

Higgs couplings in SMEFT via Zh production at the HL-LHC

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(Received 16 November 2024; accepted 10 June 2025; published 30 June 2025; corrected 5 August 2025)

We study the Higgs couplings involved in the Zh associated production mode at the Large Hadron Collider (LHC) in presence of Higgs-gauge boson coupling modifiers via κ framework and dimension-six Standard Model (SM) effective theory operators. The analysis is performed mainly in the context of the High-Luminosity LHC (with $\sqrt{s} = 14$ TeV and luminosity 3000 fb^{-1}) setup using cut-based as well as machine learning techniques. The analysis shows significant betterment in the signal significance by using the machine learning technique. We also do a χ^2 analysis, which reveals an appreciable change in the sensitivity of the coupling modifiers due to the presence of effective operators, in particular, due to the $qqZh$ Higgs-current interactions. The dipole operators concerning the same vertex combine quarks of different chiralities and do not interfere with the SM diagrams, hence contributing only at $\mathcal{O}(\Lambda^{-4})$. In order to observe better sensitivity for this class of operators, we need to move to higher center-of-mass energy, where the effects of both Higgs-current and dipole four-point interactions are more prominent.

DOI: [10.1103/h3wk-gnfb](https://doi.org/10.1103/h3wk-gnfb)

I. INTRODUCTION

The Higgs boson discovery at the LHC provided the first conclusive portrait of the electroweak symmetry breaking (EWSB) mechanism [1] and mass generation of the Standard Model (SM) particles. Over a decade since the Higgs discovery, we have been able to probe many of its properties, some of which are precise and closely mimic that of a SM-like isodoublet (H), some are not, allowing for new physics (NP) studies via Higgs sector. One standard way of parametrizing the Higgs couplings beyond the SM is to use the κ framework [2], where any deviation from the SM is taken into consideration by variation of the κ parameter, where $\kappa = 1$ depicts the SM. For example, concerning the hZZ coupling, the corresponding $\kappa_Z = \frac{g_{hZZ}}{g_{hZZ}^{\text{SM}}}$. Most of the Higgs studies at the LHC use such parametrization and so do we. However, one needs to be vigilant about the possible sources of NP that generate such contributions and need to be consistent with null

observation of NP searches while scanning the possible values that κ can acquire.¹

Over the last two runs, LHC experiments, ATLAS [3], and CMS [4] have almost pinned down the Higgs couplings to less than 10% uncertainty; however, the high-luminosity (HL) run will prove to be significant for establishing a clearer picture of Higgs characteristics. The Higgs couplings associated with gauge bosons have been studied extensively in the existing literature from various points of view. They include bounds on the anomalous couplings [5–9], Higgs CP properties [10–14], etc. The procedure involves dedicated signal observables as well as in the effective theory (EFT) framework [15–29] in a variety of production and decay channels in context of the current and future colliders.

In this analysis, we study the NP effects in hZZ and qqZ couplings as well as the fully NP induced $qqZh$ coupling in the Zh associated production mode at the HL-LHC frontier. We adhere to the κ framework to depict NP contribution coming to hZZ coupling, whereas the NP contributions to qqZ and $qqZh$ are studied within the realm of the Standard Model effective field theory (SMEFT) [30]. The SMEFT framework is arguably the best motivated scenario for searching NP in a model independent way, either via deviations in the signal pattern or excess in the cross section predicted from the SM, given the absence of a

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¹We will address this issue later in a specific context.

specific hint for NP in current scenarios. We would also like to note here that, while the contributions to $\kappa_Z \neq 1$ may very well appear from the SMEFT operators, there are restrictions like Z mass corrections that may constrain such contributions. Therefore, parametrizing the hZZ coupling via κ_Z makes us explore possibilities even beyond SMEFT. In short, by using both the κ framework and SMEFT, we are basically taking the leading contributions to the relevant couplings that affect the chosen process.

Out of the different channels of Higgs production, the $Vh(V = W, Z)$ production cross section turns out to be more sensitive to the variation of effective operators concerned in the modification of the aforementioned couplings. In this analysis, we study the Zh channel. There have been a number of analyses concerning the Wh/Zh production modes [16–22]. However, the effect of dipole contact operators in context of the $qqZ/qqZh$ couplings has been neglected. The effect of dipole operators has been studied in [31], but concerning the Wh mode only. We show that the presence of both Higgs current and dipole contact operators appreciably alter the existing bounds on the concerned couplings at the present and projected LHC sensitivities.

The organization of the paper is as follows: we discuss SMEFT operators relevant for our analysis and their sensitivities in Sec. II, constraints on the coupling modifiers as well as SMEFT coefficients from current data in Sec. III, detailed collider analysis in Sec. IV, and concluding remarks in Sec. V.

II. EFT FRAMEWORK

The couplings of our interest for this study are the $qqZ/qqZh$ and hZZ vertices that appear in both vector boson fusion (VBF) as well as Zh production modes of the Higgs boson. The set of interaction terms involves those connecting to the gauge fields and field strength tensor (or the dual of it), along with the Higgs field and quark bilinear with all possible Lorentz structure, adhering to $U(1)_{\text{EM}}$ gauge symmetry after EWSB, as furnished below,

$$\mathcal{L}_{\text{SM}} = g_{uL}^{\text{SM}} Z_\mu \bar{u}_L \gamma^\mu u_L + g_{uR}^{\text{SM}} Z_\mu \bar{u}_R \gamma^\mu u_R + g_{dL}^{\text{SM}} Z_\mu \bar{d}_L \gamma^\mu d_L + g_{dR}^{\text{SM}} Z_\mu \bar{d}_R \gamma^\mu d_R; \quad (2.1)$$

$$\mathcal{L}_\kappa = \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu h; \quad (2.2)$$

$$\begin{aligned} \mathcal{L}_{\text{NP}} = & g_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu} + g_{Z\tilde{Z}} \frac{h}{v} Z^{\mu\nu} \tilde{Z}_{\mu\nu} + g_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + g_{\tilde{Z}\gamma} \frac{h}{v} A^{\mu\nu} \tilde{Z}_{\mu\nu} + g_u^L Z_\mu \bar{u}_L \gamma^\mu u_L + g_u^R Z_\mu \bar{u}_R \gamma^\mu u_R + g_d^L Z_\mu \bar{d}_L \gamma^\mu d_L \\ & + g_d^R Z_\mu \bar{d}_R \gamma^\mu d_R + \delta_u^L \frac{h}{v} Z_\mu \bar{u}_L \gamma^\mu u_L + \delta_u^R \frac{h}{v} Z_\mu \bar{u}_R \gamma^\mu u_R + \delta_d^L \frac{h}{v} Z_\mu \bar{d}_L \gamma^\mu d_L + \delta_d^R \frac{h}{v} Z_\mu \bar{d}_R \gamma^\mu d_R \\ & + g_u \frac{1}{v} (\bar{u}_L \sigma^{\mu\nu} u_R + \bar{u}_R \sigma^{\mu\nu} u_L) Z_{\mu\nu} + g_d \frac{1}{v} (\bar{d}_L \sigma^{\mu\nu} d_R + \bar{d}_R \sigma^{\mu\nu} d_L) Z_{\mu\nu} \\ & + \delta_u \frac{h}{v^2} (\bar{u}_L \sigma^{\mu\nu} u_R + \bar{u}_R \sigma^{\mu\nu} u_L) Z_{\mu\nu} + \delta_d \frac{h}{v^2} (\bar{d}_L \sigma^{\mu\nu} d_R + \bar{d}_R \sigma^{\mu\nu} d_L) Z_{\mu\nu}. \end{aligned} \quad (2.3)$$

Note here that in writing Eqs. (2.1)–(2.3), we have adhered to $H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$ after EWSB. Here, κ_Z is the SM hZZ coupling modifier. The advantage of κ framework in addition to heavy integrable NP scenarios, is that it enables us to consider undetected light degrees of freedom without explicitly introducing a NP scale. In the above equations, the notations have their usual meanings, particularly note $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$ and $\tilde{Z}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} Z^{\alpha\beta}$, where Z_μ denotes the physical Z boson, $\epsilon_{\mu\nu\alpha\beta}$ is a completely antisymmetric tensor, and $\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$.

In absence of a direct observational evidence of NP signal at current experiments, one of the best possible ways to gauge the effects of NP is through higher-dimensional effective operators constructed out of the SM fields respecting the SM gauge symmetry. They are popularly referred as SMEFT operators. Note here that SMEFT operators also include the Higgs field as isodoublet under the SM gauge group, while there are efforts to keep it beyond, for example, in HEFT [32]; however, given the

Higgs properties closely mimicking that of a SM doublet, we choose the SMEFT framework to explore the limit of NP.² These operators are suppressed by an appropriate power of a heavy NP mass scale (Λ) integrated out, depending on the mass scale of the operator. Understandably, the effects of such operators diminish with higher mass dimension of the operators, hence we will constrict ourselves to the lowest dimension operators that contribute to the Zh associated production, which appears in dimension six³; operators of dimension eight [39,40] may also contribute, but we have not considered them in our analysis. We will provide a detailed matching of Eq. (2.3) with the standard SMEFT framework in the Warsaw basis [41] later.

²Operators with two Higgs doublets [33,34] or a right-handed neutrino [35–38] have also been found out.

³It is well known that the only SMEFT operator in dimension five is the Weinberg operator $\bar{N}N^c$; $N = H^\dagger \epsilon \ell$, which generates Majorana neutrino mass.

TABLE I. Dimension-six SMEFT operators: hZZ vertex modifiers and $qqZ/qqZh$ contact vertices (Higgs-current and dipole types), relevant to Vh associated production at the LHC. Here, p and r are quark family indices. For complex operators, the presence of respective Hermitian conjugates is assumed. For relevance, $D_\mu = \partial_\mu + ig\frac{\tau^i}{2}W_\mu^i + ig'\frac{1}{2}B_\mu$, $W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon^{ijk}W_\mu^j W_\nu^k$, $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$, $H^\dagger i\overleftrightarrow{D}_\mu H = iH^\dagger D_\mu H - i(D_\mu H)^\dagger H$, $H^\dagger i\overleftrightarrow{D}_\mu H = iH^\dagger \tau^i D_\mu H - i(D_\mu H)^\dagger \tau^i H$, $\tilde{V}_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$ ($V = W^i, B$).

CP -even hZZ vertex modifiers
$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HDD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H)$
$\mathcal{O}_{HW} = (H^\dagger H)W_{\mu\nu}^i W^{i\mu\nu}$
$\mathcal{O}_{HB} = (H^\dagger H)B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HWB} = (H^\dagger \tau^i H)W_{\mu\nu}^i B^{\mu\nu}$
CP -odd hZZ vertex modifiers
$\mathcal{O}_{H\tilde{W}} = (H^\dagger H)\tilde{W}_{\mu\nu}^i W^{i\mu\nu}$
$\mathcal{O}_{H\tilde{B}} = (H^\dagger H)\tilde{B}_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H\tilde{W}B} = (H^\dagger \tau^i H)\tilde{W}_{\mu\nu}^i B^{\mu\nu}$
Higgs-current operators
$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$\mathcal{O}_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \tau^i \gamma^\mu q_r)$
$\mathcal{O}_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
$\mathcal{O}_{Hd} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Dipole operators
$\mathcal{O}_{uW} = (\bar{q}_p \sigma^{\mu\nu} u_r) \tau^i \tilde{H} W_{\mu\nu}^i$
$\mathcal{O}_{uB} = (\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{H} B_{\mu\nu}$
$\mathcal{O}_{dW} = (\bar{q}_p \sigma^{\mu\nu} d_r) \tau^i \tilde{H} W_{\mu\nu}^i$
$\mathcal{O}_{dB} = (\bar{q}_p \sigma^{\mu\nu} d_r) \tilde{H} B_{\mu\nu}$

A. SMEFT operators relevant to Zh production

The SMEFT Lagrangian can be written as

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{i, (n>4)} \frac{c_i}{\Lambda^{(n-4)}} \mathcal{O}_i^{(n)}. \quad (2.4)$$

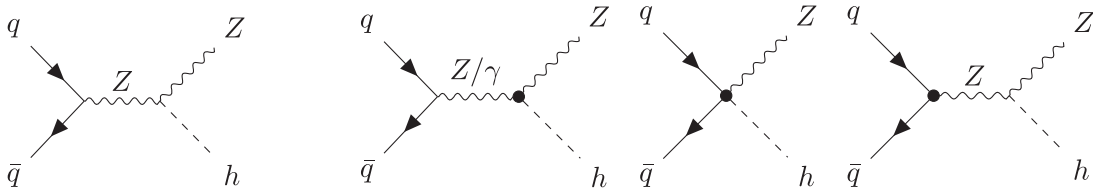


FIG. 1. SM and EFT contributions to the Zh associated production mode at the LHC. Dotted vertices refer to the presence of EFT operators.

Here, $\mathcal{O}_i^{(n)}$ represents operators of dimension n and c_i represents dimensionless couplings or Wilson's coefficients. Throughout this analysis, the effective scale is taken as $\Lambda = 1$ TeV, while the resulting bound or the sensitivity is obtained for the corresponding Wilson coefficient c_i . However, it is simple to understand that the limit on c_i can be rescaled easily for different choices of Λ , following $\frac{c_i}{\Lambda^2} = \frac{c'_i}{\Lambda'^2}$. Although the validity of effective limit depends on the choice of Λ , strictly speaking, the center-of-mass (c.m.) energy of the reaction should abide by $\sqrt{s} < \Lambda$. At the hadron collider, it is difficult to ensure such a condition; we elaborate upon the possibility later.

There is no unique basis for the choice of these operators and all the different bases are equivalent. We choose the Warsaw basis for our representation. The SMEFT operators relevant to Zh associated production mode are tabulated in Table I and the corresponding Feynman diagrams are shown in Fig. 1. The vertices with a blob represent effective operator contribution, which modifies hZZ and qqZ vertices and additional contributions are obtained via γZh and $qqZh$ vertices.

Before moving forward, it should be noted that operators are classified majorly into two categories, those generated at loop level (LG operators) or potential tree generated (PTG operators) for NP, those which are weakly coupled and decoupling [42]. The LG operators are suppressed additionally by a factor of $(4\pi)^2$ coming from the loops; hence, their contributions are expected to be suppressed in comparison to the PTG operators if the underlying NP scale is the same. However, this additional suppression factor for the LG operators is not intrinsically incorporated in most SMEFT studies and in order to maintain uniformity of the nomenclature, we will, however, use the operator classification as in [41].

