

Semivisible Higgs boson decay as a probe for new invisible particles

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We discuss the HL-LHC sensitivity to probe new invisible particles including scalars and fermions using semivisible Higgs decays in the $pp \rightarrow ZH, Z \rightarrow jj(\ell^+\ell^-), H \rightarrow \ell^+\ell^-(jj) + E_T$ production mode. The kinematics of these decays allow new particle masses below $m \lesssim 50$ GeV. We carry out our analysis using both a cut-based approach and a multivariate method based on a boosted decision tree. We work within the dark Standard Model effective field theory framework with operators up to dimension six and a discrete $\mathbb{Z}_2$ symmetry under which the new particles are odd and the SM particles are even. We compare our results to those obtained from considering the invisible Z width, as well as perturbative unitarity arguments. Finally, we outline kinematic strategies at the LHC to distinguish different operator structures of the postulated invisible particles.

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I. INTRODUCTION

Semivisible Higgs decays into a pair of leptons or two jets plus missing transverse energy (E_T) provide a window into the production of new invisible particles that complements other channels [1]. We discuss these processes assuming that the E_T is due to a pair of new light particles with $m \lesssim 50$ GeV, which can have spin zero or spin one-half.¹ We carry out the analysis using a dark Standard Model effective field theory (SMEFT) framework including operators up to dimension six and with a discrete $\mathbb{Z}_2$ symmetry under which the new particles are odd and the Standard Model (SM) particles are even. The fields corresponding to the new states are taken to be complex, thus allowing for the possibility of them carrying a dark charge. Specifically, we concentrate on ZH production at the LHC followed by the semivisible decay $H \rightarrow \ell^+\ell^- + E_T$ or $H \rightarrow jj + E_T$. Even though the gluon fusion channel for Higgs production has a larger cross section, we choose to study the ZH channel because it leads to cleaner signals [1,2].

We begin by listing the operators that we will include in our study in Sec. II and derive the theoretical constraints on their Wilson coefficients that follow from perturbative unitarity in Sec. III. In Sec. IV we consider the invisible Z width, which can constrain some of our Wilson coefficients. Our new analysis for semivisible Higgs decay is described in Sec. V, and we present our results in Sec. VI, where we discuss the fate of the Higgs-neutrino floor [1] in this context and contrast the sensitivity reach of the semivisible Higgs processes with those obtained from the invisible Z width and from perturbative unitarity considerations.

II. EFFECTIVE FIELD THEORY FRAMEWORK

We consider scenarios where a pair of beyond the Standard Model (BSM) invisible particles interact with SM particles through $SU(3) \times SU(2) \times U(1)$ gauge-invariant dimension-six operators. The possible set of operators, dubbed DSMEFT (for dark SMEFT) operators, have been cataloged before in the literature [3,4] with several subsets considered for specific cases [5–44]. The operators relevant for our analysis follow from requiring a $\mathbb{Z}_2$ symmetry under which all BSM fields are odd and all SM fields are even and by selecting only those operators that can contribute to semivisible Higgs decays. The new particles containing such a stabilizing $\mathbb{Z}_2$ symmetry can be complex scalars (ϕ) or Dirac fermions (χ) and are often motivated as possible dark matter (DM) candidates. For this reason, we use “DM” as a general acronym for the new invisible particles.

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¹There is minimal sensitivity for the mass range between 50 GeV and the kinematic limit near $m_H/2$.

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We note that operators involving multiple SM Higgs bosons and DM fields without any other SM fields or covariant derivatives are strongly constrained by the measurements of Higgs invisible decays [45,46] or from direct detection experiments [47]. The operator $\mathcal{O}_{\square\phi}^{(6)} = (H^\dagger H)\square\phi^\dagger\phi$ is an exception [48] to the direct detection limits, since this operator yields momentum-suppressed DM-nucleon interactions; however, the Higgs invisible-decay constraints on $\mathcal{O}_{\square\phi}^{(6)}$ are applicable, and they are much stronger than those from semivisible modes.² Therefore, we exclude these purely Higgs-portal operators from our study.

The relevant set of operators for scalar DM fields is then

$$\mathcal{O}_{DH\partial\phi} = (H^\dagger \overleftrightarrow{D}^\mu H)(\phi^\dagger \overleftrightarrow{\partial}_\mu \phi) \quad \mathcal{O}_{e\phi} = (\bar{l}_i e_j H)\phi^\dagger \phi \quad (1)$$

$$\mathcal{O}_{u\phi} = (\bar{q}_i u_j \tilde{H})\phi^\dagger \phi \quad \mathcal{O}_{d\phi} = (\bar{q}_i d_j H)\phi^\dagger \phi, \quad (2)$$

where the double arrow notation has the usual meaning, e.g., $(\phi^\dagger \overleftrightarrow{\partial}_\mu \phi) \equiv (\phi^\dagger \vec{\partial}_\mu \phi) - (\phi^\dagger \overleftarrow{\partial}_\mu \phi)$. The fermion DM operators are

$$\begin{aligned} \mathcal{O}_{DH\chi\chi} &= (iH^\dagger \overleftrightarrow{D}^\mu H)(\bar{\chi}\gamma_\mu \chi) \\ \mathcal{O}_{DH\chi\chi 2} &= (iH^\dagger \overleftrightarrow{D}^\mu H)(\bar{\chi}\gamma_\mu \gamma^5 \chi), \end{aligned} \quad (3)$$

where H is the SM Higgs doublet, l_i, q_i are the left-handed lepton and quark doublets, with flavor index i , and e_i, u_i, d_i are the right-handed charged lepton and up and down quarks with flavor index i , respectively. We assume that all DSMEFT operators are diagonal in flavor space and independent of the flavor.

The dimension-six DSMEFT Lagrangian that we consider is

$$L_{\text{DSMEFT}} = L_{\text{SM}} + \sum_\alpha \frac{C_\alpha}{\Lambda^2} \mathcal{O}_\alpha, \quad (4)$$

where L_{SM} is the SM Lagrangian, the dimension-six DSMEFT operators are defined in Eqs. (2) and (3), and Λ is the scale of new physics. All information about the new physics is contained in the coefficient functions C_α , considered to be real without any loss of generality.

For operators involving new particles, there is no interference between the SM and the EFT operators, which results in observables being proportional to $|C_\alpha/\Lambda^2|^2$. Therefore, the imaginary parts of these coefficients receive the same constraints as the corresponding real parts. Pure dimension-six SMEFT operators constructed solely from SM fields are not included in the present analysis, because

²Applying the constraint placed by the invisible Higgs width on $C_{\square\phi}$, $|C_{\square\phi}| \lesssim 0.55 \text{ TeV}^{-2}$ [3] results in $B(h \rightarrow \mu^+ \mu^- E_T) \lesssim 10^{-17}$, well below what can be explored with semivisible Higgs decay.

their contributions to Higgs-semivisible decay are further suppressed by additional powers of Λ . As the BSM interaction enters only in the Higgs decay, the relevant EFT expansion parameter is set by Higgs-decay kinematics, $E \sim M_H$, leading to higher-order terms being negligible for Λ in the multi-TeV range.

We do not consider spin-one dark states (X) at dimension six. When written with vector fields, the nominal dimension-six couplings produce amplitudes yielding rates that become ill behaved as $M_X \rightarrow 0$. In gauge-invariant completions where X^μ is a dark gauge boson acquiring mass by some Higgs mechanism [10,49], the effective operators inherit a coefficient that vanishes in the limit of massless X_μ . With masses $M_X \lesssim 50 \text{ GeV}$, as required kinematically for semivisible Higgs decays in the ZH process, the operators are effectively of higher dimension with coefficients (M_X/Λ) for each X_μ that cannot be rewritten as a field strength tensor. Using field strengths $X^{\mu\nu}$ to define a set of operators, on the other hand, pushes the minimal interactions to dimension-eight given the assumed $\mathbb{Z}_2$ symmetry, leading to suppressed rates at the LHC. For these reasons, vector states are not included in this dimension-six analysis.

The operators in Eqs. (2) and (3) without explicit quark fields lead to semivisible Higgs decays with leptons in the final state, whereas those with explicit quark fields result in jets in the final state.

III. PERTURBATIVE UNITARITY BOUNDS

To ascertain the significance of our results, it is useful to compare them with bounds obtained by requiring that perturbative unitarity for certain processes be satisfied. To do so, we first recall that the new physics scale of our effective theory is assumed to be larger than a few TeV. Furthermore, since we use the effective theory to explore H and Z decays, we only need it to be valid up to scales of around a few hundred GeV.

