Constraining anomalous Higgs boson coupling

in $H+\gamma$ production

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Abstract

Higgs boson production in association with a photon ($H+\gamma$) offers a promising channel to test the Higgs boson to photon coupling at various energy scales. Its potential sensitivity to anomalous couplings of the Higgs boson has not been explored with proton-proton collision data. In this paper, we reinterpret the latest ATLAS $H+\gamma$ resonance search results within the Standard Model effective field theory (EFT) framework, using 36.1 fb$^{-1}$ of proton-proton collision data recorded with the ATLAS detector at $\sqrt{s} = 13$ TeV. Constraints on Wilson coefficients of dimension-six EFT operators related to the Higgs boson to photon coupling are provided for the first time in $H+\gamma$ final state at the LHC.

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I. INTRODUCTION

After the discovery of the Higgs boson [1, 2], measurements of the Higgs boson couplings to the other fundamental particles become crucial tests of the nature of the Higgs boson. In the Standard Model (SM), coupling of the Higgs boson to photon is forbidden at the tree level, and is induced by heavy particle loops in, e.g., $H \rightarrow \gamma \gamma$ and $H \rightarrow Z \gamma$ processes. The Higgs-photon coupling has been extensively studied in various Higgs boson decay channels including $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^*/Z\gamma^*/\gamma\gamma^* \rightarrow 4\ell$ with LHC data recorded by the ATLAS and CMS experiments [3-11].

Apart from the Higgs boson decay channels involving photons, Higgs boson production in association with a photon can also be used to measure the Higgs-photon coupling. The $H+\gamma$ production cross section is predicted to be very small in the SM, but anomalous couplings introduced by models beyond the SM (BSM) can have significant effects on it. The $H+\gamma$ process was considered as a promising and clean channel at LEP [12, 13], and has been used by the DELPHI collaboration to search for anomalous couplings of the Higgs boson to vector bosons [14]. At the LHC, potential sensitivity of the $pp \rightarrow H+\gamma$ process to anomalous Higgs-photon couplings has been discussed in Ref. [15]. It is predicted that some Wilson coefficients of dimension-six operators related to Higgs-photon couplings can be probed down to $10^{-2}$ with 300 fb$^{-1}$ $pp$ collision data at 14 TeV. There is no particular analysis measuring the anomalous Higgs-photon couplings via this channel using the LHC data. ATLAS and CMS collaborations have reported the results on heavy $H+\gamma$ resonance searches in 13 TeV $pp$ collision data [16, 17]. Besides the resonance models, their results are also sensitive to non-resonant $H+\gamma$ production and to the anomalous coupling between Higgs boson and photon. However, these results have not been interpreted as limits on the anomalous Higgs-photon coupling.

In this paper, the latest $H+\gamma$ resonance search results from the ATLAS collaboration [16] are reinterpreted within the SM effective field theory (EFT) framework, and are presented as constraints on Wilson coefficients of dimension-six EFT operators. The study is based on a $pp$ collision dataset of 36.1 fb$^{-1}$ at $\sqrt{s} = 13$ TeV.

This paper is organized as follows. Section [II] gives a short overview of the EFT framework, and a brief description of the signal Monte Carlo generation for the reinterpretation. Section [III] describes the analysis strategy. Section [IV] presents the constraints on Wilson
coefficients of dimension-six EFT operators that are obtained in the $H+\gamma$ channel, and compares them with existing results from other measurements. Our conclusions are summarized in Section V.

**II. EFFECTIVE FIELD THEORY**

In the SM effective field theory approach, effects of BSM interactions are parametrized using higher-dimension operators in addition to the SM Lagrangian. Leading contributions at collider energies are expected to originate from dimension-six operators. A general effective Lagrangian with dimension-six operators $O_i$ takes the form

$$L_{\text{eff}} = L_{\text{SM}} + \sum_i \bar{c}_i O_i \ .$$

with Wilson coefficients $\bar{c}_i$ describing the strengths of the BSM interactions.