A few observations related to the operators as mentioned in Table I are as follows: The operators $\mathcal{O}_{H\Box}$ and $\mathcal{O}_{HDD}$ modify the Higgs-gauge boson coupling by a multiplicative factor without introducing any new Lorentz structure, amounting to a renormalization of the Higgs field. As such, the contribution can be absorbed in the coupling modifier. The operators $\mathcal{O}_{HW}$, $\mathcal{O}_{HB}$, and $\mathcal{O}_{HWB}$ contribute in the modification of the hZZ vertex. These amount to the CP -conserving anomalous Higgs-gauge boson coupling. The operators $\mathcal{O}_{H\tilde{W}}$, $\mathcal{O}_{H\tilde{B}}$, and $\mathcal{O}_{H\tilde{W}B}$ contribute in the modification of the hZZ vertex. These amount to the

TABLE II. Matching between coefficients in Eq. (2.3) and the SMEFT coefficients. s_w and c_w are the sine and cosine of the Weinberg angle.

Coefficient	Warsaw equivalent
g_{ZZ}	$2(c_w^2 c_{HW} + s_w^2 c_{HB} + s_w c_w c_{H\bar{W}B})v^2/\Lambda^2$
$g_{Z\gamma}$	$(2s_w c_w^2 (c_{HW} - c_{HB}) + (s_w^2 - c_w^2) c_{H\bar{W}B})v^2/\Lambda^2$
$g_{Z\bar{Z}}$	$2(c_w^2 c_{H\bar{W}} + s_w^2 c_{H\bar{B}} + s_w c_w c_{H\bar{W}B})v^2/\Lambda^2$
$g_{\bar{Z}\gamma}$	$(2s_w c_w^2 (c_{H\bar{W}} - c_{H\bar{B}}) + (s_w^2 - c_w^2) c_{H\bar{W}B})v^2/\Lambda^2$
g_u^L	$-(c_{Hq}^{(1)} + c_{Hq}^{(3)})ev^2/(2\Lambda^2 s_w c_w)$
g_d^L	$-(c_{Hq}^{(1)} - c_{Hq}^{(3)})ev^2/(2\Lambda^2 s_w c_w)$
g_u^R	$-c_{Hu}ev^2/(2\Lambda^2 s_w c_w)$
g_d^R	$-c_{Hd}ev^2/(2\Lambda^2 s_w c_w)$
δ_u^L	$-(c_{Hq}^{(1)} + c_{Hq}^{(3)})ev^2/(\Lambda^2 s_w c_w)$
δ_d^L	$-(c_{Hq}^{(1)} - c_{Hq}^{(3)})ev^2/(\Lambda^2 s_w c_w)$
δ_u^R	$-c_{Hu}ev^2/(\Lambda^2 s_w c_w)$
δ_d^R	$-c_{Hd}ev^2/(\Lambda^2 s_w c_w)$
g_u	$(s_w c_{uB} - c_w c_{uW})ev^2/\sqrt{2}\Lambda^2$
g_d	$(s_w c_{dB} + c_w c_{dW})ev^2/\sqrt{2}\Lambda^2$
δ_u	$\sqrt{2}(s_w c_{uB} - c_w c_{uW})ev^2/\Lambda^2$
δ_d	$\sqrt{2}(s_w c_{dB} + c_w c_{dW})ev^2/\Lambda^2$

CP -violating anomalous Higgs-gauge boson coupling. The operators $\mathcal{O}_{Hq}^{(1)}$, $\mathcal{O}_{Hq}^{(3)}$, $\mathcal{O}_{Hu}$, and $\mathcal{O}_{Hd}$ contribute to the four-point interaction $qqZh$. These operators also contribute to the qqZ vertex. These operators are referred to as Higgs-current operators since their form is analogous to current, $j^\mu = \bar{\psi}\gamma^\mu\psi$. The operators $\mathcal{O}_{uW}$, $\mathcal{O}_{uB}$, $\mathcal{O}_{dW}$, and $\mathcal{O}_{dB}$ contribute to the four-point interaction $qqZh$. These operators also contribute to the qqZ vertex. These operators contribute to the dipole moments of quarks and hence can be referred to as dipole operators. A complete matching between the coefficients of $\mathcal{L}_{NP}$ in Eq. (2.1) and the SMEFT coefficients as in Table I are shown in Table II.

B. Parametrization of production cross sections

When SMEFT effects are included, the cross section consists of three types of terms, viz. the pure SM contribution, the SM plus EFT interference ($\propto \Lambda^{-2}$ from dimension-six operators), and the pure EFT contribution ($\propto \Lambda^{-4}$). Inclusion of dimension-eight operators would result in SM plus EFT interference contribution $\propto \Lambda^{-4}$, which is comparable to the pure EFT contribution from dimension-six terms; however, we do not consider them in this analysis. The production cross section in presence of SMEFT operators takes the form

$$\sigma = \sigma^{(\text{SM})} + \sum_{i=1}^{n_L} c_i \sigma_i^{(L)} + \sum_{i \leq j}^{n_Q} c_i c_j \sigma_{ij}^{(Q)}, \quad (2.5)$$

where n_L and n_Q refer to the number of linear and quadratic SMEFT contributions. The effective scales Λ^{-2} and Λ^{-4} are absorbed in the cross sections $\sigma_i^{(L)}$ and $\sigma_{ij}^{(Q)}$, respectively. In presence of coupling modifiers κ , the cross section in Eq. (2.5) takes the form as follows:

$$\begin{aligned} \sigma &= \kappa^2 \sigma^{(\text{SM})} + \sum_{i=1}^{n_L} \left(\alpha_i^{(L)} \kappa + \beta_i^{(L)} \kappa^2 \right) c_i \sigma_i^{(L)} \\ &\quad + \sum_{i \leq j}^{n_Q} \left(1 + \alpha_{ij}^{(Q)} \kappa + \beta_{ij}^{(Q)} \kappa^2 \right) c_i c_j \sigma_{ij}^{(Q)}, \\ \mu &= \kappa^2 + \sum_{i=1}^{n_L} \left(\alpha_i^{(L)} \kappa + \beta_i^{(L)} \kappa^2 \right) c_i \mu_i^{(L)} \\ &\quad + \sum_{i \leq j}^{n_Q} \left(1 + \alpha_{ij}^{(Q)} \kappa + \beta_{ij}^{(Q)} \kappa^2 \right) c_i c_j \mu_{ij}^{(Q)}, \end{aligned} \quad (2.6)$$

where μ is the signal strength, i.e., $\mu = \sigma/\sigma_{\text{SM}}$. Differential cross sections can be parametrized in a similar manner. At the hadron collider, an analytical form of the cross section is difficult to write due to the uncertainty of the incoming momenta of the partons. However, we can numerically fit the production cross section as a function of the parameters and this turns out to be equally useful for gauging the effects of NP. In the following, we fit the operator coefficients following (2.6) at 14 TeV LHC for the Zh associated production process considering one operator at a time. The variation of the total production cross section are shown in Fig. 2 (for CP -even hZZ modifiers and Higgs-current operators) and Fig. 3 (for CP -odd hZZ modifiers and dipole operators). The ratio of the total production cross section for moving from 13 to 14 TeV are also shown. We adopt the following methodology: the effective Lagrangian is implemented in FeynRules [43] to generate the universal Feynrules output model [44] file. The model file is validated with standard universal Feynrules outputs like SMEFTsim [45] and SMEFTatNLO [46]. This model file is then fed into the event generator MG5_aMC [47] to obtain the above cross sections at leading order (LO). The cross sections are generated at production level without decaying Z or h to any specific decay mode without any kinematic cuts. The parton distribution function (PDF) set and flavor scheme choice are NN23LO1 PDF set and $U(2)_q \times U(2)_u \times U(2)_d$, respectively. The NP scale is chosen as $\Lambda = 1$ TeV. A few key points observed are as follows: The Higgs-current operators have significant linear as well as quadratic contributions indicating large pure EFT contribution. The enhancement of the EFT terms result from the absence of propagator suppression in the production process. The dipole operators have no linear contribution. This is because they bind fermions with different chiralities and hence do not interfere with the SM process. Because of the absence of linear dependence, they cause variation in

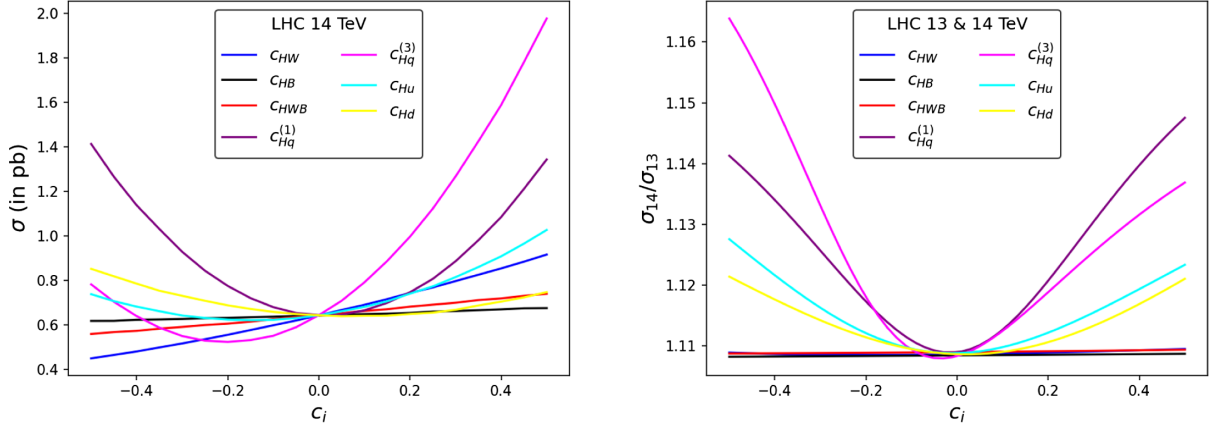


FIG. 2. Left: variation of Zh associated production cross section with variation in CP -even hZZ modifiers and Higgs-current effective operator coefficients at the 14 TeV LHC. Right: variation in the ratio of production cross section of the 14 TeV LHC to the 13 TeV LHC with variation in the effective operator coefficients. See figure inset for the color codes.

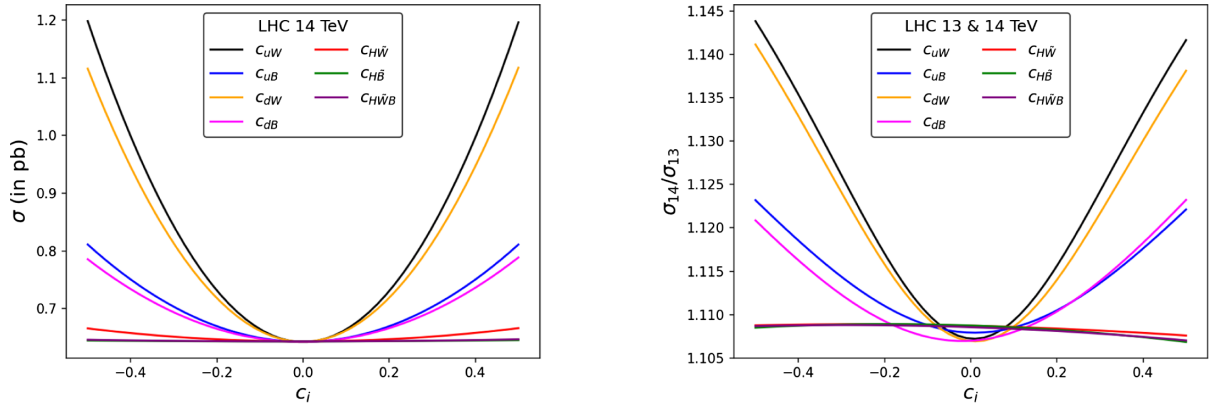


FIG. 3. Left: variation of Zh associated production cross section with change in CP -odd hZZ modifiers and dipole effective operator coefficients at the 14 TeV LHC. Right: variation in the ratio of production cross section of the 14 TeV LHC to the 13 TeV LHC with change in effective operator coefficients. See figure inset for the color codes.

the cross section only in the positive direction. All the operators except $\mathcal{O}_{Hq}^{(3)}$ show near symmetric behavior along the positive and negative side. The operator $\mathcal{O}_{Hq}^{(3)}$ dips around $c_{Hq}^{(3)} = -0.2$ and then continues to rise as we go further in the negative direction. This is due to strong linear as well as quadratic dependence and the trade-off between them happens away from $c_{Hq}^{(3)} = 0$ toward the negative axis. When moving from the 13 to the 14 TeV LHC, the contact operators, i.e., operators associated with $qqZ/qqZh$ vertices, significantly boost the production cross sections. The other operators are less sensitive.

For our analysis, we consider the two operators $\mathcal{O}_{Hq}^{(3)}$ and $\mathcal{O}_{uW}$ as a representative of the Higgs current and dipole class, respectively. It should be noted that the choice is based on their sensitivity to the production cross section, however, other operators from the respective classes may be more sensitive to particular observables or be less bounded from experiments. Our consideration is based on proof of

concept and any other operator can be chosen in lieu of these. Along with the coupling modifier κ_Z (which approximately estimates the EFT effect to the hZZ vertex), this forms our EFT parameter space: $\{\kappa_Z, c_{uW}, c_{Hq}^{(3)}\}$. The parametrized coefficients for signal strength associated with Zh production with these operators following Eq. (2.6) are tabulated in Table III. This parametrization gives an overview of the EFT effects on the inclusive cross section. Coefficients of linear terms in $1, \kappa_Z, c_{uW}$, and $c_{Hq}^{(3)}$ are not present in our parametrization, as it is evident from Eq. (2.6) that the interference between SM and SMEFT vertices appear as coefficients of $\kappa_Z c_{Hq}^{(3)}$. Further, the coefficients of $\kappa_Z c_{uW}$, $\kappa_Z^2 c_{uW}$, $c_{uW} c_{Hq}^{(3)}$, $\kappa_Z c_{uW} c_{Hq}^{(3)}$, and $\kappa_Z^2 c_{uW} c_{Hq}^{(3)}$ vanish because of no interference between the SM and $\mathcal{O}_{Hq}^{(3)}$ operators with diagrams with $\mathcal{O}_{uW}$ operator as the dipole operator mixes quarks of different chiralities ($\bar{q}_L \sigma_{\mu\nu} q_R / \bar{q}_R \sigma_{\mu\nu} q_L$), contrary to the SM or

TABLE III. The parametrized coefficients (μ_i, μ_{ij}) for operators $\mathcal{O}_{Hq}^{(3)}$, $\mathcal{O}_{uW}$, and κ_Z contributing to Zh production at 14 TeV LHC, following Eq. (2.6).