A. Operators with only one Higgs field

For $\mathcal{O}_{e\phi} = (\bar{l}_i e_j H)\phi^\dagger \phi$, we consider tree-level scattering $e^+ e^- \rightarrow \tilde{\phi} \phi$. The leading partial wave is $\ell = 0$, and requiring it to be less than $\frac{1}{2}$ results in the bound³

$$\frac{C_{e\phi}}{\Lambda^2} < \frac{8\pi}{v\sqrt{M_{\phi\phi}^2}} \left(\frac{M_{\phi\phi}^2 - 4M_\phi^2}{M_{\phi\phi}^2} \right)^{-1/4}, \quad (5)$$

where v denotes the usual Higgs vacuum expectation value ($v \simeq 246 \text{ GeV}$). The corresponding operators with quarks $\mathcal{O}_{u\phi}, \mathcal{O}_{d\phi}$ have unitarity bounds that are smaller by a factor of $\sqrt{3}$ relative to that of Eq. (5), which follow from considering the color singlet channel for the two quarks.

³We employ unitarity bounds including threshold kinematic factors instead of the more common asymptotic bounds as required for our comparisons. See, for example, Ref. [50].

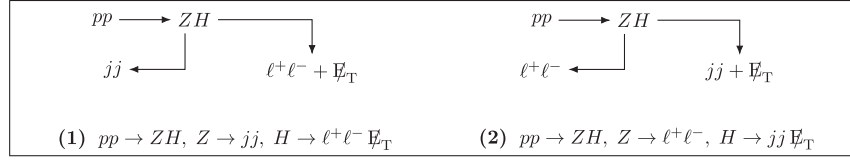


FIG. 1. Signal final states explored in this study for the semivisible leptonic (left) and hadronic (right) Higgs decays.

B. Operators with the factor \$(H^\dagger \vec{D} H)\$

In this case, we consider both tree-level scattering \$HZ \rightarrow \bar{\phi}\phi\$ and \$Z\$ mediated \$\bar{\phi}\phi \rightarrow \bar{\phi}\phi\$ scattering. For the former, the leading partial wave is \$\ell = 1\$, whereas for the latter it is \$\ell = 0\$.

For scalar operators \$\mathcal{O}_{DH\partial\phi}\$, these bounds are, respectively,

$$\begin{aligned} \frac{|C_{DH\partial\phi}|}{\Lambda^2} &< \frac{24\pi M_Z}{g_Z v (M_{\phi\phi}^2 + M_Z^2 - M_H^2)} \frac{\lambda^{1/2}(M_{\phi\phi}^2, M_Z^2, M_H^2)}{M_{\phi\phi}^2 \beta_\phi}, \\ g_Z &= \frac{2M_W}{v} \\ \frac{|C_{DH\partial\phi}|}{\Lambda^2} &\leq \frac{1}{g_Z v^2} \frac{\sqrt{8\pi}}{\left[\left(\frac{(1+\beta_\phi^2)}{\beta_\phi^2} + \frac{M_Z^2}{M_{\phi\phi}^2 \beta_\phi^2} \right) \ln \left(1 + \frac{M_{\phi\phi}^2 \beta_\phi^2}{M_Z^2} \right) - 1 \right]^{1/2}}, \end{aligned} \quad (6)$$

where \$\beta_\phi = \sqrt{1 - \frac{4M_\phi^2}{M_{\phi\phi}^2}}\$ and \$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc\$. For fermionic operators \$\mathcal{O}_{DH\chi\chi}\$ and \$\mathcal{O}_{DH\chi\chi 2}\$, the unitarity bounds are

$$\begin{aligned} \frac{|C_{DH\chi\chi}|}{\Lambda^2} &< \frac{24\pi M_Z}{g_Z v (M_{\chi\chi}^2 + M_Z^2 - M_H^2)} \frac{\lambda^{1/2}(M_{\chi\chi}^2, M_Z^2, M_H^2)}{M_{\chi\chi}^2 \beta_\chi}, \\ \frac{|C_{DH\chi\chi 2}|}{\Lambda^2} &< \frac{1}{g_Z v^2} \frac{\sqrt{8\pi}}{\left[\frac{M_{\chi\chi}^2 (1+\beta_\chi^2)}{2(M_{\chi\chi}^2 - m_\chi^2)} + 1 - \frac{m_\chi^2}{M_{\chi\chi}^2 \beta_\chi^2} \ln \left(1 + \frac{M_{\chi\chi}^2 \beta_\chi^2}{m_\chi^2} \right) \right]^{1/2}}, \end{aligned} \quad (7)$$

and similarly for \$C_{DH\chi\chi 2}\$, with \$\beta_\chi = \sqrt{1 - \frac{4M_\chi^2}{M_{\chi\chi}^2}}\$. These two bounds are similar in magnitude for \$M_{\phi\phi}\$ (or \$M_{\chi\chi}\$) \$\sim\$ 1 TeV, with the latter being stronger for the smaller values of \$M_{\phi\phi}\$ due to the threshold factor in the former.

IV. Z-INVISIBLE DECAY WIDTH

The operators \$\mathcal{O}_{DH\partial\phi}\$, \$\mathcal{O}_{DH\chi\chi}\$, and \$\mathcal{O}_{DH\chi\chi 2}\$ contribute to the invisible decay of the \$Z\$ boson. We calculate the \$Z\$-invisible decay width from these operators with different DM masses using MadGraph5 [51]. To obtain the corresponding constraints, we require these contributions to the invisible \$Z\$ width, \$\Gamma_{\text{inv}}^{\text{new}}\$, to be below the difference between the experimental limit and the SM contribution (\$Z \rightarrow \nu\bar{\nu}\$) at the 95% confidence level [52],

$$\Gamma_{\text{inv}}^{\text{new}} < 2.04 \text{ MeV} \quad (95\% \text{ CL}). \quad (8)$$

As a sanity check, we have verified that these contributions to the total Higgs width do not result in Higgs-decay branching fractions larger than 20%, or about twice the current 95% CL upper bound on \$\text{BR}(H \rightarrow \text{invisible})\$ [53].

V. COLLIDER PHENOMENOLOGY

The largest Higgs production cross section at the LHC originates from gluon fusion, but this process suffers from a large QCD background. For semivisible modes generating \$E_T\$, it is therefore better to choose the cleanest production mechanism at the expense of a lower cross section. This leads us to focus on the conventional channel for this type of study, \$pp \rightarrow ZH\$, \$Z \rightarrow jj\$, \$H \rightarrow \ell^+\ell^- E_T\$ [1], and \$pp \rightarrow ZH\$, \$Z \rightarrow \ell^+\ell^-\$, \$H \rightarrow jj E_T\$ for the hadronic DSMEFT operators [54], shown in Fig. 1 for illustration. We treat the leptonic and hadronic semivisible Higgs decays as two mutually exclusive analyses, despite the common object-level signature \$2\ell + 2j + E_T^{\text{miss}}\$. The channels are disentangled by the \$Z\$-tag assignment: we require the tagging system (either \$\ell^+\ell^-\$ or \$jj\$) to reconstruct to the \$Z\$ mass. The relevant Feynman diagrams for semivisible Higgs-decay mechanisms in the SM and in DSMEFT are shown in Fig. 2.

Using model files in the Universal FeynRules Output format generated by FeynRules [55] as input, we generate signal (with the presence of the DSMEFT operators) and background events for \$pp \rightarrow ZH\$, \$H \rightarrow\$ semivisible final states in MadGraph5 [51] at leading order, with the PDF4LHC15_nlo_mc parton distribution function set [56] and \$\sqrt{s} = 14\$ TeV. The renormalization and factorization scales are set to the partonic center-of-mass energy \$\sqrt{\hat{s}}\$. For the inclusive \$t\bar{t}\$ background, we employ the MLM matching scheme [57] with \$X_{\text{Qcut}} = 20\$ GeV and \$Q_{\text{cut}} = 30\$ GeV to match the partonic jets to those coming from the parton showers [58].⁴ The parton-level events are then processed with PYTHIA8 [59,60] to simulate parton showering and hadronization. Detector effects are incorporated using DELPHES3 [61], configured with the CMS detector card.

