

Prospects for measuring electroweak production of $Z\gamma\gamma$ and two jets at the LHC

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Vector boson scattering (VBS) serves as a powerful channel for probing the Standard Model (SM), particularly the electroweak symmetry breaking mechanism. Currently, studies of VBS mainly focus on $2 \rightarrow 2$ scattering. In this study, we investigate the $2 \rightarrow 3$ VBS process of $pp \rightarrow Z\gamma\gamma + 2 \text{ jets}$ through Monte Carlo simulations, including signal generation and background analysis. The signal significance is evaluated across different phase-space regions. With an integrated luminosity of 500 fb^{-1} , the signal significance can reach about 4.5σ . Furthermore, the analysis is extended to a beyond the SM scenario involving Higgs boson decays into a Z boson and an axionlike particle, providing projected exclusion limits on the relevant coupling parameters. These results suggest that, given the ongoing release of the LHC Run 3 dataset, there will be promising opportunities to explore and potentially discover a series of $2 \rightarrow 3$ VBS processes, starting with the $Z\gamma\gamma$ channel.

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I. INTRODUCTION

Following the observation of the Higgs boson at the Large Hadron Collider (LHC) in 2012 [1,2], ATLAS [3] and CMS [4] collaborations have conducted both precision measurements of Higgs boson properties and detailed studies of electroweak (EWK) interactions [5,6]. Crucially, vector boson scattering (VBS) stands out among these as a key channel for probing EWK interactions [7]. These processes involve multiple self-coupling vertices among the EWK bosons W , Z , and γ , thus offering direct sensitivity to the electroweak symmetry breaking mechanism [8].

Currently, studies of VBS processes mainly focus on $2 \rightarrow 2$ scattering, with outgoing vector bosons types including WW [9,10], ZZ [11,12], WZ [9,13], $W\gamma$ [14], and $Z\gamma$ [15,16]. These analyses are largely based on data from LHC Run 2, with a total integrated luminosity of about 140 fb^{-1} and a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$. In recent years, the LHC has been conducting Run 3 data-taking at $\sqrt{s} = 13.6 \text{ TeV}$, and the combined luminosity of both Run 2 and Run 3 is expected to exceed 400 fb^{-1} [17]. With this large dataset, it will be possible not only to improve the precision of previous measurements but also to strongly

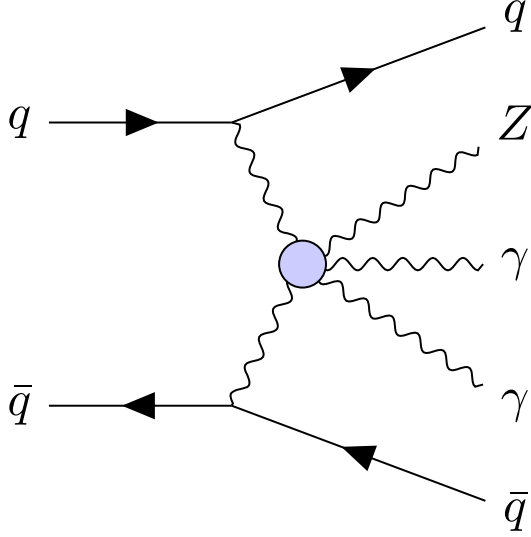
support the search, discovery, and cross section measurement of $2 \rightarrow 3$ VBS processes.

Though no officially released results for $2 \rightarrow 3$ VBS processes have been reported, studies on the production of triple vector bosons via vector boson fusion (VBF) are relatively common. Examples include final states with only weak bosons, such as WWW [18], WWZ [19,20], WZZ [19], and ZZZ [19], as well as processes involving photons like $WW\gamma$ [21,22], $WZ\gamma$ [21,23], $W\gamma\gamma$ [24,25], and $Z\gamma\gamma$ [25,26]. Although the phase-space regions examined in these analyses differ considerably from those typical of VBS processes, their well-developed methodologies offer valuable insights for future VBS studies. In summary, newly available data, together with established analysis techniques from diboson VBS and triboson VBF studies, provide a solid foundation for the next stage of $2 \rightarrow 3$ VBS research.

While several $2 \rightarrow 3$ VBS processes are accessible at the LHC, we dedicate this study specifically to the $Z\gamma\gamma$ channel due to several compelling reasons. The presence of two photons ensures competitive signal yields, and the $\ell^+\ell^-\gamma\gamma$ final state provides a remarkably clean signature with fully reconstructible kinematics, avoiding the complexities associated with large missing transverse energy. From a phenomenological perspective, a dedicated study of $Z\gamma\gamma$ is also more reliable than channels such as $W\gamma\gamma$. The latter is heavily impacted by “fake lepton” backgrounds (primarily from e/γ misidentification), which depend on specific detector conditions and algorithms, and are difficult to model accurately without data-driven methods. Consequently, the $Z\gamma\gamma$ channel serves as an ideal and robust candidate for a simulation-based evaluation

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FIG. 1. Feynman diagram of VBS $Z\gamma\gamma$ production.

