma$ and $Z+\gamma$ events are simulated at NLO accuracy in QCD using the same program and with the FxFx scheme [1209.6215].

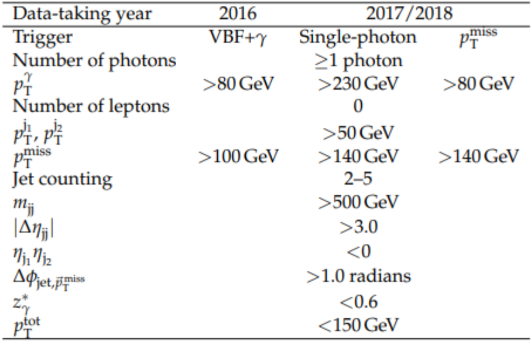
Having the matrix elements, Monte Carlo (MC) simulations are used to model the expected signal and background yields. The implementation is done using the POWHEG v2 library [1002.2581], which includes the VBF and ggH Higgs production processes at NLO and most other relevant productions. The MC generated events this way are processed through a simulation of the CMS detector based on [GEANT4, 2003] and reconstructed with the same algorithms used for data.
Jets reconstructed using the anti-k_T algorithm [0802.1189] and only considered for $p_T > 30\ GeV$ and $|\eta| < 4.7$. The associated missing momentum $\vec{p}_T^{\,\text{miss}}$ is calculated as the negative vector sum of those jets.

Event selection

The selection starts at the Level-1 Trigger (L1) that only uses input from calorimeters and muon chambers, in $2.5\,\mu s$ into the high-level trigger (HLT) that runs a version of the full event reconstruction software, in $300\,ms$.

Collision events were first collected using a dedicated VBF $+\,\gamma$ trigger in 2016, while in 2017-18, a combination of single-photon and p_T^{miss} triggers was used.

The modulus of the vector sum of the two leading jets, the photon and missing energy is also constrained.



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	

Selection criteria in the signal region. Rows with a single entry indicate that the same requirement is applied for all.

Background estimation

The most significant SM background comes from $W(e\nu) + \text{jets}$ production, where the photon candidate is a misidentified electron. The background signal for large values of missing energy is that of neutrinos that cannot be observed by the detectors, coming from a Z boson decay $Z(\nu\bar{\nu}) + \gamma$, and W boson decay $W(l\nu) + \gamma$. Another significant process is that of $\gamma + \text{jets}$ production with mismeasured p_T^{miss}.

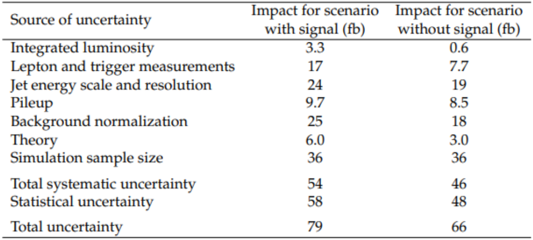
The main background processes are normalized by comparing the predicted events with data in several control regions (CR) defined to be close to the signal region (SR). The regions are then considered in the final maximum-likelihood hit:

- $W(e\nu) + \text{jets}$
- $Z(\mu^+\mu^-) + \gamma$
- $W(\mu\nu) + \gamma$
- $\gamma + \text{jets}$

The other SM processes are considered more rare and estimated directly from MC simulation.

Systematic uncertainties

For each source of uncertainty, the effects on the signal and background distributions are considered correlated.

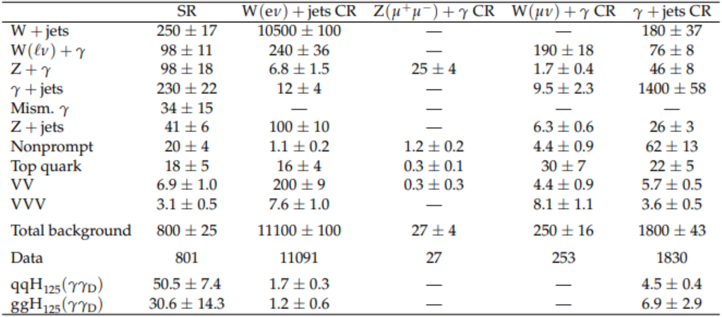


Source of uncertainty	Impact for scenario with signal (fb)	Impact for scenario without signal (fb)
Integrated luminosity	3.3	0.6
Lepton and trigger measurements	17	7.7
Jet energy scale and resolution	24	19
Pileup	9.7	8.5
Background normalization	25	18
Theory	6.0	3.0
Simulation sample size	36	36
Total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

Summary of the uncertainties.

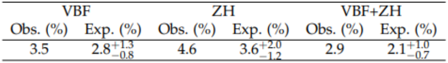
The systematic uncertainties are dominated by the limited number of simulated events, the background normalization factors, and the jet energy scale.

Results



	SR	$W(e\nu)+\text{jets}$ CR	$Z(\mu^+\mu^-)+\gamma$ CR	$W(\mu\nu)+\gamma$ CR	$\gamma+\text{jets}$ CR
$W+\text{jets}$	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
$\gamma+\text{jets}$	230 ± 22	12 ± 4	—	9.5 ± 2.3	1400 ± 58
Mism. γ	34 ± 15	—	—	—	—
$Z+\text{jets}$	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

Data, expected backgrounds, and estimated signal.

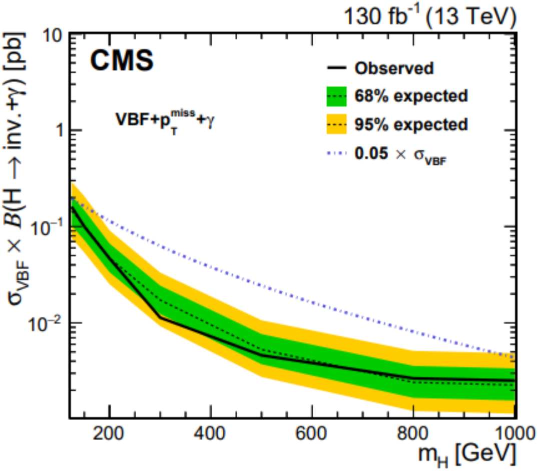


VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.5	$2.8^{+1.3}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+1.0}_{-0.7}$

95% CL limits at $m_H = 125\,GeV$ on $\mathcal{B}(H \to \text{inv.} + \gamma)$.

Results

These limits apply to other models where a scalar particle decays to a photon and light invisible particles.



Upper limits

Summary

- No significant excess of events above the expectation from the standard model background is found.
- Limits on the product of the VBF cross section and the branching function for the decay studied, in the context of a model with a massless dark photon.
- The observed (expected) 95% CL upper limit at $m_H = 125\,GeV$ on the branching function $\mathcal{B}(H \rightarrow \text{inv.} + \gamma)$ is $3.5(2.8)\%$ for the VBF production channel.

The End