⁴Here \$X_{\text{Qcut}}\$ is the minimum matrix-element-level jet measure (\$k_T\$), while \$Q_{\text{cut}}\$ is the corresponding PYTHIA shower-level matching scale; together they define the transition between matrix-element partons and parton-shower emissions.

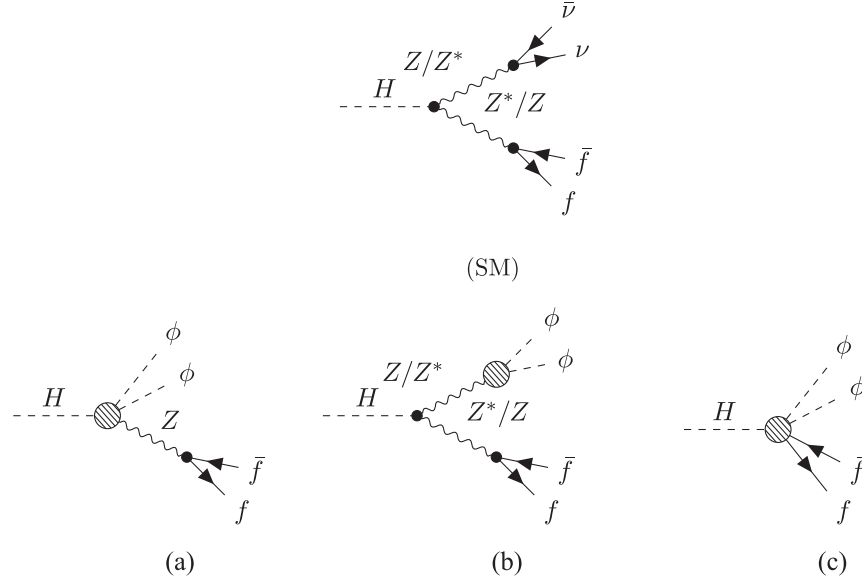


FIG. 2. Representative Feynman diagrams illustrating semivisible Higgs decays, independent of the production mode. Top: the SM process. Bottom: possible EFT-induced contributions. The cross-hatched circles represent insertions of DSMEFT operators.

Both categories of the signal final states presented in Fig. 1 contain two leptons, two jets, and E_T . We select events with $p_T(\ell_1) > 20$ GeV for the leading lepton and $p_T(\ell_2) > 10$ GeV for the subleading lepton. In addition, we require the pseudorapidity of all leptons in the range $|\eta| < 2.5$. To ensure lepton isolation, we use the energy-flow objects from DELPHES, following the prescription of Ref. [62]. The isolation criterion is given by

$$\frac{\sum p_{T,\ell}^{R < r}}{p_{T,\ell}} < I, \quad \ell = e, \mu, \quad (9)$$

where the isolation cone size is fixed to $r = 0.3$, and the threshold I is set to 0.12 for electrons and 0.25 for muons.

We use FastJet 3.3.2 [63] to reconstruct jets from the DELPHES energy-flow objects, which emulates a particle-flow reconstruction algorithm [64] with the anti- k_T algorithm [65] and a radius parameter $R = 0.4$. Only jets with $p_T^j > 20$ GeV and $|\eta| < 4.0$ are considered. Although b jets are absent in the signal, they arise in the dominant top-quark background. To identify b jets, we match the reconstructed jets to b quarks at the parton level, requiring them to lie within $|\eta| < 2.5$ and within a cone of $\Delta R < 0.3$ around the jet axis. The b -tagging efficiency (ϵ_b^{eff}) in our study arises solely from this matching procedure and is essentially the same for all the background processes having top quarks before applying analysis cuts. After the kinematic selection cuts, ϵ_b^{eff} varies mildly from process to process (typically ~ 0.78 – 0.86), reflecting selection-induced differences in jet kinematics and event topology. The top-quark backgrounds are reduced by vetoing events containing any reconstructed b jet.

A. Higgs-neutrino floor

For the semivisible Higgs decay $H \rightarrow Z + E_T \rightarrow 2\ell + E_T$, there is an irreducible background $H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ dubbed the “Higgs-neutrino floor,” which has been studied for several models that produce $Z + E_T$ [1,46,53,66]. In our study, we expect this background to affect results for all of the operators with factors of $(H^\dagger \overleftrightarrow{D}^\mu H)$, as these operators result in diagrams such as those in the center panel of Fig. 2. As demonstrated below, however, this background is not dominant in our case. For the remaining operators, with two explicit fermion fields, the two leptons (or jets) in the final state $2\ell + E_T$ do not reconstruct to the Z -boson mass, as shown in the right panel of Fig. 2. All in all, the Higgs-neutrino-floor background is a reducible background in our study.

In Fig. 3, we display the dilepton invariant mass distribution, the invisible mass distribution (which is not observable), and the transverse mass $M_T(\ell, \ell, E_T)$ distribution for the SM, as well as for all leptonic DSMEFT operators. The dilepton and invisible mass distributions for the SM show a large peak at the Z mass, as expected. In these figures we use the values $\mathcal{C} = 1$, $\Lambda = 1$ TeV and have taken $M_{\text{DM}} = 10$ GeV as a representative value, chosen to lie in between the massless limit and the kinematic suppression that sets in for $M_{\text{DM}} \gtrsim 30$ GeV.

For the DSMEFT operators that induce the topology in the center panel of Fig. 2, $\mathcal{O}_{DH\partial\phi}$ and $\mathcal{O}_{DH\chi\chi}$, there is a large Z peak in the invisible mass distributions, but only a very small one in the dilepton mass distributions. This curious feature is due to a partial cancellation between the topologies in the first two diagrams in the bottom panel of Fig. 2 when the dilepton mass $M_{\ell\ell} \sim M_Z$. The sum of these two