Coefficients	1×1	$1 \times c_{uW}$	$1 \times c_{Hq}^{(3)}$	$c_{uW} \times c_{uW}$	$c_{Hq}^{(3)} \times c_{Hq}^{(3)}$	$c_{uW} \times c_{Hq}^{(3)}$
1×1	...	...	...	3.0277	4.2429	...
$1 \times \kappa_Z$	...	...	1.7060	0.2106	0.3880	...
$\kappa_Z \times \kappa_Z$	1.0000	...	0.1439	0.2000	-0.0472	...

Higgs-current operators, which mixes quarks of same chirality ($\bar{q}_L \gamma_\mu q_L / \bar{q}_R \gamma_\mu q_R$).

We shall also note that the variation of the cross section presented here with EFT operator coefficients have been done without considering the constraints on these operators. We shall do it in the next section. We get the dominant physics contribution to the process under consideration and the resultant parametrization, which remains intact with the modified range of the operator coefficients that will be used for scanning the parameter space.

It should be further noted that, due to the presence of momentum dependence in EFT vertices or absence of propagators, effects of EFT operators are evident mostly at the tails of differential distribution. Hence, the presence of EFT, if any, can be best interpreted from changes to the differential distributions. Figure 4 shows the ratio of the invariant mass distribution, $M_{Zh} = \sqrt{(p_Z + p_h)^2}$ for Zh production in the presence of EFT operators to the corresponding SM prediction at the 14 TeV LHC.

C. Comparison with other Higgs production modes

The operators $\mathcal{O}_{uW}$ and $\mathcal{O}_{Hq}^{(3)}$ are not unique to the Vh ($V = W, Z$) associated production mode. It appears in the VBF and single top production in association with Higgs (thj) as well. The thj process has a comparatively smaller cross section and it is not ideal for the study of these operators, but the VBF mode has a larger cross section compared to the Vh associated production mode, as considered here. These operators are also associated with the diboson production ($VV = WW, WZ, ZZ$) processes. However, the ratio of the signal production cross section including EFT and that of the SM contribution is more sensitive to the changes in the Wilson coefficients in Vh mode compared to that of VBF and VV channels. This has been illustrated in Fig. 5 for the operators $\mathcal{O}_{Hq}^{(3)}$ (left) and $\mathcal{O}_{uW}$ (right).⁴ Also, for both VV and VBF modes, pure contact interaction diagrams are absent, so EFT contributions always come in presence of one or more propagators.

⁴One should, however, note here that the sensitivity of a specific channel not only depends on the signal cross section, but also relies on the background contribution and the efficiency in extracting the signal.

Hence, for the study of $qqZ/qqZh$ vertices, Zh production is considered in our analysis.

III. CONSTRAINTS ON THE hZZ COUPLING FROM CURRENT DATA

The κ framework is the most preferred way to incorporate uncertainties in the measurement of Higgs couplings. This has been adopted in most of the experimental results reported so far, and we will also follow the same here. The current uncorrelated bounds from ATLAS (139 fb^{-1}) and CMS (138 fb^{-1}) are based on Run II data and involve global fit over the main five production and decay channels. Since we intend to study Zh associated production with h subsequently decaying to a bottom pair, the bottom Higgs coupling modifier κ_B is also important for this analysis. Higgs decay to a bottom pair has been studied intensely at the LHC across several channels and the bounds are given in terms of signal strength (μ), i.e., the ratio of the observed signal to the SM predicted value. In Table IV, we list the uncorrelated bounds on the coupling modifiers as well as the signal strengths of the Higgs decay to a bottom pair in the Zh production channel.

Considering the bounds on the signal strength, we can limit the coupling modifiers using the measured signal strengths as shown in Eq. (3.1),

$$\begin{aligned} \mu_{hbb}^{Zh} &= \frac{(\sigma^{Zh} \times (B.R.)_{hbb})}{(\sigma^{Zh} \times (B.R.)_{hbb})_{\text{SM}}} \\ &= \frac{\kappa_Z^2 \kappa_B^2}{0.1775 + 0.5809 \kappa_B^2 + 0.2416 \kappa_Z^2}. \end{aligned} \quad (3.1)$$

In evaluating Eq. (3.1), both the Higgs couplings with the bottom quark as well as with Z bosons have been modified, keeping coupling with other fermions unchanged. κ_Z appears from the production cross section, while κ_B appears from the decay branching fraction; pertaining to the fact that Higgs production and decay modes are those predicted in the SM, the NP effects only enter via rescaling of the Higgs coupling strength. The denominator comes from the modification of the Higgs decay width, which is easily adjusted within the observed total Higgs decay width at LHC for moderate values of κ parameters. We can see that, for $\kappa_Z = \kappa_B = 1$, the signal strength turns one. We further invoke the custodial

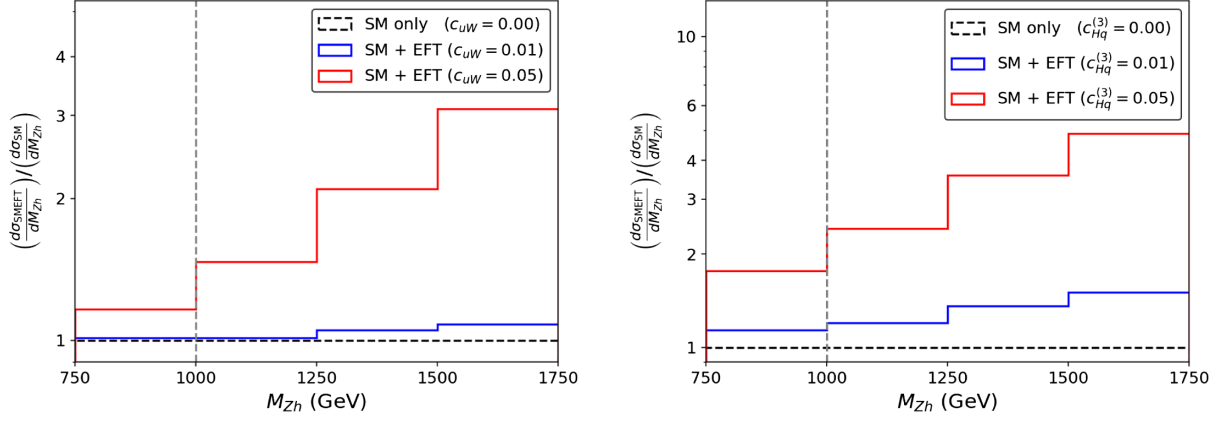


FIG. 4. Left: ratio of the invariant mass distribution, M_{Zh} for Zh production in presence of $\mathcal{O}_{uW}$ operator to the corresponding SM prediction at the LHC 14 TeV. Right: same for $\mathcal{O}_{Hq}^{(3)}$ operator. The gray vertical line refers to the EFT scale, $\Lambda = 1$ TeV.

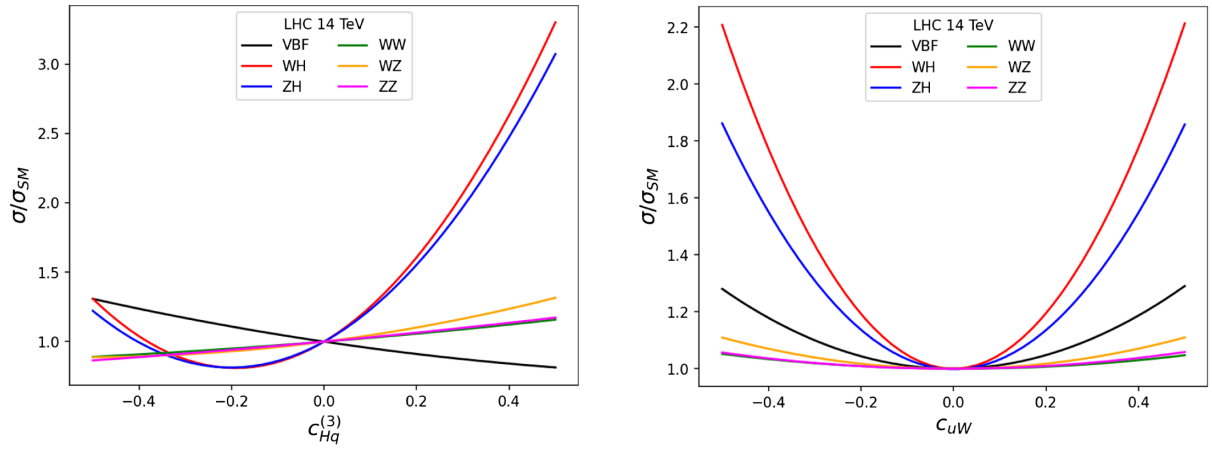


FIG. 5. Left: variation in the ratio of production cross section to the SM cross section in VBF, Vh , and VV processes at the 14 TeV LHC with variation in effective coefficient $c_{Hq}^{(3)}$. Right: same for c_{uW} .

symmetry requirement $\kappa_W = \kappa_Z$. This assumption reduces the number of free parameters in the model and is consistent with the LHC bounds reported in [3,4]. However, this assumption can be relaxed, and the impact of doing so in our analysis is discussed in Appendix E. The bounded region is shown in Fig. 6. Additionally, superimposing the current correlated bound on the $\kappa_V - \kappa_F$ space

TABLE IV. Constraints on κ_Z , κ_B , and μ_{Hbb}^{Zh} [at 95% confidence level (CL)] from ATLAS and CMS experiments.

Measurable	Bound	Source
κ_Z	[0.97, 1.11]	CMS ($pp \rightarrow h$) [4]
	[0.94, 1.05]	ATLAS ($pp \rightarrow h$) [3]
κ_B	[0.85, 1.11]	CMS ($pp \rightarrow h$) [4]
	[0.79, 1.01]	ATLAS ($pp \rightarrow h$) [3]
μ_{hbb}^{Zh}	[0.59, 1.17]	CMS ($pp \rightarrow Zh, h \rightarrow b\bar{b}$) [48]
	[0.85, 1.33]	ATLAS ($pp \rightarrow Zh, h \rightarrow b\bar{b}$) [49]

from the combined Higgs measurement gives the status of the most accurate constraint from the current data. The uncertainties are less than 10% from the SM prediction.

A. Constraints on the effective coupling coefficients

In context of the study of Higgs couplings in the effective framework, several collaborations [52,54–57] have attempted to provide global bounds based on Higgs, top, and diboson data from Tevatron, LHC, and Large Electron-Positron Collider (LEP). Similar fits have been done including B-physics data with LHC top and bottom quark studies [53,58]. Similarly, global fits have also been performed based on electroweak precision data, as well as Δ_{CKM} measurement [59]. Customarily, both ATLAS and CMS have done a number of studies on constraining the EFT operators across various channels using latest data. While ATLAS uses SMEFT, CMS uses Higgs effective Lagrangian parametrization, we will consider bounds from ATLAS [49,60–62] only. Also, there have been numerous

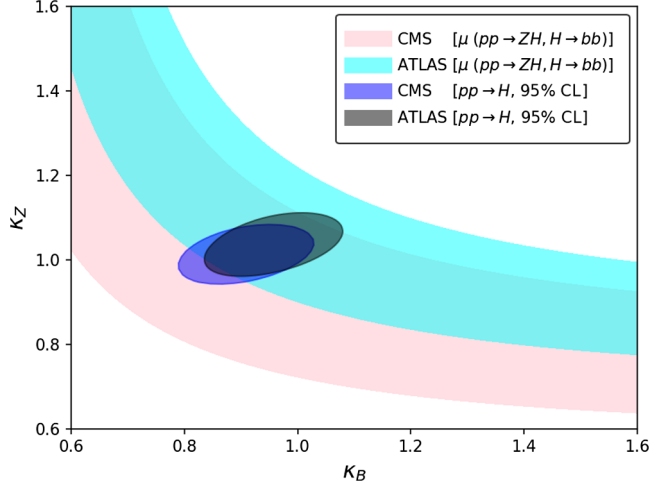


FIG. 6. Constraints on coupling modifiers κ_Z and κ_B based on combined limit on $pp \rightarrow Zh, h \rightarrow b\bar{b}$ production signal strength (bands) [48,49] as well as the combined experimental best fit from all Higgs production and decay processes (ellipses) [3,4] at ATLAS and CMS experiments.

studies concerning SMEFT, projecting constraints for future collider experiments [63–65]. We tabulate the constraints on the coefficients c_{uW} and $c_{Hq}^{(3)}$ from current data in Tables V and VI. The constraints on other dipole and Higgs-current operators are listed in Appendix A.

A few comments and clarifications on the existing bounds are in order: The bounds in Tables V and VI are individual bounds for the operator coefficients, where all other operator coefficient values are set to zero. The bounds for some of the studies in Tables V and VI are provided for (c/Λ^2) or (cv^2/Λ^2) . The values provided on the tables are normalized to $\Lambda = 1$ TeV. The flavor schemes associated with different analyses are tabulated as well in the tables. The bounds significantly change as per flavor assumptions. In this analysis, we will assume a $U(2)_q \times U(2)_u \times U(2)_d$, stating that the third generation is completely decoupled from the first two generations. This assumption is guided by the fact that the collisions at LHC contributing to Zh production are evidently light quarks (b quark collisions are suppressed by PDFs). The bounds are from different analyses at difference confidence levels. For our analysis in succeeding sections, we consider the EFT benchmarks: $c_{uW} = 0.01, 0.05$ and $c_{Hq}^{(3)} = \pm 0.01, \pm 0.05$. Since, only the flavor scheme of [51] matches with our flavor scheme, we only adhere to their bounds for c_{uW} . For $c_{Hq}^{(3)}$, none of the flavor schemes match with our choice and we need not adhere to any of them. Still, numerically, for c_{uW} , the benchmark 0.01 is consistent with all the bounds in Table V, while the benchmark 0.05 is consistent with [50,51,54,55] only. Similarly, for $c_{Hq}^{(3)}$, the benchmark

TABLE V. Constraints on dipole operator coefficient c_{uW} from existing studies, see the listed references for details. q, u , and d are the SM left-hand (LH) quark doublet and right-hand (RH) up- and down-type quark singlets, respectively. Q and t refer to the third generation LH quark doublet and RH top quark singlet, respectively.