The example Feynman diagram of VBS $Z\gamma\gamma$ is shown in Fig. 1. It naturally mixes and interferes with other QCD-induced and EWK $pp \rightarrow Z\gamma\gamma + 2 \text{ jets}$ diagrams, which is a common challenge in VBS analyses. Following previous studies, we define the signal as the full EWK component of $pp \rightarrow Z\gamma\gamma + 2 \text{ jets}$, while we focus primarily on the VBS-enriched phase-space region [7]. The QCD-induced processes are treated as a major background, and the interference between EWK and QCD contributions is examined in Sec. II C. For simplicity, only events with $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) are considered.

This paper is structured as follows. After this introduction, Sec. II details the signal definition, classifies relevant backgrounds, and describes the Monte Carlo (MC) simulation setup. Section III presents the event selection, then gives the comparison of the distributions among signal and background. Section IV shows the final signal and background event yields in different regions, together with the estimated signal significance. To further explore the phenomenological potential of this channel, Sec. V introduces a new physics study. A summary of the study is provided in Sec. VI.

II. PROCESS CLASSIFICATION AND SIMULATION

A. Process classification

As introduced in Sec. I, the signal under study is the EWK-induced process $pp \rightarrow Z\gamma\gamma + 2 \text{ jets}$, with $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$). In the following study, we further categorize the signal process into two scenarios: the first is the EWK $Z\gamma\gamma + 2 \text{ jets}$ process, where an on-shell Z boson subsequently decays to a lepton pair, while the second is referred to as the inclusive process, namely the EWK production of $\ell^+\ell^-\gamma\gamma + 2 \text{ jets}$. Typical VBS kinematics

are characterized by two jets with a large rapidity gap, $|\Delta\eta_{jj}|$, and large invariant mass, m_{jj} , which can be used to suppress both backgrounds and non-VBS electroweak contributions.

In typical real-world experiments, the backgrounds for VBS processes associated with W, Z, and γ primarily include the following categories [14,15]:

- (i) QCD-induced processes.
- (ii) Fake photon backgrounds.
- (iii) Fake lepton backgrounds.

In our study, the QCD-induced background refers specifically to the $Z\gamma\gamma + n \text{ jets}$ process produced via QCD interactions. Additionally, the fake photon or lepton backgrounds, referring to cases where these objects do not originate from hard scattering but result from soft processes or misidentification, must also be carefully evaluated. In processes involving γ and W bosons, both fake photons and fake leptons typically contribute significantly. In contrast, for processes with only γ and Z bosons, the dominant background comes from fake photons. These primarily arise from jet-photon misidentification, which occurs when a high-momentum π^0 decays into a photon pair and the resulting jet is reconstructed as a photon. In experimental analysis, such backgrounds are commonly estimated using data-driven methods [25]. However, in our simulation-based study, the absence of real data prevents the use of this approach. Instead, we evaluate the fake photon contribution through direct MC simulation using $Z\gamma + n \text{ jets}$ events. Specifically, energetic photons naturally generated during the parton showering and hadronization of the simulated jets are passed through the detector simulation. Those that satisfy the default photon identification criteria and survive our subsequent signal selections are directly retained as fake photons. The $Z + n \text{ jet}$ process is preliminarily neglected, as the probability of double misidentification is substantially lower than that of single misidentification. Other minor backgrounds, including $t\bar{t}\gamma$ and $tW\gamma$, are also estimated through this direct simulation approach. Though these processes yield at least one fake photon, they are not covered by the $Z\gamma$ simulation.

B. Event simulation

The production cross sections and MC event samples for both signal and background processes are generated using MadGraph5_aMC@NLO (MG5) v3.6.3 [27] at leading order (LO). The MG5 simulation is performed at $\sqrt{s} = 13.6 \text{ TeV}$ with generator-level cuts, requiring $p_T^\ell > 10 \text{ GeV}$, $p_T^\gamma > 15 \text{ GeV}$, $p_T^j > 20 \text{ GeV}$, $|\eta^{\ell,\gamma}| < 2.5$, $|\eta^j| < 5$, $\Delta R > 0.4$, and $m_{\ell^+\ell^-} > 50 \text{ GeV}$. Then parton showering and hadronization are carried out using PYTHIA8 (PY8) [28] with its default models. The detector response is then simulated using DELPHES v3.5 [29], employing the built-in CMS detector card [30]. Specially for QCD $Z\gamma$ and QCD $Z\gamma\gamma$, we consider events with up to two jets and merge them

TABLE I. Summary of the signal and background processes investigated in this study.

Category	Simulated syntax
Signal	$p p > z a a j j \text{ QCD}=0, z > l+ l-$
Signal (inclusive)	$p p > l+ l- a a j j \text{ QCD}=0$
QCD $Z\gamma\gamma$	$p p > l+ l- a a$ $p p > l+ l- a a j$ $p p > l+ l- a a j j$
QCD $Z\gamma$	$p p > l+ l- a$ $p p > l+ l- a j$ $p p > l+ l- a j j$
EWK $Z\gamma$	$p p > l+ l- a j j \text{ QCD}=0$
$t\bar{t}\gamma$	$p p > t \bar{t} a, (t > w+ b, w+ > l+ \nu l), (t \sim w- b \sim, w- > l- \nu l \sim)$
$tW\gamma$	$p p > t \bar{t} w+ a, w+ > l+ \nu l, (t \sim w- b \sim, w- > l- \nu l \sim)$ $p p > t w- a, w- > l- \nu l \sim, (t > w+ b, w+ > l+ \nu l)$

TABLE II. Comparison of the cross sections among the signal, QCD, and interference (fb).