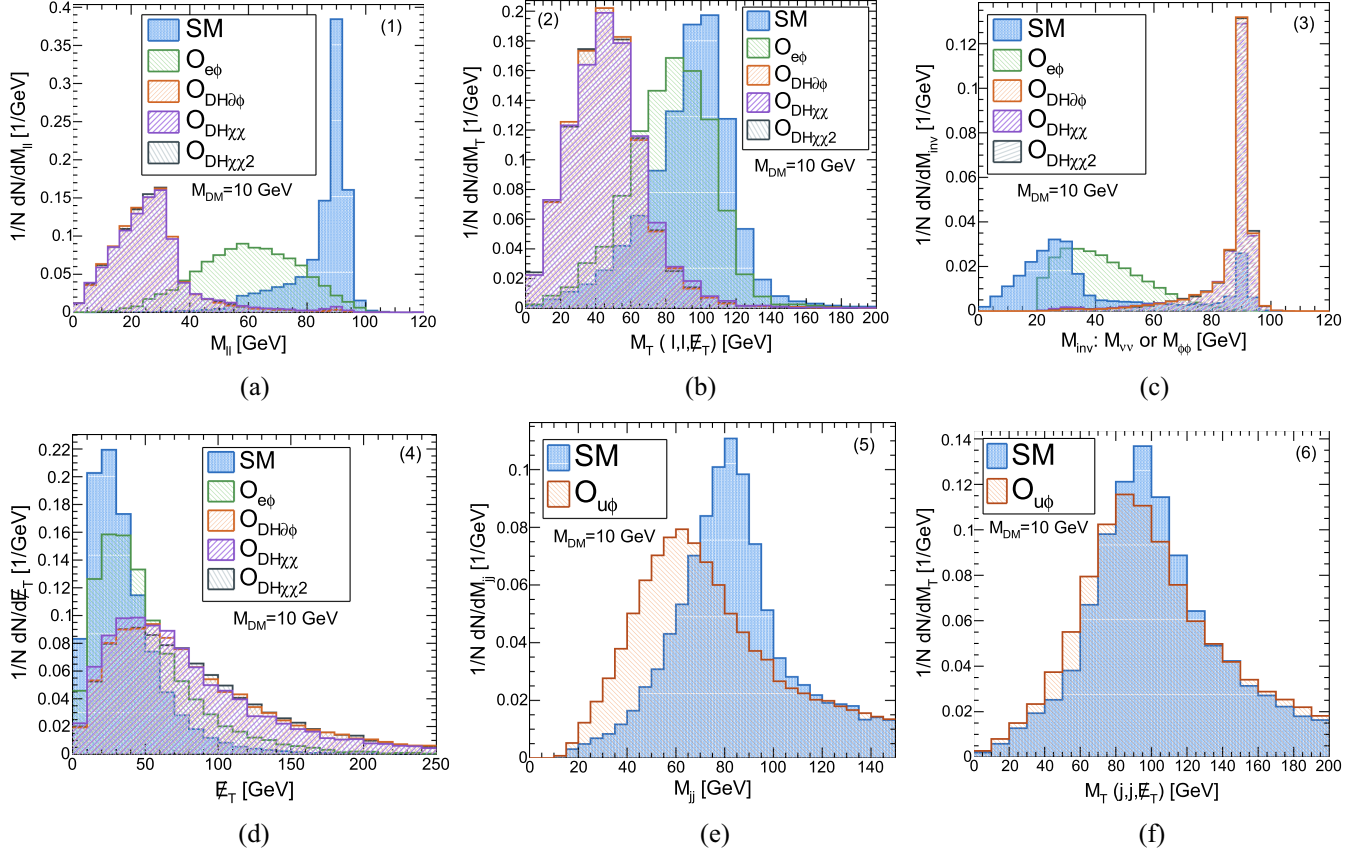


FIG. 3. Distributions for the topology (1) in Fig. 1: (a) reconstructed invariant mass of the two leptons, (b) transverse mass of the two leptons and E_T , (c) parton-level invariant mass of the invisible system, namely, $\nu\bar{\nu}$ for the SM contribution through $H \rightarrow ZZ^*$ and $\phi\phi$ for DSMEFT, (d) E_T , (e) invariant mass of the reconstructed jets, and (f) transverse mass of the two jets and E_T . All histograms are normalized to unit area and therefore show shape only. We use $C = 1$, $\Lambda = 1$ TeV, and $\sqrt{s} = 14$ TeV in all panels.

diagrams is proportional to

$$\propto \left(1 - \frac{1}{1 - M_{\phi\phi}^2/M_Z^2}\right) \lesssim 0.15. \quad (10)$$

The numerical result for $M_{\ell\ell} \sim M_Z$ follows from energy conservation, which requires $M_{\phi\phi} < M_H - M_Z$. This has two important consequences:

- (i) The SM background $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\nu\bar{\nu}$ is reducible for these DSMEFT scenarios and a cut on the dilepton invariant mass $M_{\ell\ell}$ effectively removes it, thereby eliminating the Higgs-neutrino floor.
- (ii) The dominant contribution to semivisible Higgs decays for these operators is due to invisible Z decays. As we show below, invisible Z decays provide the main constraint in this case.

Operators that only generate the contact topology of the right panel of Fig. 2, e.g., $\mathcal{O}_{e\phi}$, do not show Z peaks in either distribution. We quantify below the importance of the different SM background processes for this case and note that semivisible Higgs decays yield the strongest constraint on these couplings.

In semivisible Higgs decays, it is not possible to fully reconstruct the Higgs boson invariant mass. Instead, we reconstruct the dilepton- E_T transverse mass,

$$\begin{aligned} M_T^2(\ell, \ell, E_T) &= (p_{T1} + p_{T2} + E_T)^2 - |\vec{p}_{T1} + \vec{p}_{T2} + \vec{p}_T^{\text{miss}}|^2 \\ &= 2p_{T1}p_{T2}(1 - \cos \Delta\phi_{12}) \\ &\quad + 2p_{T1}E_T(1 - \cos \Delta\phi_{1m}) \\ &\quad + 2p_{T2}E_T(1 - \cos \Delta\phi_{2m}), \end{aligned} \quad (11)$$

which we show in Fig. 3(b). The $M_T(\ell, \ell, E_T)$ spectrum is kinematically bounded above by the Higgs mass $M_H \simeq 125$ GeV; this end point can be exploited to suppress backgrounds with similar final states that do not originate from a Higgs boson decay. For the derivative DSMEFT operators $\mathcal{O}_{DH\partial\phi}$ and $\mathcal{O}_{DH\chi\chi}$, the distribution shifts to lower values since the lepton p_T distribution peaks at much lower p_T , as can be seen in Fig. 4.

For the hadronic semivisible Higgs-decay modes, we present the invariant mass of the two reconstructed jets and the transverse mass of the two jets and E_T in Figs. 3(e) and 3(f), respectively. The broadening of the peaks relative to

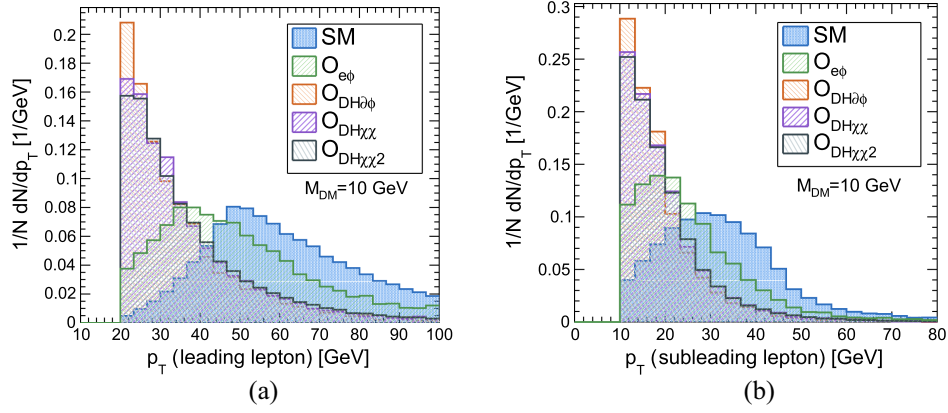


FIG. 4. Distributions of the transverse momentum of (a) the leading lepton and (b) the subleading lepton for the SM and different DSMEFT operators. All histograms are normalized to unit area and therefore show shape only. We use $C = 1$, $\Lambda = 1$ TeV, and $\sqrt{s} = 14$ TeV in both panels.

those in leptonic final states is expected due to ambiguities in the jet reconstruction.

Although both channels yield $2j + 2\ell + E_T^{\text{miss}}$, the signal is essentially channel specific: lepton-only operators populate the leptonic category and quark operators the hadronic category, with only small spillover (0.7% and 2%, respectively). For SM backgrounds, the cuts $m_{\ell\ell} < 60$ and $m_{jj} < 60$ GeV suppress events where the corresponding pair comes from an on-shell Z , making the contribution to the other channel negligible.

B. Signal and SM backgrounds

In addition to SM ZH production followed by the decay chain $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\nu\bar{\nu}$, several other SM processes are potential sources of background to the semivisible Higgs decays. The leading-order estimates for these background cross sections are presented in Table I, whereas

TABLE I. Leading-order cross sections at $\sqrt{s} = 14$ TeV at the LHC with selections $p_T(j) > 20$, $p_T(\ell_1) > 20$, and $p_T(\ell_2) > 10$ GeV. SM backgrounds (including the relevant branching fractions); for $t\bar{t}Z$, tWZ , and WWZ , the quoted rates are inclusive sums over all decay combinations that can yield the reconstructed $2 - 3\ell + jj + E_T$ final state, allowing for the possibility that in the 3ℓ case one lepton is missed.

Process	$\sigma_{\text{SM,LO}}$ (fb)
ZH-lep: $H \rightarrow ZZ^* \rightarrow \ell^+\ell^- + \nu\bar{\nu}, Z \rightarrow jj$	0.05
ZH-had: $H \rightarrow ZZ^* \rightarrow 2j + \nu\bar{\nu}, Z \rightarrow \ell^+\ell^-$	0.05
ZZ, $Z \rightarrow jj, Z \rightarrow \ell^+\ell^-$	547
ZZZ, $Z \rightarrow jj, Z \rightarrow \ell^+\ell^-, Z \rightarrow \nu\bar{\nu}$	0.33
WWZ, $\rightarrow jj\ell^+\ell^+\nu\bar{\nu}$	2.2
$t\bar{t}Z, \rightarrow jj\ell^+\ell^-\nu\bar{\nu}b\bar{b}$	17.7
$tWZ, \rightarrow jj\ell^+\ell^-\nu\bar{\nu}b$	6.7
ZH-W: $H \rightarrow WW^* \rightarrow \ell^+\ell^- + \nu\bar{\nu}, Z \rightarrow jj$	0.06
$t\bar{t}$ -inc: $t \rightarrow b\ell^+\nu, \bar{t} \rightarrow \bar{b}\ell^-\bar{\nu}$	45719

representative values for the signal cross sections for different operator contributions are presented in Table II. These background cross sections are significantly larger than the signal, and we now turn our attention to ways of suppressing them. QCD multijet backgrounds are negligible in this channel after requiring two isolated leptons and sizable E_T [67,68], so we do not include them.