Coefficient	Bound	CL (%)	Flavor scheme (Ref.)
c_{uW}	$[-0.375, 0.375]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [50]
	$[-0.290, 0.290]$	95	$U(2)_q \times U(2)_u \times U(2)_d$ [51]
	$[-0.084, 0.029]$	95	$U(1)_Q \times U(1)_t$ [52]
	$[-0.012, 0.048]$	90	$U(3)_q \times U(3)_u \times U(3)_d$ [53]
	$[-0.079, 0.109]$	95	$U(1)_Q \times U(1)_t$ [54]
	$[-0.120, 0.510]$	95	$U(1)_Q \times U(1)_t$ [55]

TABLE VI. Constraints on Higgs-current operator coefficient $c_{Hq}^{(3)}$ from existing studies, see the listed references for details.

Coefficient	Bound	CL (%)	Flavor scheme (Ref.)
$c_{Hq}^{(3)}$	$[-0.432, 0.062]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [52]
	$[-0.375, 0.344]$	95	$U(1)_Q \times U(1)_t$ [52]
	$[-0.702, 0.104]$	68	$U(3)_q \times U(3)_u \times U(3)_d$ [59]
	$[-0.080, 0.100]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [61]
	$[-0.018, 0.026]$	68	$U(3)_q \times U(3)_u \times U(3)_d$ [49]
	$[-0.150, 0.520]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [60]
	$[-0.023, 0.053]$	90	$U(3)_q \times U(3)_u \times U(3)_d$ [53]
	$[-0.017, 0.012]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [55]
	$[-0.032, 0.048]$	95	$U(1)_Q \times U(1)_t$ [55]
	$[-0.008, 0.016]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [57]

0.01 is consistent with all the bounds in Table VI, while -0.01 is not consistent with [57]. The benchmarks 0.05 and -0.05 are more wishful and are incompatible with Refs. [49,55,57] and [49,53,55,57], respectively, caveat to the flavor assumptions. The CP -violating gauge-Higgs operators listed in Table I are constrained by the fermion dipole moment observables, such as electron and neutron dipole moments, as they contribute at one loop to dipole operators. The current limits on the electron and neutron dipole moments are 1.1×10^{-29} and 3.0×10^{-26} (in units of e cm), respectively [66]. These operators are also constrained by the measurements of the triple gauge interactions of the form $WW\gamma$ and WWZ at LEP and the CP asymmetry measured in the $B \rightarrow X_s \gamma$ decay. The CP asymmetry measured in $B \rightarrow X_s \gamma$ decay is $A_{B \rightarrow X_s \gamma} = 0.015(20)$. The bound on the imaginary part of dipole operator c_{uW} from neutron electric dipole moments (EDMs) [67] [assuming $U(2)_q \times U(2)_u \times U(2)_d$ flavor scheme] is shown as follows:

$$\Im(c_{uW}) < 0.000672. \quad (3.2)$$

The bounds on other dipole operators are listed in Appendix A. The bounds are extremely stringent, hence difficult to probe at collider experiments. For our case, we restrict ourselves to the real dipole coefficients, hence evading these bounds. The bounds on light quark dipole operators from electron EDMs appear at two loop involving a Yukawa interaction in the loop and hence are insignificant in comparison to other constraints [68].

IV. COLLIDER ANALYSIS: CURRENT AND FUTURE RUNS

In this section, we will discuss the event generation and analysis in the context of the current and future HL-LHC data. We have simulated $pp \rightarrow Zh \rightarrow (l^+ l^-)(b\bar{b})$ process at the LHC 13 and 14 TeV center-of-mass energies. The PDF set used is NN23LO1 [69] and the renormalization and factorization scales are set at the default dynamical scale choice of MadGraph. The signal and background information will be detailed in Sec. IV A. Before proceeding for a collider analysis in presence of the EFT operators, it is important to check validity of the effective approximation for the collider setup. The validity condition is $\sqrt{\hat{s}} < \Lambda$, where $\sqrt{\hat{s}}$ is the partonic center-of-mass energy. However, ensuring this criterion is difficult in hadron colliders like LHC, where collisions between partons happen at variable center-of-mass energies. One way to deal with this is to construct the invariant mass of the final state particles M_{Zh} to guess the energy scale at which the partonic collisions take place. This is depicted in Fig. 7 for the production process at a particular EFT benchmark point and we observe that almost all the events obey the effective validation criteria, when $\Lambda = 1$ TeV. Now, the generated

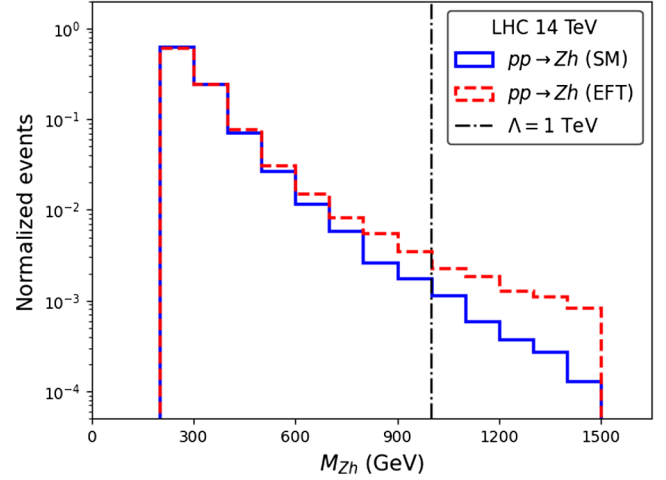


FIG. 7. Invariant mass of Zh for the parton level processes in absence as well as presence of EFT operators at $\Lambda = 1$ TeV. Here we consider the EFT benchmark point corresponding to $\{\kappa_Z, c_{uW}, c_{Hq}^{(3)}\} = \{1.00, 0.05, 0.05\}$.

signal and background events are fed in Pythia8 [70] for parton showering. The showered events are fed in FastJet3 [71] for jet clustering using the anti- k_t algorithm [72] with jet radius 0.5 and jet $p_T \geq 20$ GeV. Finally, the events are processed through Delphes3, using the card `delphes_card_cms`, to take into account finite detector resolution effects, as well as particle identification, reconstruction, and jet tagging. The processed events are analyzed using MadAnalysis5 [73].

A. Cut-based analysis

We consider the signal to be $pp \rightarrow Z(l^+ l^-)H(b\bar{b})$, i.e., a dilepton di-b-jet signal. This signal is comparatively clean due to the presence of charged leptons with invariant mass of the dilepton system peaking around Z mass. The possible SM backgrounds for this signal process are $pp \rightarrow t\bar{t}$, $pp \rightarrow ZZ$, $gg \rightarrow Zh$, and $pp \rightarrow Zb\bar{b}$. Next-to-leading order (NLO) corrections to both signal and background processes are taken into account by multiplying the production cross sections for each process by its NLO K factor, where $K = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$. The LO and NLO cross sections are calculated using MG5_aMC@NLO at LHC 13 TeV and the K factors for different processes are Zh : 1.288 (for $pp \rightarrow Zh$), 2.000 (for $gg \rightarrow Zh$), $Zb\bar{b}$: 1.230, $t\bar{t}$: 1.338, and ZZ : 1.461 [74–76].

We perform the analysis for two different setups, viz. LHC 13 TeV 139 fb^{-1} (equivalent to Run II) and LHC 14 TeV 3000 fb^{-1} (future HL-LHC projection). We introduce some basic cuts common for all the analyses. These can be detailed as $P_T^j > 20.0$ GeV, $P_T^l > 10.0$ GeV, $-5.0 < \eta_j < 5.0$, $-2.5 < \eta_l < 2.5$, $\Delta R_{jj} > 0.4$, $\Delta R_{lj} > 0.4$, and $\Delta R_{ll} > 0.4$, where subscripts j and l refer to jets and leptons, respectively, and the kinematic variables have their usual definitions as in collider literature [77]. Apart

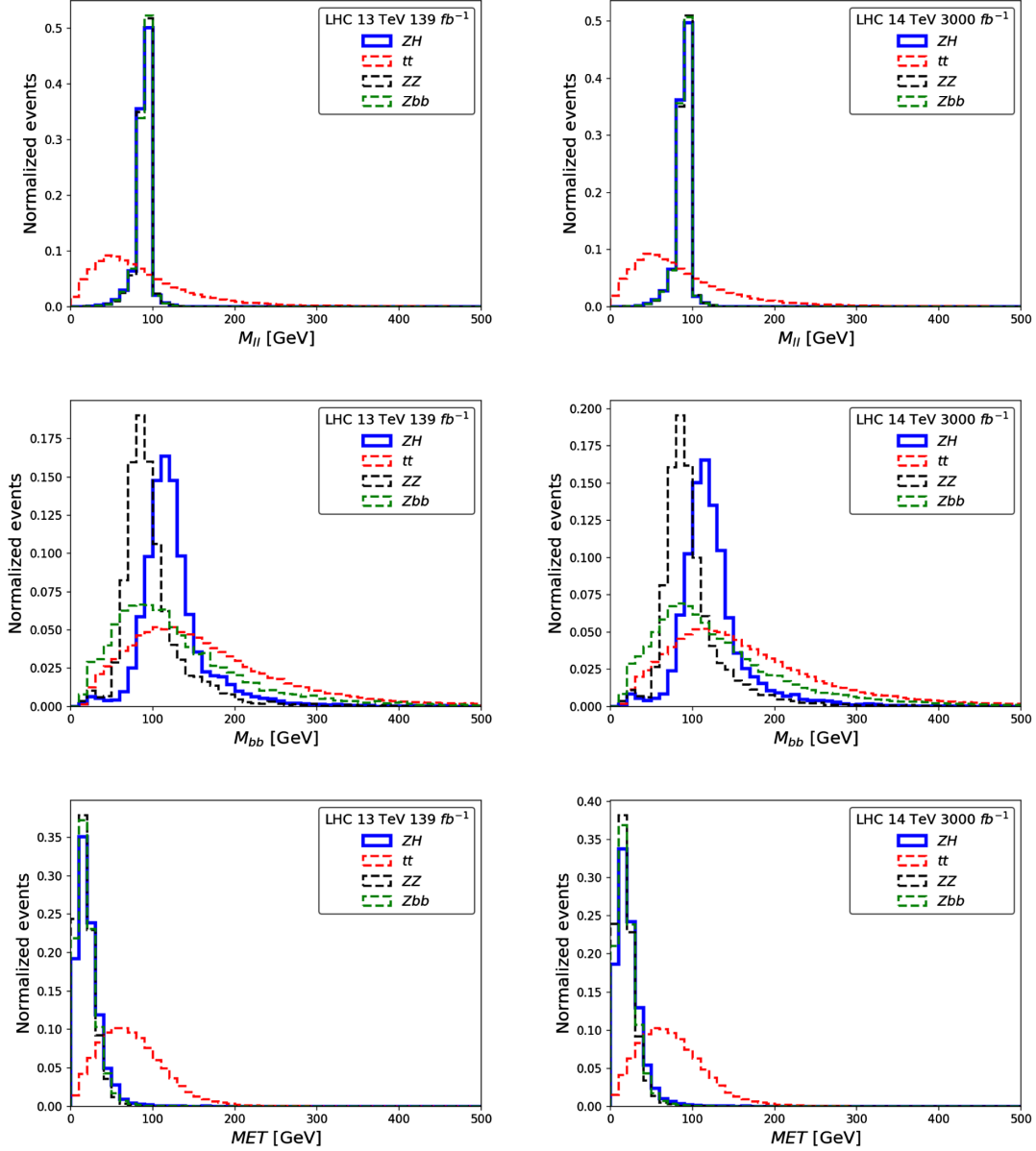


FIG. 8. Top left: invariant mass of dilepton at the LHC 13 TeV corresponding to the SM signal and backgrounds. Top right: same for LHC 14 TeV. Middle left: invariant mass of di-b-jet at the LHC 13 TeV. Bottom right: same for LHC 14 TeV. Bottom left: missing transverse energy at the LHC 13 TeV. Bottom right: same for LHC 14 TeV.

from these, to ensure exclusive $l^+l^-b\bar{b}$ signal, we select events with $N_b = 2$ and $N_l = 2$. The relevant distributions of kinematic variables and observables are plotted in Fig. 8 for 13 and 14 TeV LHC. Choosing $N_j < 5$ for Zh considerably reduces the pure hadronic backgrounds at LHC. We further choose a wide M_{bb} cut around the Higgs mass to make sure that we retain most of the signal while eliminating the backgrounds. The presence of dileptons enables us to use some additional cuts. Owing to the better detectability of leptons, a narrow cut on M_{ll} around the Z mass significantly reduces the $t\bar{t}$ background. Finally, due to the absence of invisible particles in the final state (apart from neutrinos possibly coming b decay) rejecting events

with large missing transverse energy ($MET > 30$ GeV) removes backgrounds with neutrinos in the final state like the leptonic $t\bar{t}$ mode. The entire cut flow for the SM Zh process (in absence of EFT contributions) is tabulated in Table VII.

For signal significance, we use the Asimov definition [78]

$$z = \sqrt{2 \left((S+B) \ln \left(1 + \frac{S}{B} \right) - S \right)}, \quad (4.1)$$

where S is the number of signal events and B is the number of background events. The Asimov significance

TABLE VII. Cut flow and signal significance (z) for the SM $Z(l^+l^-)h(b\bar{b})$ associated production signal with the SM background processes at LHC with $\sqrt{s} = 13$ TeV and luminosity of 139 fb^{-1} and at LHC with $\sqrt{s} = 14$ TeV and integrated luminosity of 3000 fb^{-1} . We use the following notations: S, signal events; B, background events; S/B, signal-to-background ratio.