We focus on a set of dimension-six operators known as the strongly-interacting light Higgs (SILH) Lagrangian [18]. It is written as

$$L_{\text{SILH}} = \frac{\bar{c}_\mu}{2v^2} \partial^\mu [\Phi^\dagger \Phi] \partial_\mu [\Phi^\dagger \Phi] + \frac{\bar{c}_T}{2v^2} [\Phi^\dagger \overset{\leftrightarrow}{D}^\mu \Phi] [\Phi^\dagger \overset{\leftrightarrow}{D}_\mu \Phi] - \frac{\bar{c}_\lambda}{v^2} [\Phi^\dagger \Phi]^3$$

$$+ \left[ \frac{\bar{c}_u}{v^2} y_u \Phi^\dagger \Phi \overset{\leftrightarrow}{D}_\mu \Phi u_R + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger \Phi \overset{\leftrightarrow}{D}_\mu \Phi d_R + \frac{\bar{c}_l}{v^2} y_\ell \Phi^\dagger \Phi \overset{\leftrightarrow}{D}_\mu \Phi L e_R \right] + \text{h.c.}$$

$$+ \frac{i g}{m_W^2} \left[ \Phi^\dagger T_{2k} \overset{\leftrightarrow}{D}^{\mu} \Phi \right] D^{\nu} W_{\mu\nu} + \frac{i g' c_B}{2m_W^2} \left[ \Phi^\dagger \overset{\leftrightarrow}{D}^\mu \Phi \right] \partial^\nu B_{\mu\nu}$$

$$+ \frac{2ig}{m_W^2} \bar{c}_{HW} \left[ D^{\mu} \Phi^\dagger T_{2k} D^{\nu} \Phi \right] W_{\mu\nu}^k + \frac{ig' c_{HB}}{m_W^2} \left[ D^{\mu} \Phi^\dagger D^{\nu} \Phi \right] B_{\mu\nu}$$

$$+ \frac{g'^2}{m_W^2} \bar{c}_{\gamma} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g^2}{m_W^2} \bar{c}_g \Phi^\dagger \Phi G_{\mu\nu}^a G^{a\mu\nu},$$

where $W_{\mu\nu}^k$, $B_{\mu\nu}$ and $G_{\mu\nu}^a$ are the gauge field strength tensors, and $\Phi$ is the Higgs doublet. Among all the Wilson coefficients in the SILH Lagrangian, $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$ are related to the anomalous Higgs-photon coupling through a direct $HZ\gamma$ or $H\gamma\gamma$ vertex. With the presence of these BSM vertices, additional tree level diagrams, in particular an $s$-channel diagram via a virtual photon or Z boson as the mediator, can contribute to the $pp \rightarrow H+\gamma$ process and lead to a large relative change in its production cross section. Therefore, the $H+\gamma$ process is a sensitive probe to explore the anomalous Higgs-photon coupling [15].

A public implementation of the SILH Lagrangian is available in a general Higgs Effective Lagrangian (HEL) [19, 20]. The HEL model is implemented in FeynRules [21], comprising 39 dimension-six operators and their corresponding Wilson coefficients. Its Universal
FeynRules Output \cite{22} has been interfaced to the MadGraph5_aMC@NLO \cite{23} event generator. In this work, the HEL model is used with all the other Wilson coefficients fixed at 0 except $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$. The $pp \rightarrow H+\gamma$ production cross section is computed at different values of $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$, using MadGraph5_aMC@NLO v2.6.2 with NNPDF2.3 \cite{24} parton distribution functions. We then parametrize the signal cross section as functions of the Wilson coefficients according to the computation. Figure \ref{fig:1} presents a two-dimensional parametrization of the signal cross section parametrized as functions of every two of the three Wilson coefficients with the third coefficient fixed at 0. Monte Carlo event samples are also generated with the same configurations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Two-dimensional parametrization of the signal cross section of the $H+\gamma$ process with different values of $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$. Besides the two parameters indicated in each plot, the third parameter is fixed at 0.}
\end{figure}