We begin with a simple cut-based analysis to understand the effectiveness of various kinematic variables in reducing the background for the contributions from the operators $\mathcal{O}_{DH\chi\chi}, \mathcal{O}_{DH\chi\chi 2}, \mathcal{O}_{DH\partial\phi}$, and $\mathcal{O}_{e\phi}$ with $M_{\text{DM}} = 10$ GeV and $\frac{C}{\Lambda^2} = 10$ TeV $^{-2}$ as benchmark points. In Fig. 5, we compare several distributions for different background channels at the reconstructed level and compare them with the signal distributions for $\mathcal{O}_{DH\chi\chi}$, while the other signal distributions can be found in Fig. 3. All of these backgrounds have a peak at the Z -boson mass, which is dominant for the ZH-lep, ZZ, ZZZ, and WWZ channels. An $M_{\ell\ell} < 60$ GeV selection cut reduces these backgrounds significantly.

A selection cut of $M_T(\ell, \ell, E_T) < 125$ GeV significantly reduces the backgrounds from ZZZ, WWZ, $t\bar{t}Z, tWZ$ as shown in Fig. 5(b). A selection cut of

TABLE II. Contributions to total cross section (with cuts) from DSMEFT operators. The total cross section is $\sigma_{\text{TOT,LO}} = \sigma_{\text{SM,LO}} + \sum \frac{C_i^2}{\Lambda^4} f_{ii} = \sigma_{\text{SM,LO}} + \delta\sigma_{\text{LO}}$, since there is no interference between the SM and the DSMEFT contributions.

WC	$\frac{C}{\Lambda^2}$ [TeV $^{-2}$]	$\delta\sigma_{\text{LO}}$ (fb)
$C_{DH\partial\phi}$	10	0.005
$C_{e\phi}$	10	0.004
$C_{u\phi}$	10	0.001
$C_{d\phi}$	10	0.001
$C_{DH\chi\chi}$	10	0.021
$C_{DH\chi\chi 2}$	10	0.019

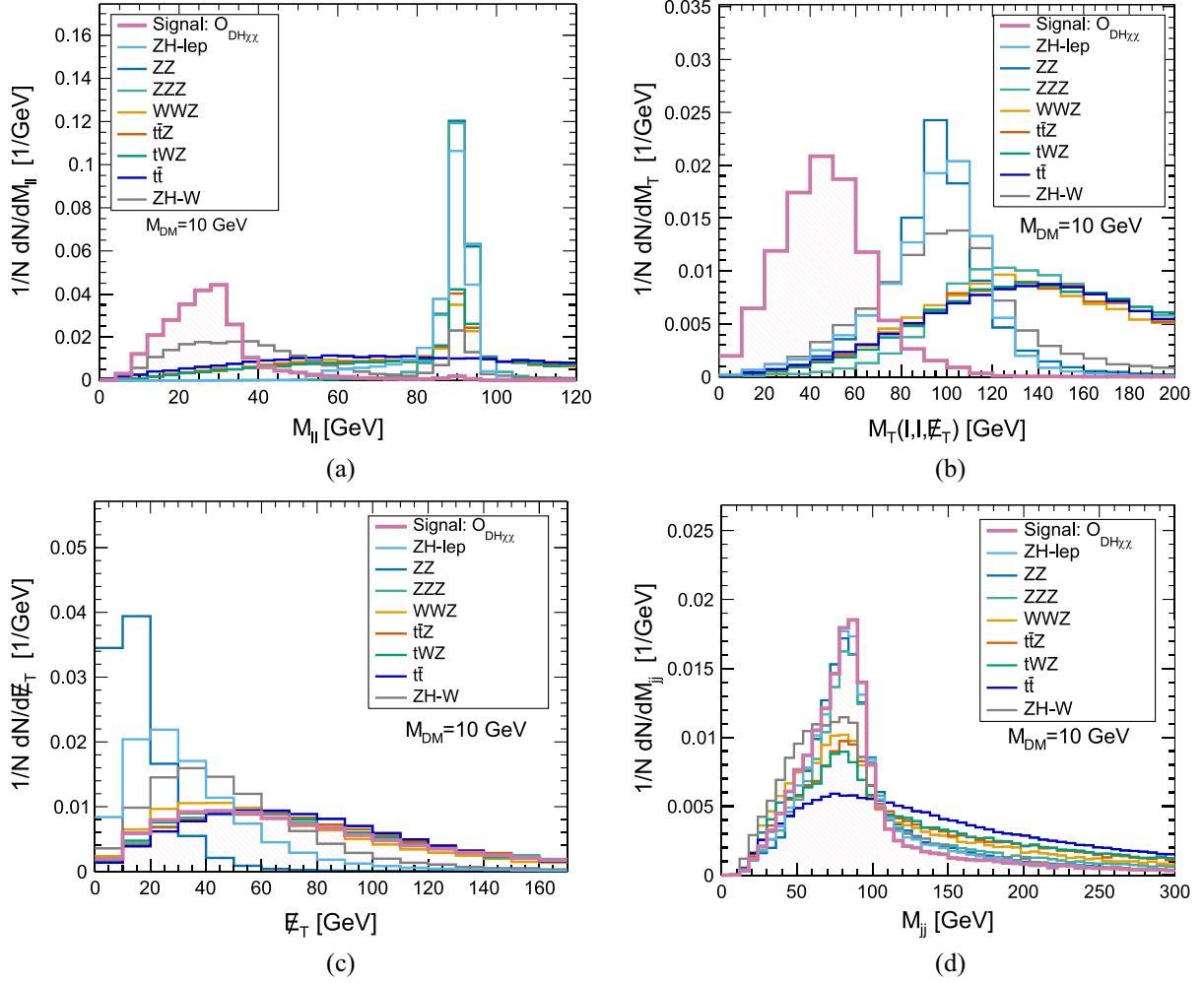


FIG. 5. Distributions of (a) the dilepton invariant mass, (b) the transverse mass of the two leptons and E_T , (c) E_T , and (d) the invariant mass of the two leading non- b jets. All histograms are normalized to unit area and therefore show shape only. We use $C = 1$, $\Lambda = 1$ TeV, and $\sqrt{s} = 14$ TeV in all cases.

$E_T > 20.0$ GeV turns out to be helpful for reducing the ZZ^* background and to some extent for the ZH-lep background. Finally, the top-quark background includes b jets in the final state and can be suppressed by vetoing these jets. An example cut-flow-based analysis is presented in Tables III and IV. For the leptonic semivisible Higgs decay, where the other Z decays hadronically, we impose an

additional Z-tag requirement $70 < M_{jj} < 110$ GeV which further suppresses the $t\bar{t}$ background.

The total background cross section after cuts is $\sigma_{bkg} = 1.5$ fb. For the illustrative choice of $\frac{C}{\Lambda^2} = 10$ TeV $^{-2}$ and $M_{DM} = 10$ GeV used in Table III, we find the signal sensitivities to C_{DHXX} and C_{DHXX2} are around $S_0 = S/\sqrt{S+B} = 0.18\sigma$, $S_0 = 0.045\sigma$ for $C_{DH\partial\phi}$, and lowest

TABLE III. Effects of various selection criteria on the signals corresponding to $(C_{DHXX}, C_{DHXX2}, C_{DH\partial\phi}, C_{e\phi})$, with $M_{DM} = 10$ GeV and $\Lambda = 1$ TeV. The Wilson coefficients C are dimensionless. The rows show the cumulative effects of applying the various cuts.

	$C_{DHXX} = 10$	$C_{DHXX2} = 10$	$C_{DH\partial\phi} = 10$	$C_{e\phi} = 10$
Cross section (fb)	0.021	0.019	0.005	0.004
$M_{\ell\ell} < 60$ GeV	0.013	0.012	0.0026	0.0011
$M_T(\ell, \ell, E_T) < 125$ GeV	0.013	0.012	0.0026	0.0011
$E_T > 20.0$ GeV	0.012	0.011	0.0023	0.0009
$70 < M_{jj} < 110$ GeV + N(b - jets) = 2	0.004	0.004	0.001	0.0003
b -jet veto	0.004	0.004	0.001	0.0003

TABLE IV. Effects of various selection criteria on the SM backgrounds : ZH-lep, ZH-W, ZZ, ZZZ, WWZ, $t\bar{t}Z$, tWZ , and $t\bar{t}$ -inc. The rows show the cumulative effects of applying the various cuts.