Signal	Signal (inclusive)	QCD $Z\gamma\gamma$	Interference
2.63×10^{-1}	4.26×10^{-1}	2.30×10^1	2.44×10^{-2}

using the MLM [31] scheme, with the merging scale parameter cut set to 45 GeV, while all other relevant parameters are kept as default. Table I gives a summary of the processes and their simulated syntax in MG5 investigated in this study.

C. Interference study

The interference term between the signal and QCD $Z\gamma\gamma$ can be evaluated by simulating through MG5 and requiring $\text{QCD}^2=2$. Table II shows the cross section comparison among the signal, QCD, and interference. The interference contribution of $Z\gamma\gamma + 2$ jets is more than an order of magnitude lower than the EWK signal, so it can be safely neglected in this study.

III. SIGNAL SELECTION AND DISTRIBUTION

For events that have undergone DELPHES simulation, the signal selection and background suppression procedures are applied sequentially. A signal candidate should contain at least two good photons, one pair of opposite-sign same-flavor good leptons, and two good jets. The definitions of good particles are $p_T^\ell > 15$ GeV, $p_T^\nu > 20$ GeV, $p_T^j > 25$ GeV, $|\eta^{\ell,\nu}| < 2.5$, and $|\eta^j| < 5$. These criteria can effectively suppress soft photons and leptons produced during hadronization.

It is worth noting that since the photons can also be generated during PY8 simulation, there might be double counting effects between the processes QCD $Z\gamma$ and QCD $Z\gamma\gamma$, similarly EWK $Z\gamma$ and the signal. By tracking the

parent particles of the reconstructed-level photons, they can be categorized into two types: those originating from quarks or bosons, referred to as hard photons, and those originating from leptons or hadrons, known as soft photons. For the $Z\gamma\gamma$ processes, ignoring the loss in detection efficiency, it should contain two hard photons. Therefore, we require that those $Z\gamma$ events must not contain two or more hard photons, thereby avoiding overlap with the $Z\gamma\gamma$ events.

For events that pass the initial selection, the signal jets and photons are defined as the top two jets or photons with the highest p_T . Meanwhile, the signal leptons pair is the one with the closest $M_{\ell^+\ell^-}$ to M_Z (91.2 GeV). Then distributions of some variables are shown in Figs. 2 and 3. All histograms, except for Fig. 2(a), employ capping at the end points to retain outliers, Fig. 2(a), in contrast, excludes events outside the plotted range. The per-event weight is calculated by $w_i = \sigma_i/N_i$, where σ_i and N_i are the cross section and the number of simulated events of the corresponding process, respectively. Due to the low cross section of the signal processes, they are scaled 5 or 30 times in the plots for better illustrating the shapes.

It shows that the most significant background contribution comes from QCD $Z\gamma$, while the QCD $Z\gamma\gamma$ background is also non-negligible. These backgrounds can be efficiently removed by applying a lower cut on M_{jj} . Furthermore, additional variables including $M_{\ell^+\ell^-}$, $|\Delta\eta_{jj}|$, and $M_{\ell^+\ell^- \gamma\gamma}$ may also be applied for background suppression.

IV. EVENT YIELD AND SIGNIFICANCE STUDY

Applying $M_{\ell^+\ell^- \gamma\gamma} > 100$ GeV and $70 \text{ GeV} < M_{\ell^+\ell^-} < 120$ GeV sequentially to events that pass the preliminary signal selection, the relative efficiency (ϵ_{rel} , defined as the fraction of events surviving a specific cut with respect to the preceding step) and remaining cross section (σ) for each step are shown in Table III.

The background can be suppressed substantially by applying additional cuts on M_{jj} and $|\Delta\eta_{jj}|$. Given the