\section{Analysis Strategy}

The ATLAS $H+\gamma$ resonance search \cite{16} is carried out to search for heavy resonances decaying to a SM Higgs boson and a photon, using the $b\bar{b}$ decay of the Higgs boson. In its signal region, both the selected photon and the Higgs boson are highly boosted (with large momenta). The search is performed by looking for a bump on a smooth background of the $H+\gamma$ invariant mass spectrum $m_{H\gamma}$. As reported by the ATLAS paper, the mass spectrum observed is consistent with the background-only hypothesis and no evidence of new resonances is found.

This highly boosted signature is of particular interest for probing the anomalous Higgs-photon coupling, as the BSM signal contribution may show longer tails extending up to TeV scale in the $m_{H\gamma}$ and photon $p_T$ distributions, while the SM expectation drops more
steeply [15]. Instead of performing a bump hunt on the $m_{H\gamma}$ spectrum as in the original ATLAS paper, we perform a counting experiment with the published $m_{H\gamma}$ spectrum to constrain anomalous coupling of the Higgs boson. According to the ATLAS paper [16], 138 events have been observed in signal region $800 \, \text{GeV} < m_{H\gamma} < 3.2 \, \text{TeV}$, consistent with the expected number of background events $138 \pm 12$. We reinterpret the ATLAS data as follows.

The expected number of events in signal region can be expressed as $s + b$, with $s$ and $b$ being the expected number of signal and background events, respectively. To constrain the Wilson coefficients parameters, we construct a likelihood function assuming that the number of observed events $n$ follows a Poisson distribution with an expectation value $s + b$:

$$\mathcal{L} = \text{Pois}(n|s + b) \times \text{Gaus}(b_0|b, \sigma_b).$$

(3)

Here $b$ is treated as a nuisance parameter. It is constrained by a Gaussian term with a mean value $b_0$ and a standard deviation $\sigma_b$. Both $b_0$ and $\sigma_b$ are obtained from the background fit results in the ATLAS $H+\gamma$ paper [16]. The expected number of signal events $s$ depends on the Wilson coefficients $\bar{c}_i$. It can be further expressed as:

$$s = L_{\text{int}} \times \varepsilon \times \sigma(\bar{c}_i) \times Br,$$

(4)

The integrated luminosity $L_{\text{int}}$ of the ATLAS data sample is 36.1 fb$^{-1}$. A Standard Model $H \rightarrow b\bar{b}$ branching ratio $Br = 58\%$ for a 125 GeV Higgs boson [25] is used. The signal efficiency $\varepsilon$ accounts for event loss due to detector effects, reconstruction and selection efficiencies in the ATLAS analysis. It is determined by applying the efficiency table published in the ATLAS $H+\gamma$ paper [16] to the simulated $m_{H\gamma}$ spectra in the signal Monte Carlo samples and evaluate the overall efficiency. The $H+\gamma$ production cross section $\sigma(\bar{c}_i)$ is computed in terms of Wilson coefficients $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$, as described in Section [11]. Wilson coefficients $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$ are treated as the parameters of interest (POIs).

Constraints on the Wilson coefficients are obtained by evaluating the profiled likelihood ratio assuming the asymptotic approximation [26]:

$$\lambda(\bar{c}_i) = \frac{\mathcal{L}(\hat{c}_i, \hat{b})}{\mathcal{L}(\hat{\bar{c}}_i, \hat{b})}.$$  

(5)

Here the numerator is the conditional maximum-likelihood function, with $\hat{b}$ being the value of nuisance parameter $b$ that maximize the likelihood function for a given set of values of the Wilson coefficients $\bar{c}_i$. The denominator is the unconditional maximum-likelihood function with $\hat{\bar{c}}_i$ and $\hat{b}$ being the maximum-likelihood estimates of $\bar{c}_i$ and $b$, respectively.
IV. RESULTS AND DISCUSSIONS

A one-dimensional likelihood scan is performed to obtain constraints on each of the three Wilson coefficients in the EFT framework with the other two fixed at 0. Constraints on $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$ are shown in Figure 2. The 68% and 95% confidence intervals are shown in Table I.