	ZH-lep	ZH-W	ZZ	ZZZ	WWZ	$t\bar{t}Z$	tWZ	$t\bar{t}$ -inc
Cross section (fb)	0.05	0.06	547	0.33	2.2	17.7	6.7	45 719
$M_{\ell\ell} < 60$ GeV	1.35×10^{-3}	0.014	5.87	4.27×10^{-3}	0.15	2.4	0.7	3533
$M_T(\ell, \ell, E_T) < 125$ GeV	1.33×10^{-3}	0.013	5.76	2.30×10^{-3}	0.097	1.4	0.4	2025
$E_T > 20.0$ GeV	9.7×10^{-4}	0.011	1.12	1.89×10^{-3}	0.085	1.2	0.36	1782
$70 < M_{jj} < 110$ GeV + $N(b\text{-jet}) = 2$	2.3×10^{-4}	0.002	0.09	2×10^{-4}	0.016	0.13	0.033	74
b -jet veto	2.2×10^{-4}	0.002	0.09	2×10^{-4}	0.016	0.0065	0.006	1.4

for $C_{e\phi}$ with $\mathbb{S}_0 = 0.013\sigma$. As there is no DSMEFT-SM interference, the DSMEFT contribution is purely quadratic and kinematic shapes also remain unchanged over the range of C values considered here. So we can rescale the individual coefficients by

$$C^{\min} = C_0 \times \left(\frac{\mathbb{S}^{\text{target}}}{\mathbb{S}_0} \right)^{1/2}, \quad (12)$$

to find the minimum values of $C^{\min}$ required to obtain the target sensitivity $\mathbb{S}^{\text{target}}$, given an initial value C_0 . This indicates that the minimum values to achieve a 3σ signal significance is around $C^{\min} \simeq 40 \text{ TeV}^{-2}$ for $C_{DH\chi\chi}$ and $C_{DH\chi\chi^2}$, $C^{\min} \simeq 81 \text{ TeV}^{-2}$ for $C_{DH\partial\phi}$, and $C^{\min} \simeq 152 \text{ TeV}^{-2}$ for $C_{e\phi}$ with a cut-based analysis.

A certain amount of improvement is expected through a multivariate analysis (MVA), which takes into account the possible correlations among variables and optimizes the selection criteria through a multidimensional variable

space. We employ a boosted decision tree (BDT) with gradient boosting and decorrelation within the standard ROOT TMVA framework [69,70]. This method builds a sequence of disjoint decision trees by optimizing cuts on the training kinematic variables. After each tree, events misclassified as signal or background are given higher weights, and a new tree is trained on this reweighted sample. Iterating this procedure progressively refines the classifier and finally yields an optimized discriminator. In addition to the kinematic variables described above, we also use various $\Delta\phi$ distributions, such as $\Delta\phi(\ell, \ell)$, $\Delta\phi(\ell_1, E_T)$, and $\Delta\phi(\ell_2, E_T)$, as well as the p_T of the leading lepton, the invariant mass of the two leading jets, $M(\text{jet1}, \text{jet2})$, for the hadronically decaying Z boson in the signal (see Fig. 1), the invariant mass $M(\ell, \ell, j, j)$, the minimum between the transverse mass combinations of the E_T and the two leptons [$M_T^{\min}(\ell, E_T)$], $R_T(2) = (p_T(j_1) + p_T(j_2)) / \sum_i p_T(j_i)$ [71], the number of non- b jets with $p_T > 20$ GeV, and the resultant p_T of the two leptons. These variables are presented in Table V according to their

TABLE V. Ranking of input variables for the leptonic semivisible Higgs decays shown in Fig. 1 (left) corresponding to the $\mathcal{O}_{DH\chi\chi}$ scenario ($\frac{C_{DH\chi\chi}}{\Lambda^2} = 10 \text{ TeV}^{-2}$ and $M_{DM} = 10$ GeV) by relative separation power. The higher the rank, the more discriminating power.

Rank	Variable	Description
1	$M_T(\ell, \ell, E_T)$	Transverse mass of two leptons and E_T
2	$M_{\ell\ell}$	Invariant mass of two leptons
3	$M_T^{\min}(\ell, E_T)$	Minimum of the transverse masses $M_T(\ell_1, E_T)$ and $M_T(\ell_2, E_T)$
4	$M(\ell, \ell, j, j)$	Invariant mass of the ℓ_1, ℓ_2, j_1 and j_2
5	$p_T(\ell)$	Transverse momentum of the leading lepton
7	$\Delta\phi(\ell_1, E_T)$	$\Delta\phi$ between leading lepton and E_T
8	$p_T(\ell_1)$	p_T of the leading leptons
9	$R_T(2)$	Ratio of $p_T(j_1) + p_T(j_2)$ and HT (scalar sum of p_T of all jets)
10	$N(b\text{-jets})$	Number of non- b jets with $p_T > 20$ GeV
11	$M(\text{jet1}, \text{jet2})$	Invariant mass of two jets
12	$\Delta\phi(\ell, \ell)$	$\Delta\phi$ between two leptons
13	$p_T(\ell_1, \ell_2)$	Resultant p_T of the two leptons
14	$\Delta\phi(\ell_2, E_T)$	$\Delta\phi$ between leading lepton and E_T
15	E_T	Missing E_T

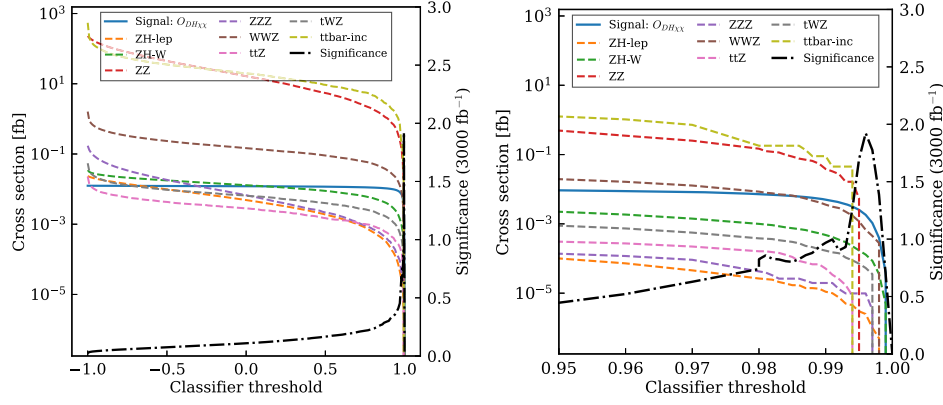


FIG. 6. Distributions of the effective cross sections and signal significance at the LHC, with $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000 \text{ fb}^{-1}$ as functions of the MVA discriminator for the fermionic operator scenario $\mathcal{O}_{DHXX}$ ($\frac{C_{DHXX}}{\Lambda^2} = 10 \text{ TeV}^{-2}$ and $M_{DM} = 10 \text{ GeV}$), where we train the MVA with signal and background events after b -jet vetoing and requiring two leptons. The right panel shows an enlarged view of the left panel, highlighting the region with larger classifier-threshold values.

relative power of separation or effectiveness in background reduction in decreasing order. We use 60% of the events from each signal and background sample for training the BDT, reserving the remaining 40% for testing. The final BDT classifier is then used as a single discriminant to separate signal from background.

As an illustration, we show the effective cross sections for the fermionic DM scenario with the operator $\mathcal{O}_{DHXX}$, together with the corresponding SM backgrounds, after applying a cut on the BDT (MVA) output classifier in Fig. 6. For each choice of the BDT threshold, we also report the resulting expected significance at an integrated luminosity of $\mathcal{L} = 3000 \text{ fb}^{-1}$. The scan over thresholds highlights the usual trade-off between background rejection and signal efficiency and identifies the working point that maximizes the expected sensitivity. Applying a classifier cut at 0.997, we observe a significant improvement in signal significance ($S/\sqrt{S+B}$) relative to the simple cut-based analysis presented above.⁵

Finally, we observe that the signal characteristics vary depending on the choice of operators and DM masses. To separately treat different kinematic regions, we split the signal into three regions based on the DM mass: (a) $M_{DM} : [1, 20] \text{ GeV}$, (b) $M_{DM} : [20, 40] \text{ GeV}$, (c) $M_{DM} : [40, 50] \text{ GeV}$. For each DSMEFT operator, we perform the MVA separately for these three kinematic regions by training the BDT at the mean values of M_{DM} corresponding to each region. Using the BDT that is trained at the nearest masses, we first calculate the sensitivity to each of the operators with different DM-mass choices for a given value of the coefficient and then use the scaling of Eq. (12) to calculate the lower limit of each coefficient that can be probed at the HL-LHC with

3000 fb^{-1} at the 3σ level. The results are presented in Fig. 9.