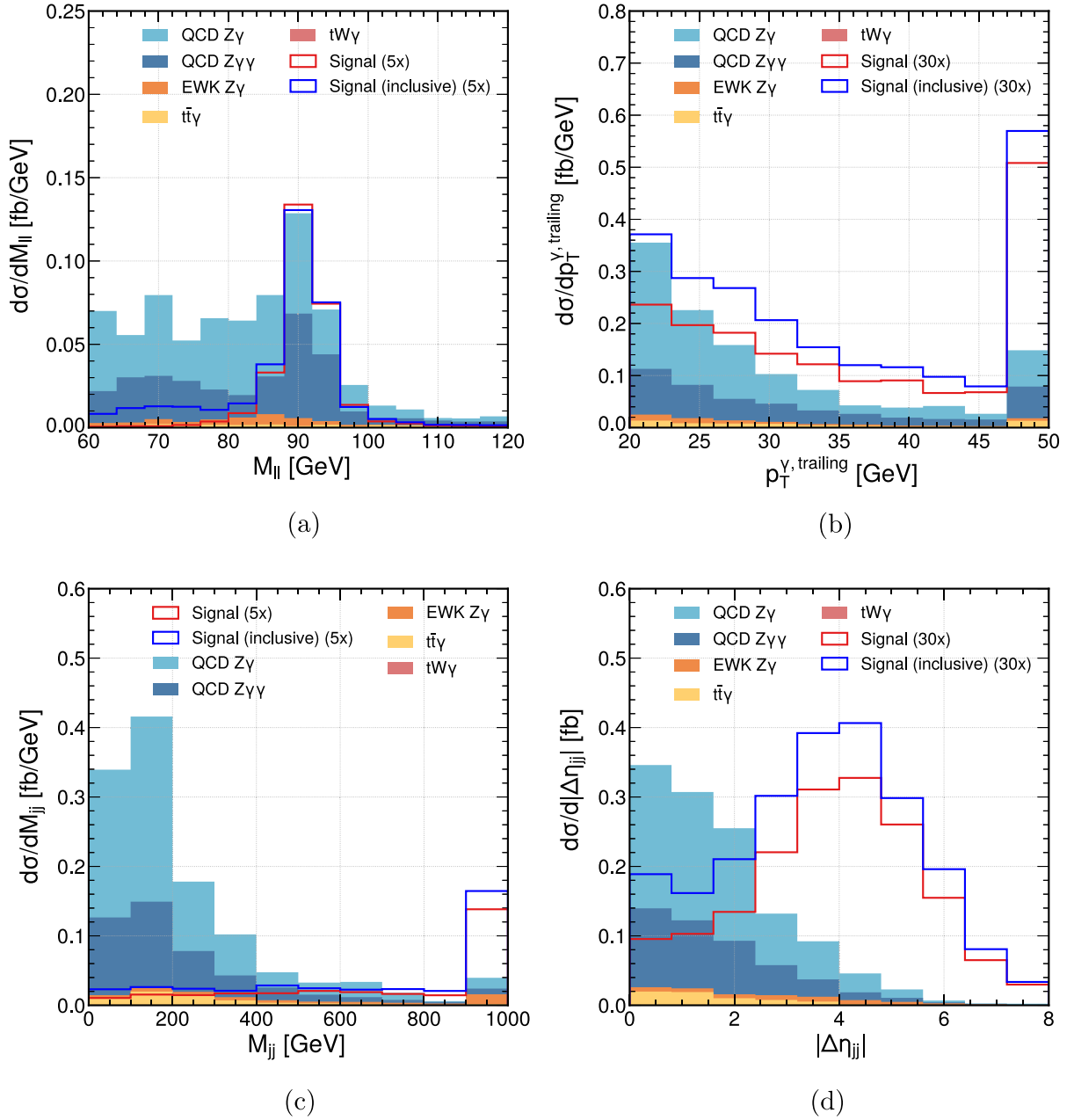


FIG. 2. Distributions of signal and background after initial signal selection. (a) $M_{\ell^+\ell^-}$, (b) $p_T^{\gamma, trailing}$, (c) M_{jj} , and (d) $|\Delta\eta_{jj}|$.

correlation between them, a two-dimensional parameter scan is adopted to determine the optimal selection criteria, with the lower cut of M_{jj} varying from 200 to 800 GeV in steps of 100 GeV and $|\Delta\eta_{jj}|$ from 0 to 4.0 in steps of 0.5. The signal significance for each $(M_{jj}^{lower}, |\Delta\eta_{jj}|^{lower})$ combination, derived from the corresponding signal and background yields, is calculated by

$$Z = \sqrt{2 \left[(s+b) \ln \left(1 + \frac{s}{b} \right) - s \right]}, \quad (1)$$

where s and b are the signal and the total background yield, respectively. Specially, the signal yield is from the “Signal (inclusive)” process.

The result with $L = 500 \text{ fb}^{-1}$ is given in Fig. 4. It shows a peak significance of 4.51σ at (700 GeV, 2.5). Due to the limited statistics of the simulation, the statistical uncertainties of s and b must be considered. These are calculated from the number or proportion of the remaining events, where the signal yield follows a binomial distribution, and the background processes can be further approximated by a Poisson distribution. The statistical uncertainties of the regions among the peak significance are approximately