Cuts	LHC 13 TeV 139 fb^{-1}				LHC 14 TeV 3000 fb^{-1}			
	S	B	S/B	z	S	B	S/B	z
Basic cuts	569	1016890	0.0006	0.56	13327	25581580	0.0005	2.63
$N_j < 5$	309	369549	0.0008	0.51	7054	9079825	0.0008	2.34
$M_{bb} \in (110.0, 140.0) \text{ GeV}$	126	56059	0.0022	0.53	2858	1382411	0.0021	2.43
$M_{ll} \in (80.0, 100.0) \text{ GeV}$	107	11674	0.0092	0.99	2456	285269	0.0086	4.59
$MET < 30 \text{ GeV}$	91	5472	0.0166	1.23	2026	129095	0.0156	5.62

is derived from the likelihood ratio, which takes into account the full statistical model, including the Poisson nature of signal and background events. Hence, it is more statistically rigorous, not only for small event counts or comparable signal-background scenarios, but also in the general case. On Taylor expansion in the limit $S \ll B$, the Asimov significance approximates to $S/\sqrt{B}$, which is the more common definition. The number of signal and background events can further be parametrized in terms of the coupling modifiers and the effective operator coefficients as shown in Eq. (4.2),

$$\begin{aligned} S &= \mathcal{L} \times \sigma_{\text{SM+EFT}}^S(\kappa_V, c_i) \times \text{BR}^S(\kappa_B, c_i) \times \epsilon_S, \\ B &= \mathcal{L} \times \sigma_{\text{SM}}^B \times \text{BR}^B \times \epsilon_B, \end{aligned} \quad (4.2)$$

where $\mathcal{L}$ is the integrated luminosity, and ϵ_S and ϵ_B are the signal and background cut efficiencies, respectively. The EFT effects on Z branching to leptons is parametrized in Appendix D. From Table VII, it is clear that the signal significance improves significantly as we move to the high-luminosity frontier.

The second part of the analysis features inclusion of EFT operators. In presence of EFT operators, there is a significant change in the signal significance. This has been illustrated in Table VIII in presence of SMEFT operators at some benchmark values. The relevant kinematic variables and observables for the different benchmark points are shown in Fig. 14 of Appendix C. The deviation from the SM signal is minuscule. The benchmarks are chosen at some standard values to gauge the effect on the overall parameter space.

B. Boosted-decision-tree-based analysis

With the advent of modern machine learning tools, multivariate analysis has become a norm in collider analysis [79,80]. Among the machine learning techniques, boosted decision tree (BDT) based algorithms are extremely popular due to their stability as well as accuracy, even for smaller datasets. With an aim to improve the signal background separation with more accuracy, we perform an analysis using the XGBoost classifier [81]. The core setup of the analysis is kept similar to the cut-based counterpart. Since we observed higher significance at 14 TeV, 3000 fb^{-1} LHC, we will perform the BDT-based analysis exclusively for the HL-LHC run. The training sets for signal [$pp \rightarrow Z(l^+l^-)H(b\bar{b})$] and backgrounds ($pp \rightarrow t\bar{t}$, $pp \rightarrow ZZ$, $gg \rightarrow Zh$, and $pp \rightarrow Zb\bar{b}$) are prepared and weighted according to the number strength at 3000 fb^{-1} . These weighted data are subjected to the same basic cuts as used in the cut-based analysis. The feature selection is done in a similar way as with the Vh , $h \rightarrow b\bar{b}$ analysis at ATLAS [49]. The features are detailed below:

- (i) transverse momentum of the leading lepton: p_T^l ;
- (ii) transverse momentum of the leading b jet: p_T^b ;
- (iii) number of jets (inclusive of b jets): N_j ;
- (iv) missing transverse energy;
- (v) transverse momentum of the dilepton system: p_T^{ll} ;
- (vi) transverse momentum of the di-b-jet system: p_T^{bb} ;
- (vii) invariant mass of the dilepton system: M_{ll} ;
- (viii) invariant mass of the di-b-jet system: M_{bb} ;
- (ix) separation in (η, ϕ) space between the leptons: ΔR^{ll} ;
- (x) separation in (η, ϕ) space between the b jets: ΔR^{bb} ;

TABLE VIII. Signal significance of the $Z(l^+l^-)h(b\bar{b})$ production process (at LHC with $\sqrt{s} = 14$ TeV and luminosity 3000 fb^{-1}) after the final selection cuts listed in Table VII for different benchmark points (BPs) in presence of effective operators, along with signal (ϵ_s) and background (ϵ_b) efficiencies.

BPs ($\kappa_Z, c_{uW}, c_{Hq}^{(3)}$)	S	B	S/B	z	ϵ_s	ϵ_b
SM (1.00, 0.00, 0.00)	2026	129095	0.0156	5.62	2.09×10^{-2}	8.72×10^{-4}
BP1 (1.00, 0.05, 0.00)	2142		0.0166	5.94	2.19×10^{-2}	
BP2 (1.00, 0.00, 0.05)	2238		0.0173	6.21	2.10×10^{-2}	
BP3 (1.00, 0.00, -0.05)	1869		0.0145	5.19	2.09×10^{-2}	

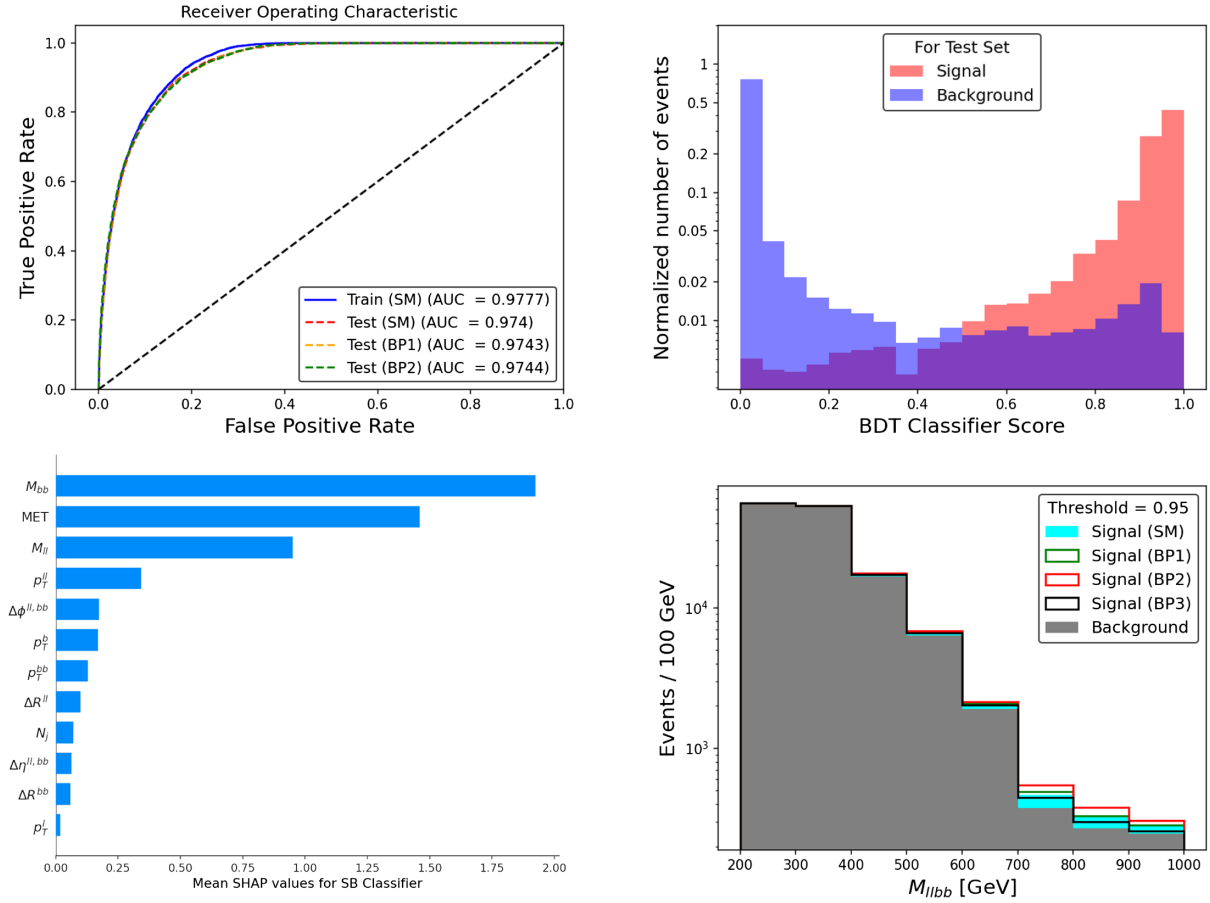


FIG. 9. Top left: the receiver operating characteristic (ROC) curve for the training and testing (SM as well as BPs) data. Top right: the distribution of the BDT classifier score for the SM signal and backgrounds. Bottom left: the mean absolute SHAP values for the features used for training the BDT model. Bottom right: M_{llbb} distribution of signal and background processes post-threshold selection of 0.95.

- (xi) difference in η between the dilepton and di-b-jet system: $\Delta\eta^{ll,bb}$;
- (xii) difference in ϕ between the dilepton and di-b-jet system: $\Delta\phi^{ll,bb}$.

The detailed correlation heat map between the features for signal and backgrounds is shown in Appendix B. To prevent features with large magnitudes (like p_T , MET, etc.) from dominating over small valued features (like $\Delta\eta$, ΔR , etc.), all the features are scaled about their mean value ($\bar{x}$) by their standard deviation (SD), i.e., $(x - \bar{x})/SD$. This ensures all features are more or less at equal footing at the beginning of the training process. The signal and background events are divided in 1:1 ratio for training and testing each process. For training, the overall signal weight is equated with the overall background weight ensuring equal number of signal and background events entering the training process. The BDT model is constructed using XGBClassifier and the hyperparameter tuning is done using GridSearchCV [82]. The details of the optimal hyperparameters are listed in Table XII in Appendix B. The model is threefold cross validated using StratifiedkFold [82]. Since the distributions for the SM plus EFT benchmarks vary very little from the SM distributions, we train only the SM signal

and backgrounds and test on the SM as well as on SM plus EFT benchmarks.

The highlights of the BDT analysis are shown in Fig. 9. As a metric for evaluation of our model, we use the ROC area under the curve (AUC). The AUC value for the training set is 0.9777. For the test sets, the AUC obtained are 0.9740, 0.9743, and 0.9744, respectively, for SM, BP1, and BP2. This indicates that there was very little overfitting and the BPs fared very well on the model trained with SM inputs. To enhance the signal significance, we have set the threshold classifier score at 0.95. This means we will only keep events with a BDT classifier score greater than or equal to 0.95. By doing this, we maintain a roughly similar background efficiency as in the cut-based analysis, making it easier to compare signal efficiencies between the two methods. The feature importance of a machine learning model can be realized using Shapley additive explanation (SHAP) [83] values for the features. SHAP values show how each feature affects each final prediction, the significance of each feature compared to others, and the model's reliance on the interaction between features. The SHAP values for the model are plotted in Fig. 9 using the SHAP module. It is distinctly observed that M_{bb} turns out to be the best discriminating feature. MET, M_{ll} , and

TABLE IX. Signal significance of the $Z(l^+l^-)h(b\bar{b})$ production process (at LHC 14 TeV 3000 fb $^{-1}$) from BDT-based analysis (with threshold 0.95) at different BPs in presence of effective operators, along with signal (ϵ_s) and background (ϵ_b) efficiencies.

BPs ($\kappa_Z, c_{uW}, c_{Hq}^{(3)}$)	S	B	S/B	z	ϵ_s	ϵ_b
SM (1.00, 0.00, 0.00)	4048		0.0313	11.20	4.17×10^{-2}	
BP1 (1.00, 0.05, 0.00)	4217	129397	0.0326	11.66	4.33×10^{-2}	8.74×10^{-4}
BP2 (1.00, 0.00, 0.05)	4762		0.0368	13.16	4.47×10^{-2}	
BP3 (1.00, 0.00, -0.05)	3484		0.0269	9.64	3.89×10^{-2}	

p_T^{ll} turn out to be the other important features, which were also taken into account in the cut-based analysis. Corresponding to the threshold value of 0.95, the significance and cut efficiencies of the signal and background processes for the BDT analysis are detailed in Table IX. It is observed that, for similar background numbers, there is a significant boost in the signal numbers for both SM and other EFT benchmark points compared to the cut-based analysis.

C. Two parameter χ^2 analysis

The χ^2 test [2] serves as a statistical measure to evaluate the degree of conformity between empirical observations and theoretical expectations within the framework of a

contingency table. In statistical literature, there exist a number of definitions for the χ^2 function. These definitions are more or less equivalent and can be used interchangeably. For our case, we shall use Pearson's definition, where the χ^2 is defined as follows:

$$\chi^2 = \sum_j^{\text{bins}} \left(\frac{\mathfrak{D}^j(\kappa_i, c_i) - \mathfrak{D}_{\text{SM}}^j}{\Delta N^j(\kappa_i, c_i)} \right)^2 = \sum_j^{\text{bins}} \left(\frac{\Delta \mathfrak{D}^j(\kappa_i, c_i)}{\Delta N^j(\kappa_i, c_i)} \right)^2. \quad (4.3)$$

Here, $\mathfrak{D}$ is a differential distribution. For our analysis, $\mathfrak{D} = (d\sigma/dM_{llbb})$, which is the invariant mass of all the visible final state particles following relevant cut/BDT