C. Operator categories and kinematic discrimination

We consider two operator classes: (i) derivative currents $H^\dagger \overleftrightarrow{D}^\mu H$ and (ii) Yukawa-type interactions $\bar{l}_p e_r H$ coupling to the postulated new noninteracting particles. These structures lead to distinct kinematic distributions (Figs. 3 and 4). We now examine whether LHC kinematics can discriminate between these two categories of operators. As a benchmark, we take $M_{DM} = 10 \text{ GeV}$ and compare one fermionic DM operator $\mathcal{O}_{DHXX}$ and one scalar DM operator $\mathcal{O}_{DH\partial\phi}$ with the Yukawa-type operator $\mathcal{O}_{e\phi}$. In addition to the variables shown earlier, we study the azimuthal angles between the decay products of the Higgs boson. Figure 7 shows that $\Delta\phi(\ell_1, \ell_2)$ discriminates between the derivative operators $\mathcal{O}_{DHXX}$ and $\mathcal{O}_{DH\partial\phi}$ and the Yukawa-like operators $\mathcal{O}_{e\phi}$ very well. By contrast, the $\Delta\phi(\ell, E_T)$ distributions are much flatter, but still retain some discriminating power. Together with Figs. 3 and 4, These basic azimuthal observables can help distinguish the two operator categories.

For a quantitative assessment, we train two separate MVAs, taking $\mathcal{O}_{e\phi}$ as the “signal” and, in turn, $\mathcal{O}_{DH\partial\phi}$ and $\mathcal{O}_{DHXX}$ as the “background.” The input kinematic variables include $M(\ell\ell)$, $M_T(\ell, \ell, E_T)$, $p_T(\ell_1)$, $p_T(\ell_2)$, E_T , and the three azimuthal angles $\Delta\phi(\ell_1, \ell_2)$, $\Delta\phi(\ell_1, E_T)$, and $\Delta\phi(\ell_2, E_T)$. As expected, the BDT identifies $M(\ell\ell)$, $M_T(\ell, \ell, E_T)$, and $\Delta\phi(\ell_1, \ell_2)$ as the most powerful discriminants, followed by the remaining variables. The resulting classifier outputs and radius of curvature (ROC) curves are shown in Fig. 8. Overall, operators

containing the current $H^\dagger \overleftrightarrow{D}^\mu H$ are efficiently separated from those with the Yukawa structure $\bar{l}_p e_r H$. This kind of kinematic discrimination among operator classes will be

⁵But note that BDT includes more variables than our cut-based analysis.

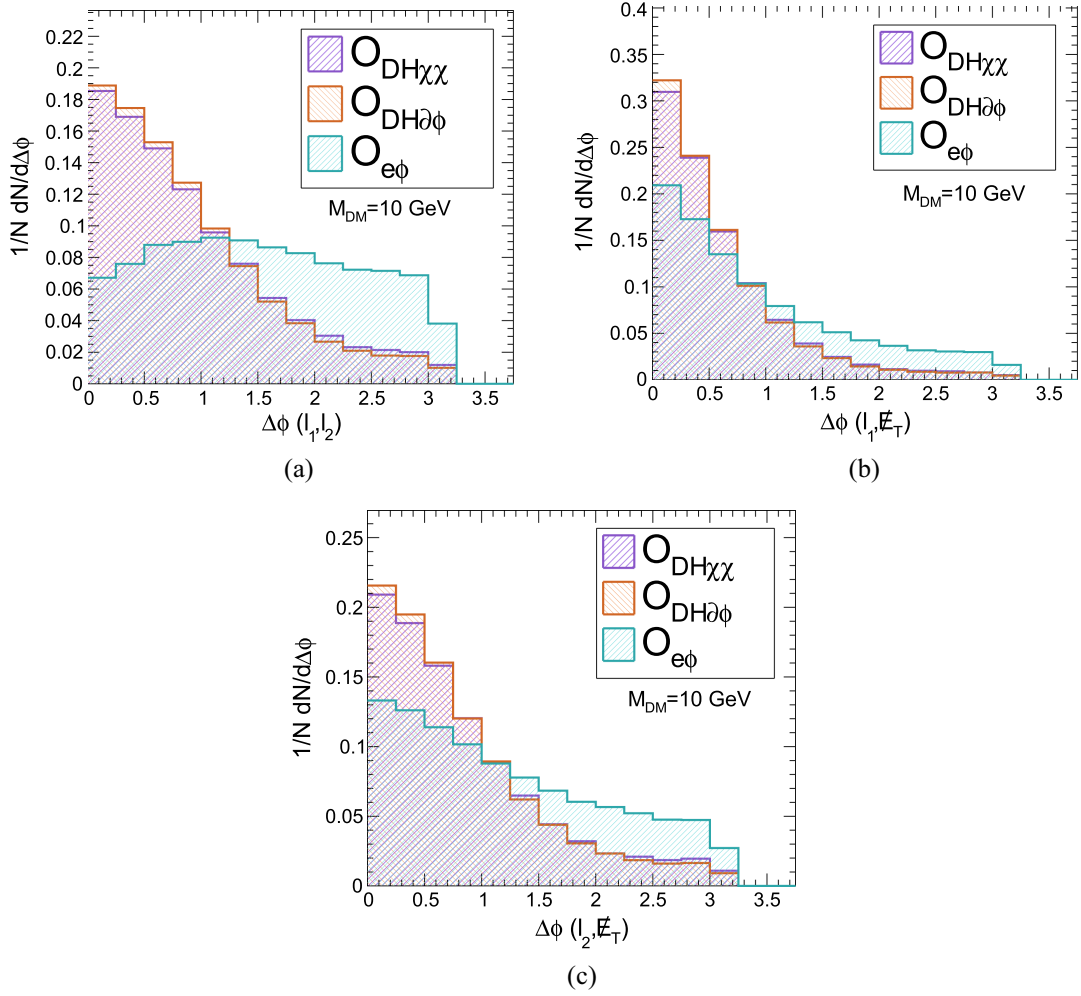


FIG. 7. Distributions of the azimuthal angular separations (a) $\Delta\phi(\ell_1, \ell_2)$, (b) $\Delta\phi(\ell_1, E_T)$, and (c) $\Delta\phi(\ell_2, E_T)$ for selected operators. All histograms are normalized to unit area and therefore show shape only. We use $C = 1$, $\Lambda = 1$ TeV, and $\sqrt{s} = 14$ TeV in all panels.

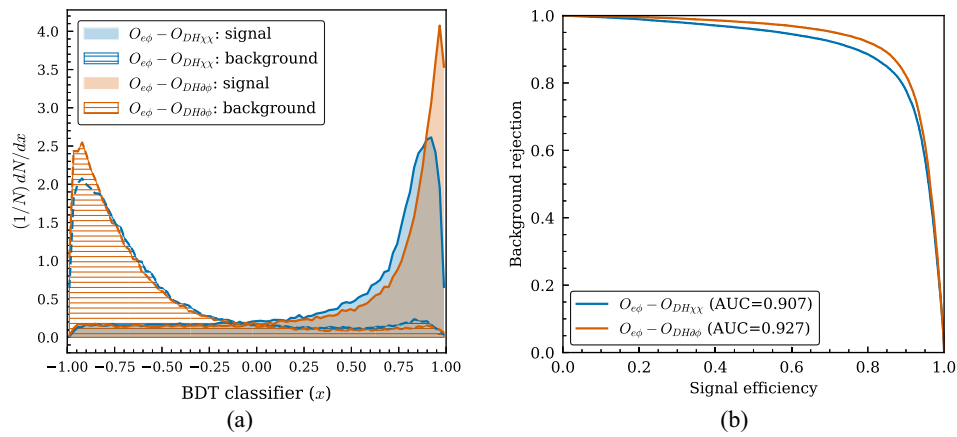


FIG. 8. Distributions of (a) the classifier response and (b) the ROC curve, considering $\mathcal{O}_{e\phi}$ as signal and $\mathcal{O}_{DH\partial\phi}$, $\mathcal{O}_{DH\chi\chi}$ individually as backgrounds. Events with $M_{DM} = 10$ GeV are used for these plots, with $C = 1$, $\Lambda = 1$ TeV, and $\sqrt{s} = 14$ TeV. The area under the curve (AUC) quantifies the performance of the BDT.