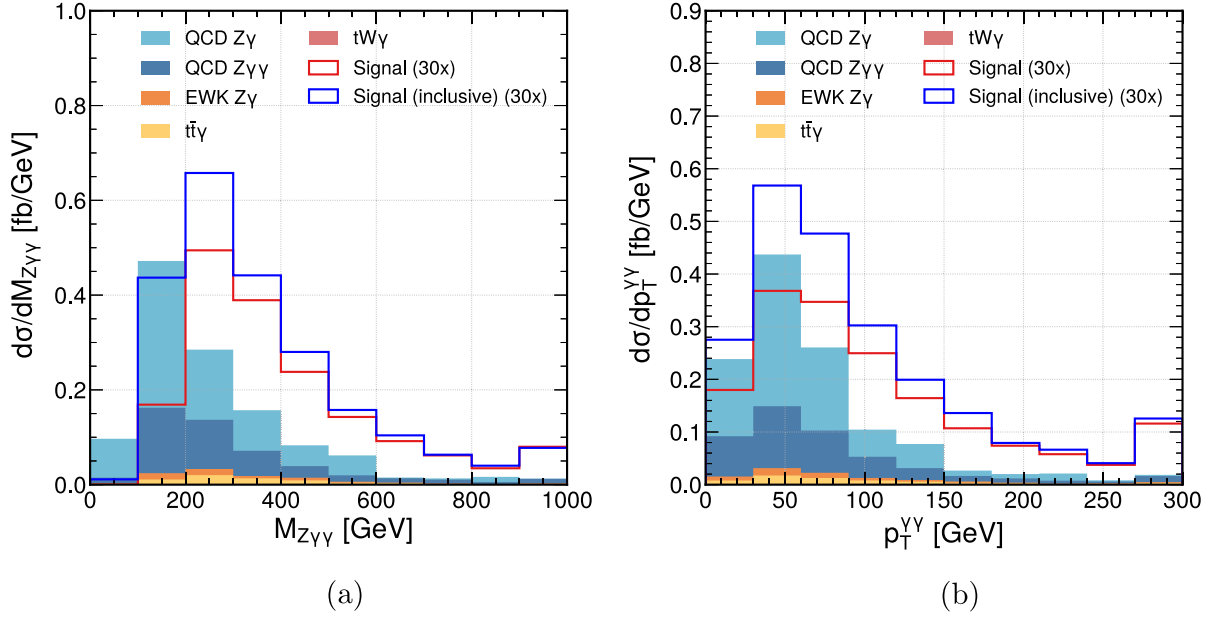


FIG. 3. Distributions of signal and background after initial signal selection. (a) $M_{\ell^+\ell^-\gamma\gamma}$ and (b) $p_T^{\gamma\gamma}$.

around 0.2. Therefore, the variations between points are mostly within 1 standard deviation, when M_{jj}^{lower} is set greater than 700 and $|\Delta\eta_{jj}|^{\text{lower}}$ is within the range of 2.0–3.0. While a definitive choice would require higher statistics, we select (700 GeV, 2.0) as the final cut in a conservative manner. Table IV shows the event yields of each signal and background process after the full selections. The final significance is $4.50 \pm 0.17\sigma$ at $L = 500 \text{ fb}^{-1}$. For the High-Luminosity LHC [32] with $L = 3000 \text{ fb}^{-1}$, the significance can exceed 10σ .

V. IMPLICATIONS FOR NEW PHYSICS

Having established the framework for measuring the Standard Model (SM) VBS $Z\gamma\gamma$ process, we now extend our analysis to the search for new physics. The clean signature of the $\ell^+\ell^-\gamma\gamma + 2 \text{ jets}$ final state,

combined with the distinctive forward-backward jet characteristics, makes this channel an excellent probe for exotic phenomena produced via VBF.

A. Axionlike particles model

Axionlike particles (ALPs) provide a well-motivated explanation for this channel. As pseudo-Nambu-Goldstone bosons appearing in various SM extensions, ALPs can couple to the Higgs and electroweak gauge bosons [33,34]. We specifically focus on the Higgs decay, where the Higgs is generated via VBF production and then undergoes an exotic decay into a Z boson and a light ALP ($H \rightarrow Za$), with the ALP subsequently decaying into a photon pair ($a \rightarrow \gamma\gamma$).

While this Higgs decay process has been explored in previous experiments, those studies primarily focused on the gluon fusion production mode (ggH) [35]. We contend

TABLE III. Summary of the relative efficiency ($\epsilon_{\text{rel.}}$) and remaining cross section (σ) after each selection or cut.

Category	Initial selection		$M_{\ell^+\ell^-\gamma\gamma}$ cut		$M_{\ell^+\ell^-}$ cut	
	σ (fb)	$\epsilon_{\text{rel.}}$ (%)	σ (fb)	$\epsilon_{\text{rel.}}$ (%)	σ (fb)	$\epsilon_{\text{rel.}}$ (%)
Signal	5.66×10^{-2}	21.56	5.66×10^{-2}	100.00	5.56×10^{-2}	98.25
Signal (inclusive)	7.56×10^{-2}	17.76	7.52×10^{-2}	99.51	6.27×10^{-2}	83.39
QCD $Z\gamma\gamma$	3.76×10^{-1}	1.64	3.64×10^{-1}	96.82	2.18×10^{-1}	59.82
QCD $Z\gamma$	7.29×10^{-1}	0.01	6.47×10^{-1}	88.69	3.04×10^{-1}	47.06
EWK $Z\gamma$	4.54×10^{-2}	0.13	4.31×10^{-2}	95.04	2.61×10^{-2}	60.58
$t\bar{t}\gamma$	6.44×10^{-2}	0.19	6.40×10^{-2}	99.31	1.76×10^{-2}	27.48
$tW\gamma$	4.41×10^{-5}	0.19	4.39×10^{-5}	99.47	7.43×10^{-6}	16.93
Background in total	1.22×10^0	0.01	1.12×10^0	92.01	5.66×10^{-1}	50.62