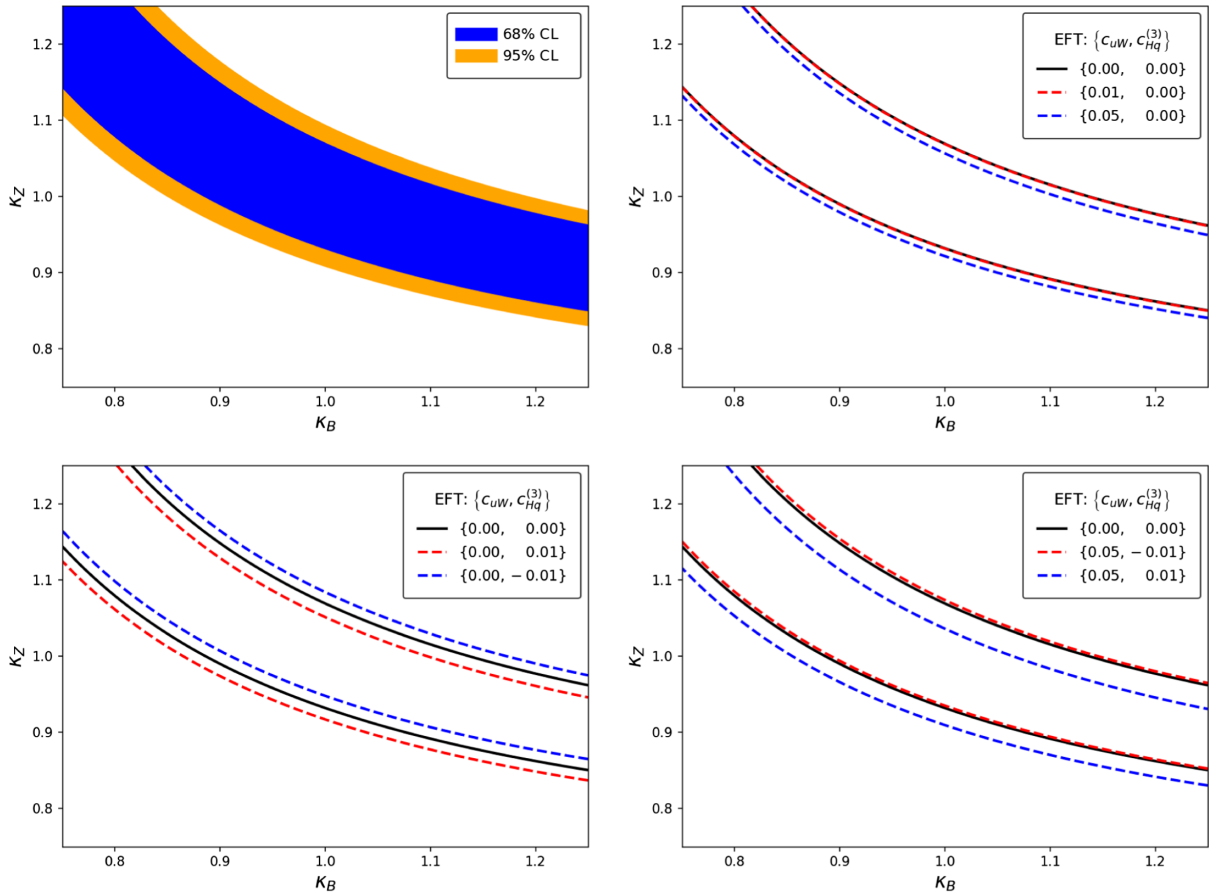


FIG. 10. Top left: χ^2 plots showing 68% and 95% CL bounds in the $\kappa_Z - \kappa_B$ space at LHC 14 TeV 3000 fb $^{-1}$. Top right, bottom left, and bottom right: shift in 68% CL bounds for different values of effective coefficients.

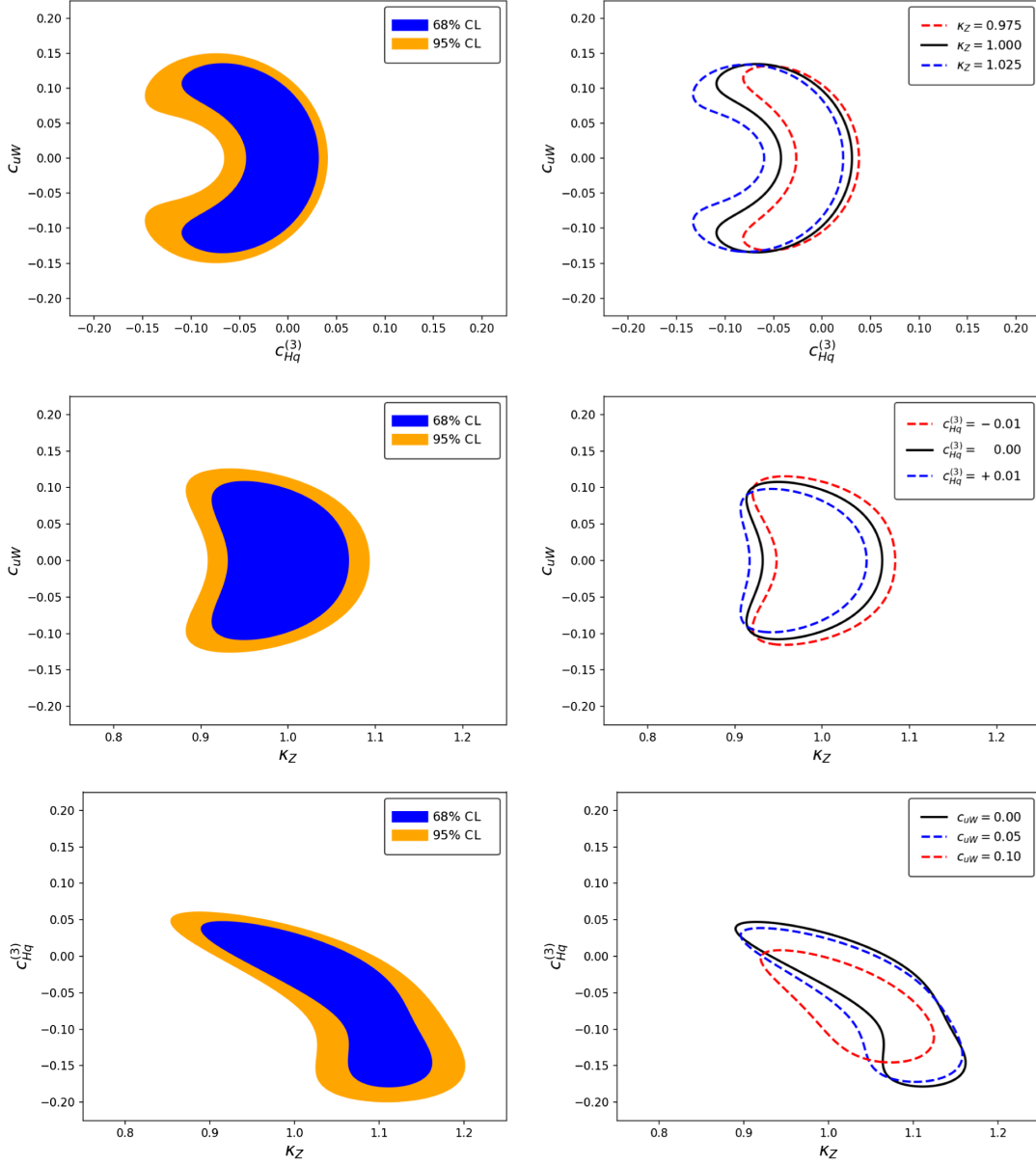


FIG. 11. Top left, middle left, and bottom left: 68% and 95% CL bounds on effective coefficients at the 14 TeV 3000 fb⁻¹ LHC. Top right, middle right, and bottom right: shift in 68% CL in presence of different modifiers or EFT coefficients.

analysis. We define $\Delta \mathfrak{D}^j(\kappa_i, c_i) = \mathfrak{D}^j(\kappa_i, c_i) - \mathfrak{D}_{\text{SM}}^j$, where $\mathfrak{D}^j(\kappa_i, c_i)$ corresponds to events in the j th bin of the M_{llbb} distribution, in presence of effective operators and coupling modifiers, and $\mathfrak{D}_{\text{SM}}^j$ corresponds to signal events in the same bin under the SM process. $\Delta N^j(\kappa_i, c_i) = \sqrt{\mathfrak{D}^j(\kappa_i, c_i) + \mathfrak{D}_{\text{SM}}^j}$ is the statistical uncertainty in the number of events for that bin.

Considering the better performance of the BDT analysis over the cut-based analysis, we use the signal and background efficiencies based on the BDT analysis. The χ^2 analysis is performed corresponding to the binned M_{llbb} distribution. The dataset post-threshold cut is divided

into eight bins from 200 to 1000 GeV in intervals of 100 GeV. The events with higher values of M_{llbb} are removed in order to adhere to the EFT limit. The BDT analysis is repeated for several benchmarks on the parameter space and the distributions corresponding to some of the benchmarks are shown in Appendix C. For Poisson distributed binned data, the number of degrees of freedom is given by $D = N - M$, where N is the number of bins and M is the number of fitted parameters. In this case, $D = 8 - 2 = 6$. Usually the constraints on the parameter space of physical parameters are reported in terms of confidence levels. The confidence levels can be interpreted from the χ^2 values. The 68% and 95% CL for $D = 6$ corresponds to $\chi^2 \approx 7.01$ and $\chi^2 \approx 12.59$, respectively. The

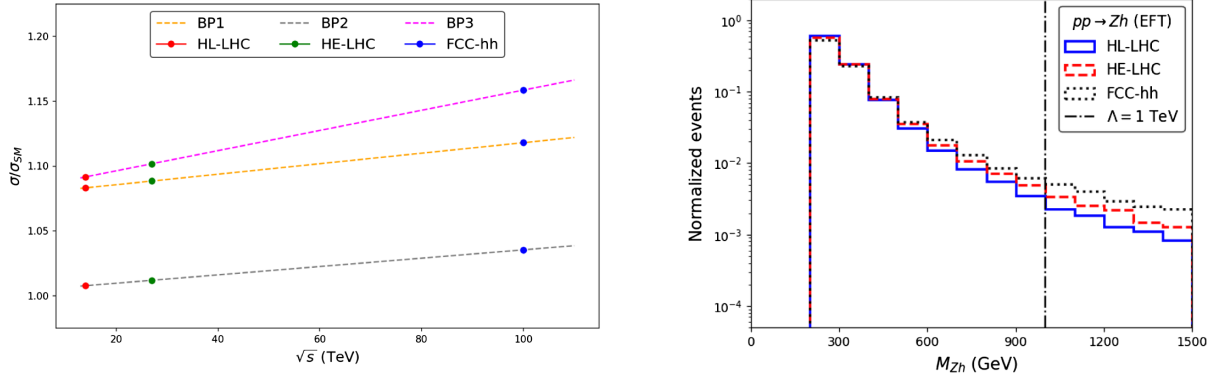


FIG. 12. Left: variation in the ratio of Zh production cross section to the SM cross section at different c.m. energies for benchmarks $\{c_{uW}, c_{Hq}^{(3)}\}$: BP1 $\{0.05, 0.00\}$, BP2 $\{0.00, 0.05\}$, and BP3 $\{0.05, 0.05\}$. Right: invariant mass of Zh for the parton level processes in presence of EFT operators at BP3 for different future pp collider runs.

χ^2 for different parameter benchmarks in the $\kappa_Z - \kappa_B$ plane are shown in Fig. 10.

Figure 10 shows that the 68% CL bounds are moderately sensitive to the parameter $c_{Hq}^{(3)}$ corresponding to the Higgs-current interaction. This is because $\frac{\sigma}{\sigma_{\text{SM}}}$ changes significantly under the variation of $c_{Hq}^{(3)}$ in the Vh channel (see Fig. 5, left). However, it requires higher values of c_{uW} to show similar effect in the χ^2 plots. This is mostly due to the fact that the dipole operators contribute at $(1/\Lambda^4)$ order. Further, it should also be noted that the EFT effects can negate each other, as evident from the benchmark $\{c_{uW}, c_{Hq}^{(3)}\} = \{0.05, -0.01\}$ (see Fig. 10, bottom right), where the positive contribution on the cross section from c_{uW} is canceled by the negative contribution from $c_{Hq}^{(3)}$, showing negligible deviation from the SM contribution even for nonzero EFT contributions.

The 68% and 95% CL bounds on the EFT couplings are shown in Fig. 11, which shows similar sensitivities of the EFT operators and modifiers as in Fig. 10. The effects of EFT contributions to Z decay branching and the assumption of custodial symmetry on these bounds are discussed in Appendixes D and E, respectively. Vh production has been studied in literature like [16,22], focusing on the boosted regime. However, neither of these analyses consider the light quark dipole operators that we include in our analysis. Considering the boosted regime is interesting, as EFT effects are strongly evident there and hence the bounds on $c_{Hq}^{(3)}$ are slightly more stringent in both studies compared to our case. However, as we emphasize in our paper, the boosted regime may invalidate the EFT assumption, necessitating careful consideration. Studies like [18,23] focus on double differential observables with combination of multiple channels, which results in further improvement in bounds. Similar to the M_{llbb} distribution, other sensitive observables like H_T (scalar sum of p_T of visible particles) can also be used to perform this analysis. Another popular method is to train

a machine-learning-based algorithm that separates the SM and SM + EFT contribution based on a set of discriminating observables. However, such model requires better segregation between the observables of the two classes, which is evidently difficult even at HL-LHC once we abide by the EFT limit.

D. Other future pp colliders

As observed in Figs. 2 and 3, the Zh production cross section enhances both the Higgs-current and dipole interactions, with increase in c.m. energy. This motivates the possibility of better extraction of these NP contributions at higher c.m. energy possible at future collider runs like the HE-LHC (expected to run at $\sqrt{s} = 27$ TeV), FCC-hh (expected to run at $\sqrt{s} = 100$ TeV), etc. $\frac{\sigma}{\sigma_{\text{SM}}}$ is plotted in Fig. 12 (left) for different c.m. energies ($\sqrt{s}$) at some of the benchmarks $\{c_{uW}, c_{Hq}^{(3)}\}$: BP1 $\{0.05, 0.00\}$, BP2 $\{0.00, 0.05\}$, and BP3 $\{0.05, 0.05\}$. All the benchmarks show enhancement in EFT effects; however, we observe stronger enhancement for the Higgs-current interaction (BP2) in comparison to the dipole interaction (BP1). The combined presence of both the operators (BP3) shows the highest enhancement in cross section. While these results show promise to better estimate the dipole operator, in particular, the prospect of accelerating protons to such high energies remains a distant possibility. Figure 12 (right) shows the validity of the EFT limit, having the invariant mass peak well below $\Lambda = 1$ TeV even in context of future pp colliders with higher c.m. energies. This happens due to the dominance of the SM process, while a larger Wilson coefficient would flatten the distribution, having more events with higher invariant mass.

V. SUMMARY AND CONCLUSION

We have presented an analysis of Zh associated production at the LHC in presence of dimension-six SMEFT operators and coupling modifiers. We choose a simple

parametrization to match the coupling modifiers that stem from dimension-six SMEFT operators in Warsaw basis. We analyzed the signal and background contributions at various benchmark points, which allows maximum cross section within the allowed values of the EFT parameters and coupling modifiers adhering to the constraints appearing from existing collider and flavor constraints. We do both cut-based and BDT analysis using kinematic variables relevant for the process. NP scale is safely chosen at $\Lambda = 1$ TeV, which abides by the effective limit having invariant mass distribution peak appearing below Λ .