TABLE I. 68% and 95% confidence intervals on the Wilson coefficients $\bar{c}_\gamma$, $\bar{c}_{HW}$ and $\bar{c}_{HB}$ in the EFT framework.

| Parameter | 68% C.L.   | 95% C.L.   |
|-----------|------------|------------|
| $\bar{c}_\gamma$ | [-0.061, 0.064] | [-0.087, 0.090] |
| $\bar{c}_{HW}$ | [-0.167, 0.161] | [-0.236, 0.231] |
| $\bar{c}_{HB}$ | [-0.162, 0.167] | [-0.230, 0.236] |

Two-dimensional likelihood scans are also performed and the confidence regions are shown in Figure 3. Besides the two Wilson coefficients indicated in the plot, the remaining one is fixed at 0 during the scan.

We compare the $H+\gamma$ channel results with those obtained in the combined $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels based on the same $pp$ collision dataset collected by the ATLAS

![FIG. 2. One-dimensional likelihood scan of the Wilson coefficients $\bar{c}_\gamma$ (left), $\bar{c}_{HW}$ (middle) and $\bar{c}_{HB}$ (right) in the EFT framework with all the other coefficients fixed at 0. The 95% (68%) confidence interval is indicated by the red (green) line. Constraints are obtained from data in mass range of 800 GeV < $m_{H\gamma}$ < 3.2 TeV.](image)
experiment. The 68% C.L. intervals from the combined channels are:

\[
\bar{c}_c \in [-1.5 \times 10^{-4}, \ 2.2 \times 10^{-4}], \\
\bar{c}_{HW} \in [-0.080, \ -0.024], \\
\bar{c}_{HB} \in [-0.051, \ 0.103].
\]

The limits on \( \bar{c}_c \) is much stringent, but the limits on \( \bar{c}_{HW} \) and \( \bar{c}_{HB} \) are in the same order of magnitude compared to the \( H+\gamma \) channel results. These results demonstrate excellent sensitivity of the \( H+\gamma \) production process to some of the Wilson coefficients in the EFT framework. Combination of the \( H+\gamma \) channel with other channels will further improve the sensitivity on the Higgs boson anomalous couplings.

Limits can be further improved by considering shape information from differential distributions instead of doing a simple counting experiment. In the \( H \to \gamma \gamma \) channel, the 95% C.L. observed limit of \( \bar{c}_{HW} \) has been improved to \(-0.057 < \bar{c}_{HW} < 0.051\) after including differential distributions, which is four times better than the limit achieved from the \( H+\gamma \) channel in our study. In the \( H+\gamma \) channel, improvements to the sensitivity are also anticipated by including additional information from the \( m_{H\gamma} \) and photon \( p_T \) distributions, but we consider a shape analysis beyond the scope of this paper.

![Contour plots](image)

**FIG. 3.** Two-dimensional likelihood scan of the Wilson coefficients in the EFT framework. Besides the two parameters indicated in each plot, the third parameter is fixed at 0. The 95% (68%) confidence region is indicated by the red (green) contour. Constraints are obtained from data in mass range of \( 800 \text{ GeV} < m_{H\gamma} < 3.2 \text{ TeV} \). The SM expectation at \( (0, 0) \) is also shown.
V. CONCLUSIONS

We present an interpretation of the recent ATLAS $H+\gamma$ resonance search results with 36.1 fb$^{-1}$ $pp$ collision data at $\sqrt{s} = 13$ TeV on the search for Higgs boson anomalous coupling in the $H+\gamma$ final state. We provide constraints on Wilson coefficients of dimension-six EFT operators for the first time in $H+\gamma$ final state with $pp$ collision data. These results demonstrate excellent physics potential of the $H+\gamma$ production process. With differential cross sections measured for the $H+\gamma$ process in the future, the constraints can be further improved.

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