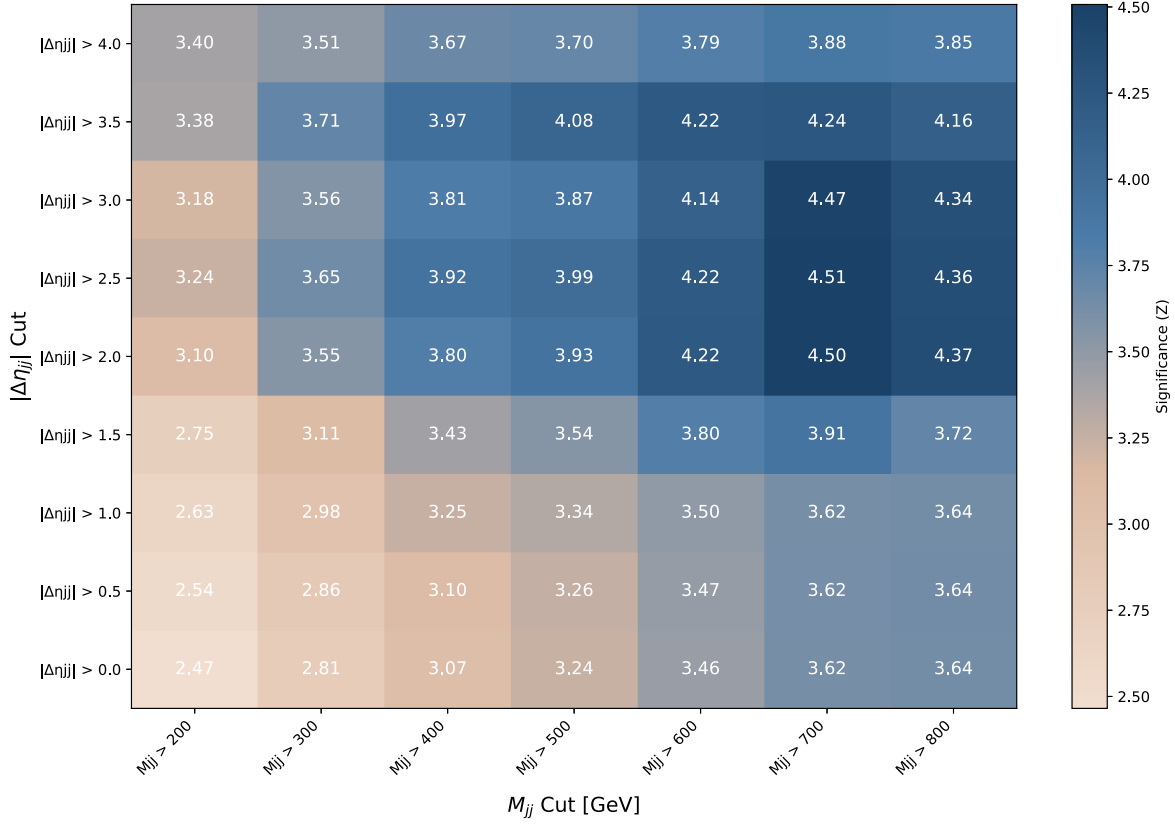


FIG. 4. Significance for each $(M_{jj}^{\text{lower}}, |\Delta\eta_{jj}|^{\text{lower}})$ combination, derived from the corresponding signal and background yields ($L = 500 \text{ fb}^{-1}$).

that if new physics is to be observed in Higgs decays, it may imply fundamental issues within the core of the SM, namely the Higgs mechanism and electroweak gauge theory. Consequently, the VBF channel plays a distinct role from the ggH, potentially offering a clearer signature for new physics. This serves as our primary motivation for investigating this process specifically within the VBF production mode.

Because this Beyond the Standard Model (BSM) process yields the exact same final state as our SM VBS signal, we can directly leverage the background estimation and signal selection strategies developed in the preceding sections. By

doing so, this analysis provides a dual benefit: it not only investigates the nonresonant SM electroweak scattering but also effectively constrains the effective coupling C_{ZH}^{eff} in the resonant Higgs sector.

The decay width of $H \rightarrow Za$ can be phenomenologically expressed as [33]

$$\Gamma(H \rightarrow Za) = \frac{M_H^3}{16\pi} \left(\frac{C_{ZH}^{\text{eff}}}{\Lambda} \right)^2 \lambda^{3/2} \left(\frac{M_Z^2}{M_H^2}, \frac{M_a^2}{M_H^2} \right), \quad (2)$$

where M_H , M_Z , and M_a denote the masses of the Higgs boson, the Z boson, and the ALP, respectively. Here, C_{ZH}^{eff} represents the effective coupling coefficient for the $H - Z - a$ vertex, Λ characterizes the scale of new physics, and the kinematic function λ is defined as $\lambda(x, y) = (1 - x - y)^2 - 4xy$. In the following sensitivity study, we fix $\Lambda = 1 \text{ TeV}$ as a reference scale, following standard practice in BSM sensitivity studies. Limits on C_{ZH}^{eff} are then expressed in units of $\Lambda/1 \text{ TeV}$, which can be rescaled trivially for other choices of Λ .