A comparison of Tables VIII and IX shows that the BDT analysis performs better than the cut-based analysis presented in the previous section, as expected. One obtains almost factor 2 enhancement in the estimation of the significances for the various BPs considered in our analysis. This is due to the fact that BDTs come with better efficiency for the signal events even though the background efficiency remains almost the same. We have obtained more than 9σ (5σ) significance using BDT (cut-based) analysis for all our chosen benchmark points. We further note that corresponding to our flavor scheme choice $[U(2)_q \times U(2)_u \times U(2)_d]$ the corresponding background contributions have limited sensitivity to the EFT operators introduced here, hence we do not include them in our analysis.

A χ^2 analysis is performed in the two-dimensional parameter space of the EFT operator coefficients as well as in the coupling modifiers. The bounds on the $c_{uW} - c_{Hq}^{(3)}$ plane is more constrained than those on $\kappa_Z - \kappa_B$ plane, owing to the fact that the differential distribution M_{llbb} is extremely sensitive to EFT effects, especially at the tail. Based on the plots in Fig. 10, it is evident that the EFT contributions significantly alter the bounds on the $\kappa_Z - \kappa_B$ plane. Similarly, coupling modifiers can also impact the bounds in the EFT coefficient planes as evident from Fig. 11. It is observed that even with the tight constraints on the operators, presence of Higgs-current operator $\mathcal{O}_{Hq}^{(3)}$ results in visible changes on the bounds in $\kappa_Z - \kappa_B$ plane. The individual impact of the dipole operator $\mathcal{O}_{uW}$ is relatively small and does not show any significant deviation from the SM predictions. This is mainly because they do not interfere with the SM process and the contributions are obtained only at $1/\Lambda^4$ order. However, as discussed in Sec. IV D, significant increase in sensitivity is expected with increase in the c.m. energy, possible at future high energy collider runs. However, the contributions from $\mathcal{O}_{Hq}^{(3)}$ will still dominate.

In this analysis, we have omitted CP -odd contributions to the dipole operators, primarily because they are strongly bounded from EDM measurements. Therefore, it is difficult to detect their effects via signal cross section. Dedicated CP -violating observables may decipher a disentanglement from that of a CP -even case. This lies outside the scope of the present work, but will be taken up in the future.

ACKNOWLEDGMENTS

S. B. would like to acknowledge Grant No. CRG/2019/004078 from DST-SERB and ANRF Grant No. CRG/2023/000580, Government of India.

DATA AVAILABILITY

No data were created or analyzed in this study.

APPENDIX A: CONSTRAINTS ON OPERATORS

The constraints on dipole (other than c_{uW}) and Higgs-current [other than $c_{Hq}^{(3)}$] operator coefficients

TABLE X. Constraints on dipole operator coefficients from existing studies, see the listed references for details.

Coefficient	Bound	CL (%)	Flavor scheme (Ref.)
c_{uB}	$[-0.602, 0.602]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [50]
	$[-0.780, 0.780]$	95	$U(2)_q \times U(2)_u \times U(2)_d$ [51]
	$[-0.199, 0.093]$	95	$U(1)_Q \times U(1)_t$ [52]
	$[-0.036, 0.324]$	90	$U(3)_q \times U(3)_u \times U(3)_d$ [53]
	$[-0.430, 0.284]$	95	$U(1)_Q \times U(1)_t$ [54]
	$[-4.500, 1.200]$	95	$U(1)_Q \times U(1)_t$ [55]
c_{dW}	$[-0.484, 0.484]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [50]
	$[-0.360, 0.360]$	95	$U(2)_q \times U(2)_u \times U(2)_d$ [51]
c_{dB}	$[-0.769, 0.769]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [50]
	$[-0.960, 0.960]$	95	$U(2)_q \times U(2)_u \times U(2)_d$ [51]

TABLE XI. Constraints on Higgs-current operator coefficients from existing studies, see the listed references for details.

Coefficient	Bound	CL (%)	Flavor scheme (Ref.)
$c_{Hq}^{(1)}$	$[-2.659, 0.381]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [52]
	$[-1.147, 1.585]$	95	$U(1)_Q \times U(1)_t$ [52]
	$[-0.260, 0.115]$	68	$U(3)_q \times U(3)_u \times U(3)_d$ [59]
	$[-1.600, 0.430]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [60]
	$[-0.048, 0.021]$	90	$U(3)_q \times U(3)_u \times U(3)_d$ [53]
	$[-0.100, 0.140]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [55]
	$[-0.031, 0.049]$	95	$U(1)_Q \times U(1)_t$ [55]
	$[-0.023, 0.047]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [57]
c_{Hu}	$[-0.458, 0.375]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [52]
	$[-1.038, 0.449]$	68	$U(3)_q \times U(3)_u \times U(3)_d$ [59]
	$[-0.060, 0.036]$	90	$U(3)_q \times U(3)_u \times U(3)_d$ [53]
	$[-0.190, 0.100]$	68	$U(3)_q \times U(3)_u \times U(3)_d$ [49]
	$[-0.075, 0.073]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [55]
	$[-1.200, 2.900]$	95	$U(1)_Q \times U(1)_t$ [55]
	$[-0.056, 0.081]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [57]
c_{Hd}	$[-0.187, 0.229]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [52]
	$[-0.520, 0.267]$	68	$U(3)_q \times U(3)_u \times U(3)_d$ [59]
	$[-2.600, 8.300]$	95	$U(3)_q \times U(3)_u \times U(3)_d$ [60]
	$[-0.130, 0.071]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [55]
	$[-0.150, 0.040]$	95	$U(2)_q \times U(2)_u \times U(3)_d$ [57]

from existing studies are listed in Tables X and XI, respectively.

Bounds on the imaginary part of dipole operators from neutron EDM [67] [assuming $U(2)_q \times U(2)_u \times U(2)_d$ flavor scheme] are shown as follows:

$$\begin{aligned}\Im(c_{uB}) &< 0.000368, \\ \Im(c_{dW}) &< 0.000002, \\ \Im(c_{dB}) &< 0.000001.\end{aligned}\quad (\text{A1})$$

APPENDIX B: DETAILS OF BDT ANALYSIS

Feature selection is an integral and significant part of any machine learning analysis. The presence of too many redundant features causes a model to learn unnecessary characteristics; as such, we expect the features to have little dependence on one another. The correlation matrix captures the interdependence among the features very accurately. For our BDT model, the feature correlation heat map is shown in Fig. 13. Darker patches refer to high correlation.

TABLE XII. The optimal hyperparameter values for the model mined using GridSearchCV. The objective hyperparameter is fixed at “binary:logistic.”

Hyperparameters for the XGBClassifier model	Optimal value
Number of boosting rounds (n_estimators)	50
Maximum depth of a tree (max_depth)	5
Learning rate for the model (learning_rate)	0.15
Fraction of samples used each tree (subsample)	0.8
Fraction of features used for each tree (colsample_bytree)	1.0
Minimum sum of instance weight in a child (min_child_weight)	50
Minimum loss reduction for further partition (gamma)	0.75
L1 regularization term on weights (reg_alpha)	8
L2 regularization term on weights (reg_lambda)	60
Maximum step size for each iteration (max_delta_step)	2

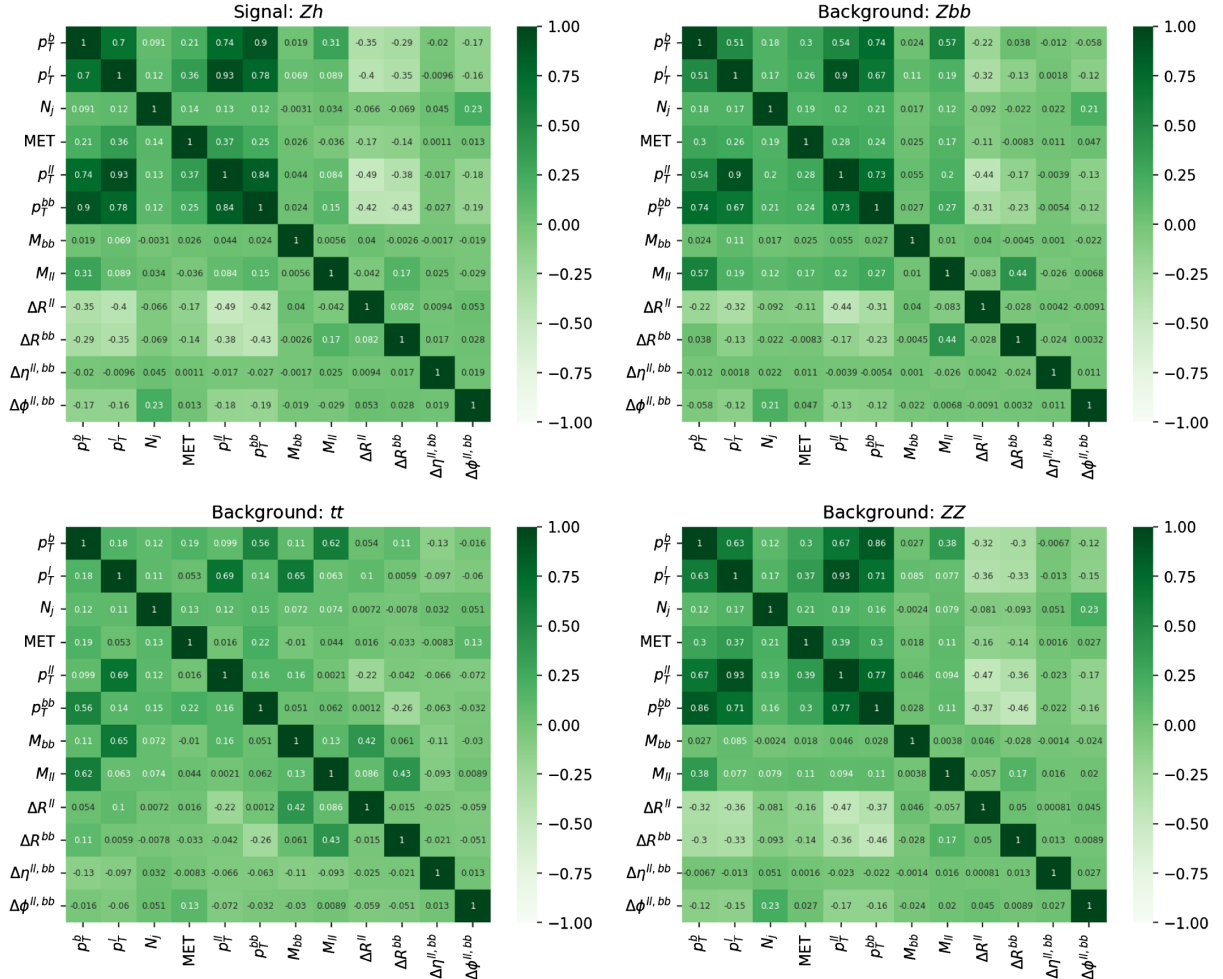


FIG. 13. Top left: correlation matrix for the features used in training the XGBoost model for Zh process. Top right: Zbb process. Bottom left: $t\bar{t}$ process. Bottom right: ZZ process.

Apart from features like p_T^l and p_T^{ll} , p_T^b and p_T^{bb} , where correlation is expected, most of the features show little to no correlation, enhancing the model's learnability against general data. Apart from feature selection, another important aspect of model tuning is the hyperparameter optimization. Proper tuning prevents the model from overfitting, resulting in better performance on new data. The optimized hyperparameters for the model are detailed in Table XII.

APPENDIX C: DIFFERENTIAL DISTRIBUTIONS

Kinematic distributions for different EFT benchmark points are shown in Fig. 14. The M_{llbb} distribution post BDT score threshold choice of 0.95 is shown in Fig. 15. The benchmarks $\{c_{uW}, c_{Hq}^{(3)}\}$ are as follows: left, BC1 $\{0.00, -0.20\}$, BC2 $\{0.00, -0.10\}$, and BC3 $\{0.00, -0.01\}$; center, BC4 $\{0.00, 0.01\}$, BC5 $\{0.00, 0.10\}$, and BC6 $\{0.00, 0.20\}$; right, BD1 $\{0.01, 0.00\}$, BD2 $\{0.10, 0.00\}$, and BD3 $\{0.20, 0.00\}$.