B. Simulation and background study

The ALP signal is simulated by MG5 using the Universal FeynRules Output (UFO) [36] model. To facilitate the derivation of upper limits, phase-space constraints for final-

TABLE IV. Event yields of each process after the full cut flow ($L = 500 \text{ fb}^{-1}$).

Category	Event yield	Uncertainty (statistical)
Signal	16.28	0.27
Signal (inclusive)	17.55	0.46
QCD $Z\gamma\gamma$	3.32	0.53
QCD $Z\gamma$	1.52	0.54
EWK $Z\gamma$	5.36	0.40
$t\bar{t}\gamma$	0.15	0.10
$tW\gamma$	0.00	0.00
Background in total	10.36	0.86

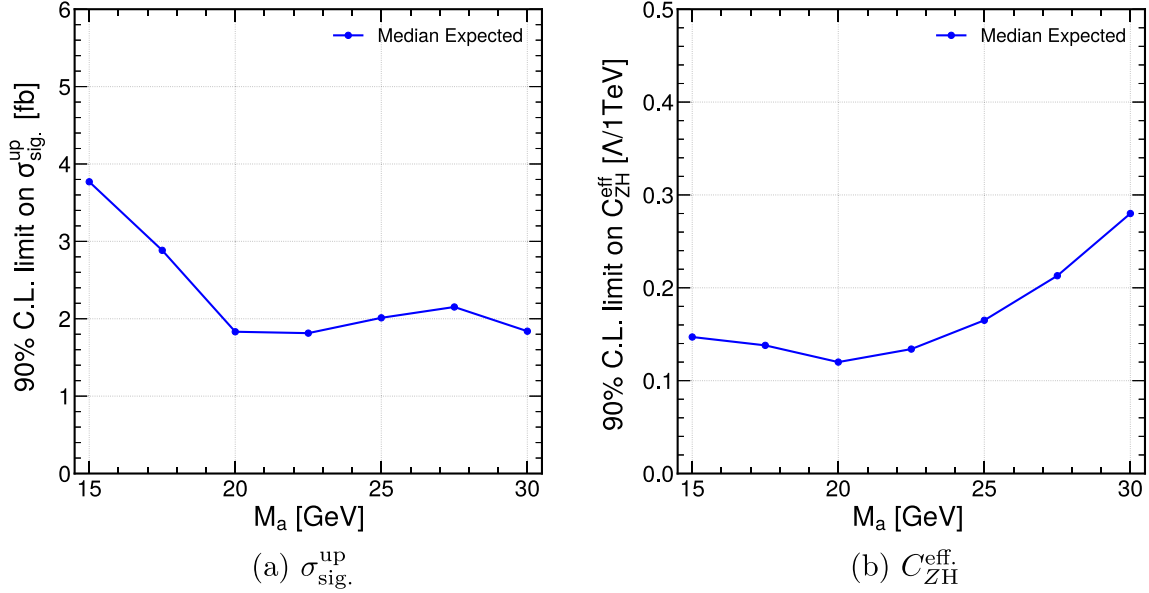


FIG. 5. The 90% CL upper limit of the cross section (a) and coupling coefficient $C_{\text{ZH}}^{\text{eff}}$ (b), with $L = 500 \text{ fb}^{-1}$. In (b), the new physics scale is fixed to $\Lambda = 1 \text{ TeV}$, and the y-axis thus shows the upper limit on $C_{\text{ZH}}^{\text{eff}}$ in units of $\Lambda/1 \text{ TeV}$.

state photons and leptons were disabled at the generator level, while jet-related requirements were maintained consistent with the aforementioned settings.

In this study, the ALP mass is investigated within the range of 15 to 30 GeV. It is important to note that at lower masses (particularly below 10 GeV), the decay photons of the ALP tend to have smaller p_T^γ and $\Delta R_{\gamma\gamma}$. Under such conditions, standard photon identification criteria become inefficient and would necessitate dedicated optimization. To ensure the robustness of our results, we restrict our analysis to $M_a > 15 \text{ GeV}$. While the impact of photon merging in this region is relatively minor, it remains non-negligible, consequently, the projected upper limits presented here are considered conservative.

The subsequent PY8 and DELPHES work flows remain consistent with those described previously. Based on the optimized cut flow, an additional invariant mass requirement, $100 < M_{\ell^+\ell^-\gamma\gamma} < 150 \text{ GeV}$, is applied to select signal events originating from the Higgs boson.

For the ALP signal search, all processes listed in Table I are treated as backgrounds. At the luminosity of $L = 500 \text{ fb}^{-1}$, the total background yield in the signal region is estimated to be 1.16 ± 0.26 . Given the low background yield, the Poisson fluctuations in the real-world experiment would far exceed the statistical error of 0.26 from this MC estimation, therefore, the latter is neglected in the subsequent statistical analysis.

C. Sensitivity on the model parameter

Based on the estimated background yield, the expected upper limit on the signal yield ($N_{\text{sig.}}^{\text{up}}$) is derived at the 90% confidence level (CL). Subsequently, the

model-independent upper limit for the cross section is determined through

$$N_{\text{sig.}}^{\text{up}} = \varepsilon_{\text{sig.}} \cdot L \cdot \sigma_{\text{sig.}}^{\text{up}}, \quad (3)$$

where $\varepsilon_{\text{sig.}}$ represents the ALP signal efficiency, $L = 500 \text{ fb}^{-1}$ is the integrated luminosity, and $\sigma_{\text{sig.}}^{\text{up}}$ denotes the upper limit of the electroweak production cross section for $pp \rightarrow H + 2 \text{ jets} \rightarrow Za + 2 \text{ jets}$, with $Z \rightarrow \ell^+\ell^-$ and $a \rightarrow \gamma\gamma$. Figure 5(a) presents the $\sigma_{\text{sig.}}^{\text{up}}$ results for various ALP masses.

The model-dependent upper limits are calculated as

$$\sigma_{\text{sig.}}^{\text{up}} = \sigma_{\text{ewk}}(pp \rightarrow H + 2 \text{ jets}) \times \text{Br}(H \rightarrow Za) \times \text{Br}(a \rightarrow \gamma\gamma) \times \text{Br}(Z \rightarrow \ell^+\ell^-), \quad (4)$$

where the branching ratio is defined as $\text{Br}(H \rightarrow Za) = \frac{\Gamma(H \rightarrow Za)}{\Gamma(H \rightarrow Za) + \Gamma_H^{\text{SM}}}$, with the SM Higgs width taken as $\Gamma_H^{\text{SM}} = 3.7 \text{ MeV}$ [37]. We assume that $\text{Br}(a \rightarrow \gamma\gamma) = 100\%$, then the cross sections and branching ratios for the SM processes are calculated using MG5. Finally, the projected upper limits on the ALP effective coupling coefficient $C_{\text{ZH}}^{\text{eff}}$ are obtained, as illustrated in Fig. 5(b).

Regarding the upper limits on the $\sigma_{\text{sig.}}^{\text{up}}$, the variations across different $M_a < 20$ are determined solely by $\varepsilon_{\text{sig.}}$. In the low M_a region (i.e., $M_a < 20 \text{ GeV}$), the efficiency is significantly lower due to the excessively small p_T^γ and $\Delta R_{\gamma\gamma}$ from the ALP decay, resulting in poorer cross section limits. Once the M_a is sufficiently high, the photon selection efficiency stabilizes, leading to a plateau in the $\sigma_{\text{sig.}}^{\text{up}}$ upper limits. As for the $C_{\text{ZH}}^{\text{eff}}$ results, in addition to $\varepsilon_{\text{sig.}}$,

they are also suppressed by the kinematic factor $\lambda^{3/2}(M_Z^2/M_H^2, M_a^2/M_H^2)$. The latter effect is more dominant—as M_a increases, the $\Gamma(H \rightarrow Za)$ are gradually suppressed, causing the upper limits to worsen. The combined effect of efficiency and kinematic suppression results in a minimum at $M_a = 20$ GeV, as shown in Fig. 5(b). It should be noted that in real-world experiments, optimizing photon selection criteria would shift this optimal position toward smaller ALP masses.

VI. CONCLUSION

VBS is crucial for testing the SM, especially the EWK symmetry breaking mechanism. The ongoing release of the LHC Run 3 dataset presents opportunities to conduct searches for a series of $2 \rightarrow 3$ VBS processes, with the prospect of breakthroughs.

This study presents an investigation of the EWK $pp \rightarrow Z\gamma\gamma + 2$ jets, $Z \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) process, with particular focus on the VBS-enriched region. Using MG5, PY8, and DELPHES to perform MC simulation and detector fast simulation, we get the distributions of the signal and series of background processes, and thus develop optimized selection criteria to suppress the background. The analysis demonstrates that requirements on $M_{jj} > 700$ GeV and $|\Delta\eta_{jj}| > 2.0$ are crucial for QCD-induced background suppression, yielding a signal significance of $4.50 \pm$

0.17σ with an integrated luminosity of 500 fb^{-1} . The significance is projected to exceed 10σ at the High-Luminosity LHC with 3000 fb^{-1} , highlighting the potential for observation and detailed study of this rare process in future LHC data.

Building on the SM VBS $Z\gamma\gamma$ analysis, this study investigates the VBF production of the Higgs boson decaying into a Z boson and an ALP. This process results in the same $l^+l^-\gamma\gamma jj$ final state as the SM process. Within this framework, the expected sensitivities are evaluated, and projected exclusion limits are derived for the relevant BSM coupling parameters. This additional study illustrates how the VBS $Z\gamma\gamma$ analysis can serve as a sensitive probe of new physics. These findings establish a solid foundation for experimental searches and underscore the viability of $2 \rightarrow 3$ VBS processes.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [38].

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