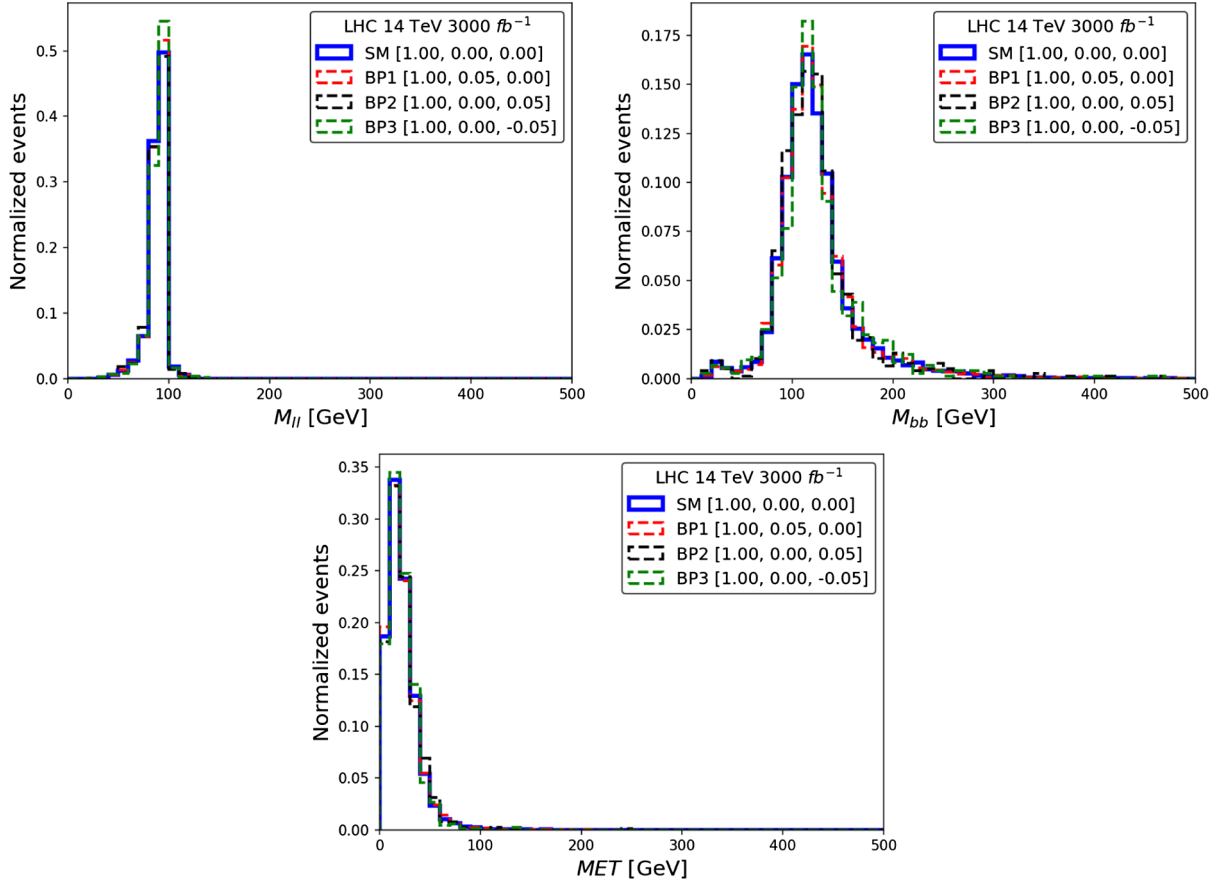
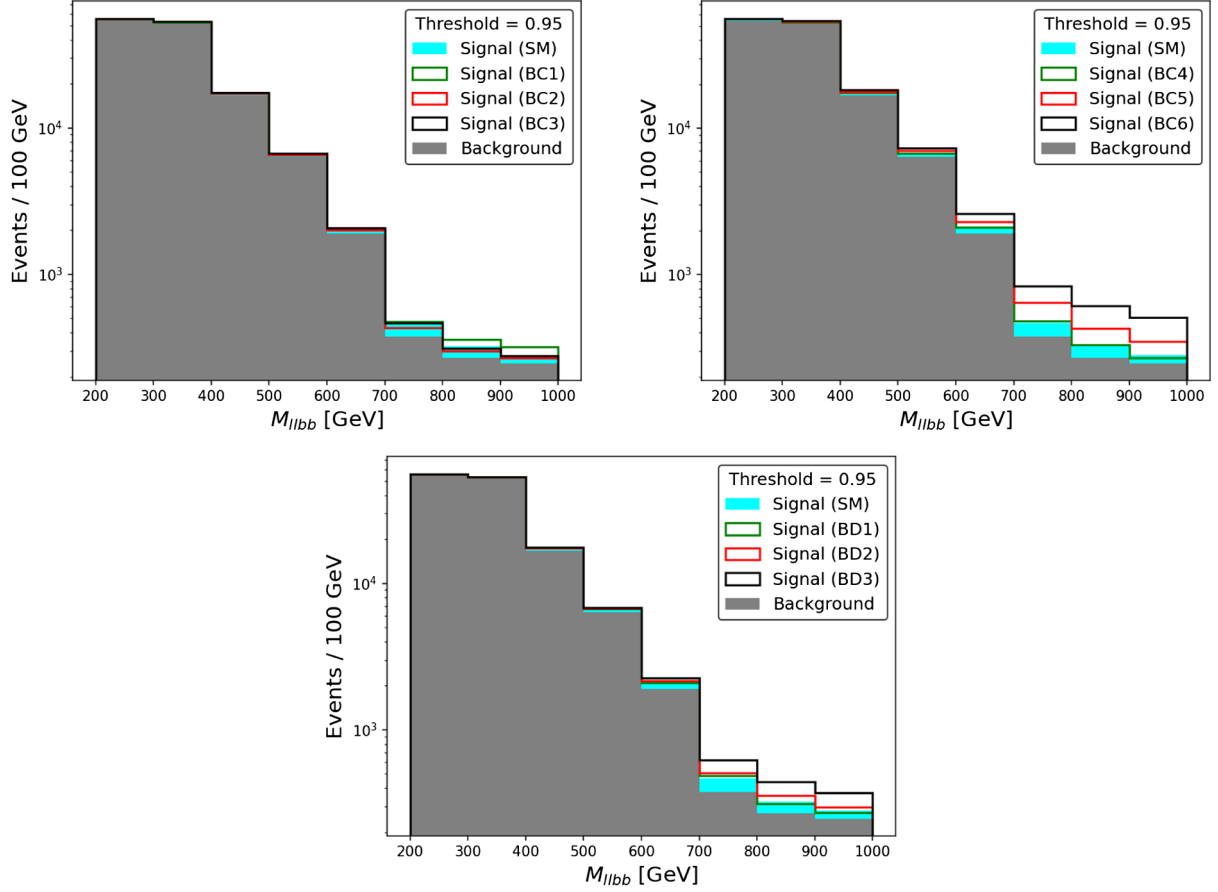


FIG. 14. Top left: invariant mass of dilepton. Top right: invariant mass of di-b-jet. Bottom: missing transverse energy corresponding to $Z(l^+l^-)h(b\bar{b})$ at $\sqrt{s} = 14$ TeV at different EFT benchmark points shown in Table VIII.

FIG. 15. M_{llbb} distributions for different EFT benchmarks post-threshold choice of 0.95.

APPENDIX D: Z BRANCHING CORRECTION

The correction to Z decay width in presence of $\mathcal{O}_{uW}$ and $\mathcal{O}_{Hq}^{(3)}$ can be parametrized as

$$\Gamma_Z = \Gamma_Z^{\text{SM}} \left[1 + 0.0047(c_{uW})^2 + 0.0099(c_{Hq}^{(3)})^2 + 0.0976(c_{Hq}^{(3)}) \right]. \quad (\text{D1})$$

The correction to $Z \rightarrow l^+ l^-$ branching is $\mathcal{O}_{Hq}^{(3)}$ and can be parametrized as

$$(B.R.)_{Zll} = \frac{\Gamma_{Zll}}{\Gamma_Z} = \frac{(B.R.)_{Zll}^{\text{SM}}}{\left[1 + 0.0047(c_{uW})^2 + 0.0099(c_{Hq}^{(3)})^2 + 0.0976(c_{Hq}^{(3)}) \right]}. \quad (\text{D2})$$

Figure 16 shows how the 68% CL limits change depending on whether EFT corrections to the Z branching are included or not. The effect is not very strong, but it is taken into account in our analysis.

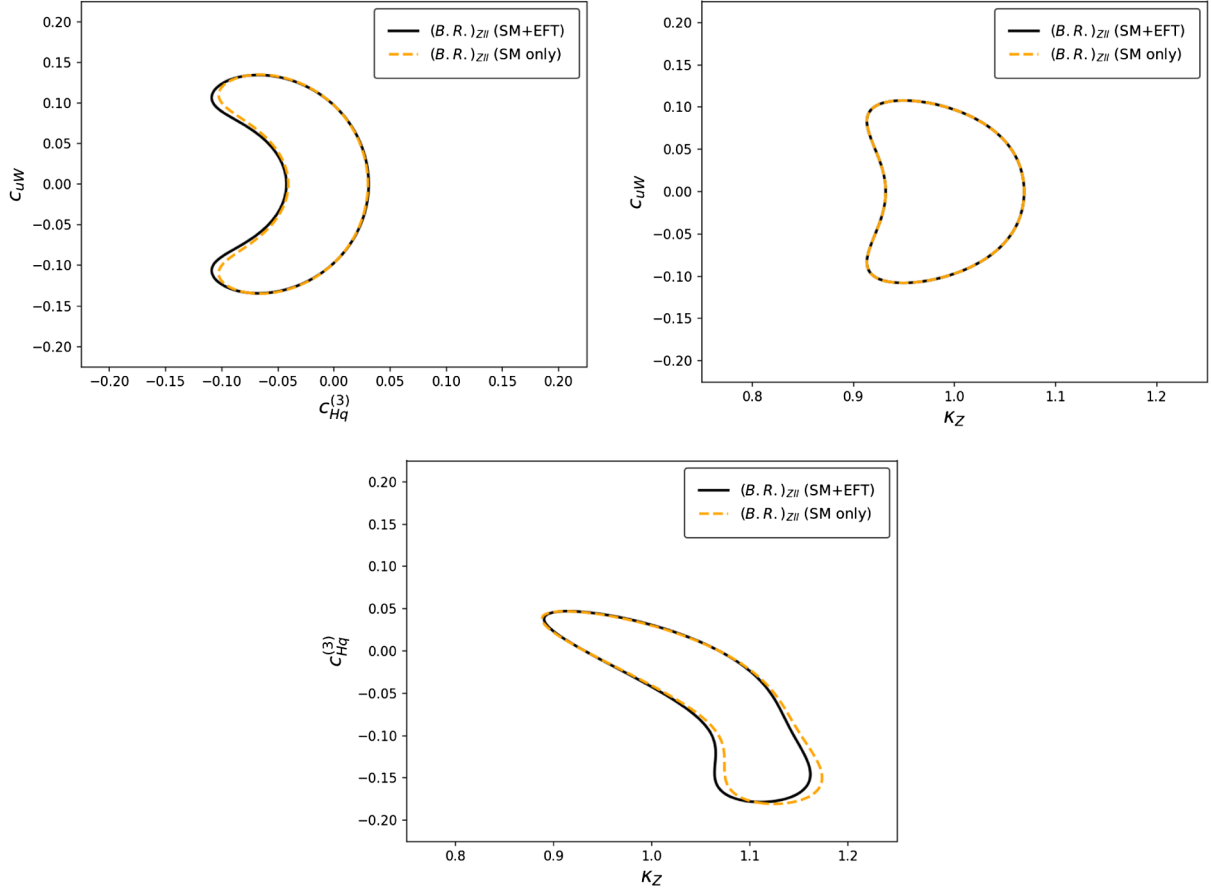


FIG. 16. Shift in 68% CL limits depending on whether EFT corrections to the Z branching are included or not.

APPENDIX E: THE EFFECT OF CUSTODIAL SYMMETRY

In Sec. III, we imposed the custodial symmetry condition $\kappa_W = \kappa_Z$. However, this assumption can be relaxed. In this section, we explore how the 68% CL limits change under two scenarios: (i) with custodial symmetry, where $\kappa_W = \kappa_Z$ (as discussed in Sec. III) and (ii) without custodial symmetry, where $\kappa_W \neq \kappa_Z$ and $\kappa_W = 1$, assuming a SM-like coupling of the Higgs to the W boson while treating κ_Z as a free parameter. For the second scenario, the Higgs production signal strength via the Zh channel is given by

$$\mu_{hbb}^{Zh} = \frac{(\sigma^{Zh} \times (B.R.)_{hbb})}{(\sigma^{Zh} \times (B.R.)_{hbb})_{\text{SM}}} = \frac{\kappa_Z^2 \kappa_B^2}{0.3929 + 0.5809 \kappa_B^2 + 0.0262 \kappa_Z^2}. \quad (\text{E1})$$

Figure 17 illustrates how the 68% CL limits are affected by the assumption of custodial symmetry. The assumption significantly impacts our bounds, particularly when κ_Z deviates from 1.

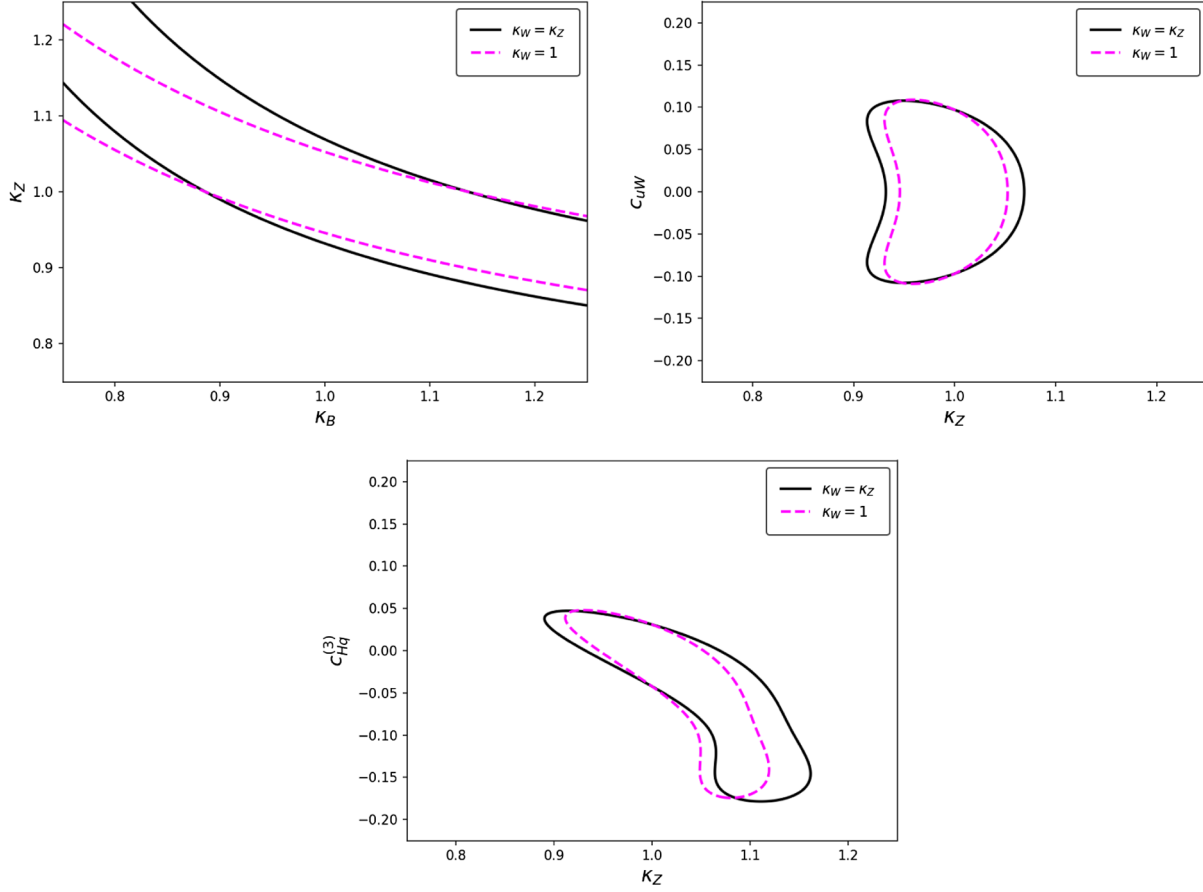


FIG. 17. Shift in 68% CL limits depending on whether custodial symmetry is assumed.

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Correction: A grant number was missing in the Acknowledgments section and has been inserted.