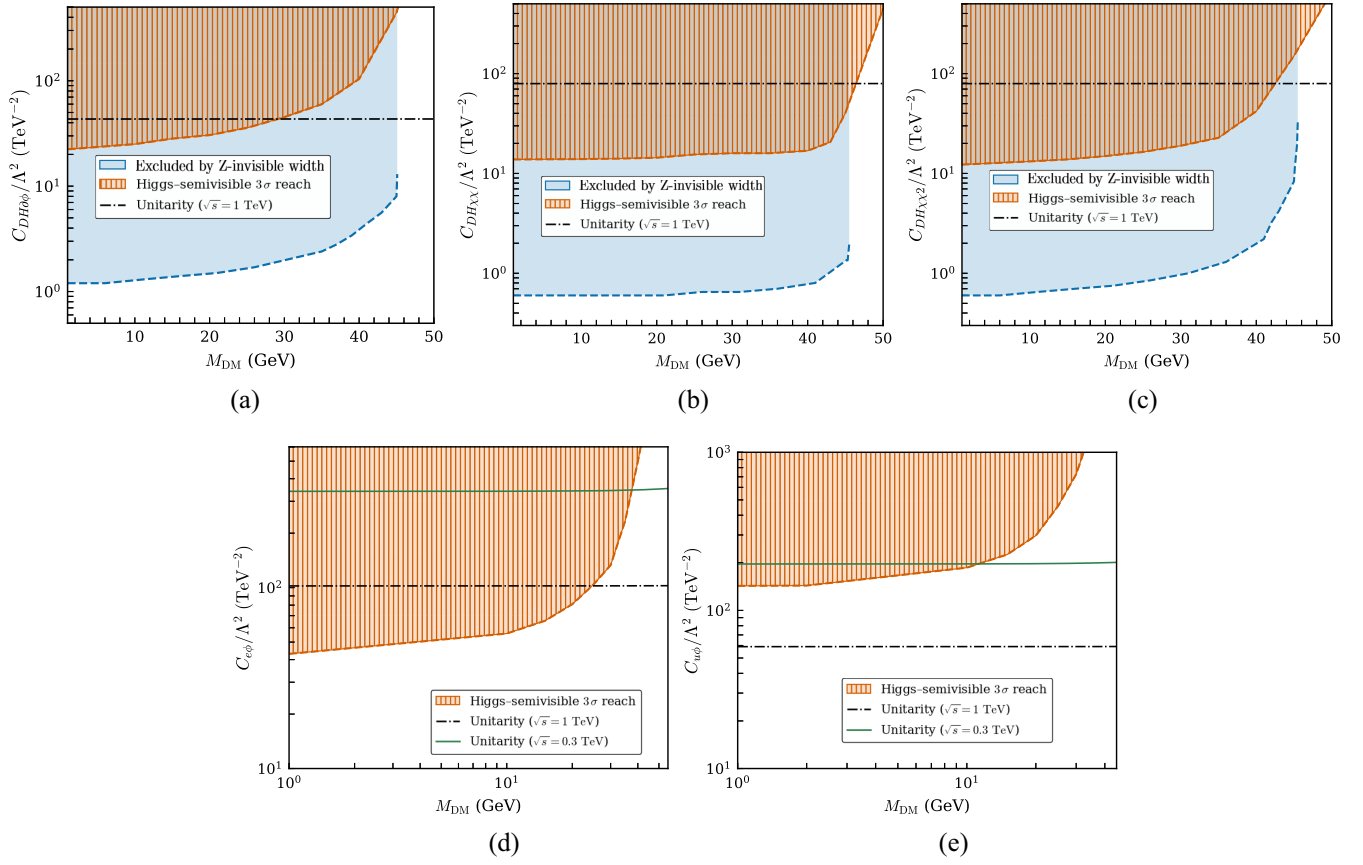


FIG. 9. Regions excluded by the Z-boson invisible-decay limits at 95% CL (blue), obtained using Eq. (8), and the 3σ sensitivity to the various coefficients at the HL-LHC with $\mathcal{L} = 3000 \text{ fb}^{-1}$ and $\sqrt{s} = 14 \text{ TeV}$, obtained from the semivisible Higgs-decay multivariate analysis. Here, we include only first- and second-generation fermions. The unitarity bounds shown here correspond to $\phi\phi \rightarrow \phi\phi$ scattering, Eqs. (6) and (7), for (a)–(c), and to $e^+e^-(u\bar{u}) \rightarrow \phi\bar{\phi}$, Eq. (5), for (d),(e). The sensitivity from semivisible Higgs decays to $\mathcal{O}_{d\phi}$ coincides with that of $\mathcal{O}_{u\phi}$.

instrumental in inferring plausible UV completions if a new-physics signal is discovered.

VI. RESULTS

In Fig. 9 we present the HL-LHC 3σ sensitivity of the semivisible Higgs-decay analysis, with $\mathcal{L} = 3000 \text{ fb}^{-1}$ and $\sqrt{s} = 14 \text{ TeV}$ alongside constraints from the Z-invisible width and partial-wave unitarity for the DSMEFT operators considered. For operators involving the derivative current $H^\dagger \overleftrightarrow{D}^\mu H$, the Z-invisible width provides the strongest bound up to $m_{\text{DM}} \simeq 45 \text{ GeV}$, while the semivisible Higgs analysis becomes competitive only for larger m_{DM} . In contrast, for the operators $\mathcal{O}_{e\phi}$, $\mathcal{O}_{u\phi}$, and $\mathcal{O}_{d\phi}$, the semivisible Higgs-decay analysis is the most sensitive. The partial-wave unitarity bounds are evaluated at $\sqrt{s} = 1$ and 0.3 TeV , the latter being close to the Higgs-decay scale. Most of the parameter space probed by the semivisible Higgs analysis is consistent with unitarity at $\sqrt{s} = 0.3 \text{ TeV}$. However, at $\sqrt{s} = 1 \text{ TeV}$ the analysis remains sensitive only to a narrow region that satisfies unitarity for

$\mathcal{O}_{DH\partial\phi}$, $\mathcal{O}_{DHXX}$, $\mathcal{O}_{DHXX2}$, and $\mathcal{O}_{e\phi}$, while it is fully excluded by unitarity for $\mathcal{O}_{u\phi}$ and $\mathcal{O}_{d\phi}$. The operators $\mathcal{O}_{u\phi}$ and $\mathcal{O}_{d\phi}$ are also constrained by monojet searches, where the bound found in [43] translates to $\frac{\mathcal{C}_{u\phi,d\phi}}{\Lambda^2} \lesssim 3 \text{ TeV}^{-2}$ for $M_{\text{DM}} \in [1, 50] \text{ GeV}$. This is much stronger than the constraint that follows from this study, shown in Fig. 9.

In Fig. 10, we present the region of sensitivity in terms of the semivisible Higgs-decay branching fraction as a function of the mass of the postulated DM particle (either ϕ or χ). We obtain the branching fraction by computing the partial widths $\Gamma(H \rightarrow \ell^+\ell^- \text{DMDM})$ or $\Gamma(H \rightarrow jj \text{DMDM})$ (where $\text{DM} = \phi$ or χ) for the regions shown in Fig. 9 using MadGraph5, and normalizing to the SM Higgs total width $\Gamma_H^{\text{tot}} = 4.1 \text{ MeV}$ [72]. The figure shows that, for the operators that induce a semivisible leptonic Higgs decay, it is possible to reach a sensitivity below the Higgs-neutrino floor, unlike with the models studied in [1], because, as shown above, this background is reducible here. Further comparing to the models in [1], we can reach sensitivities that are improved by 1–2 orders of magnitude due to the use of $M_{\ell\ell}$ as a discriminant. For the $\mathcal{O}_{u\phi}$ and

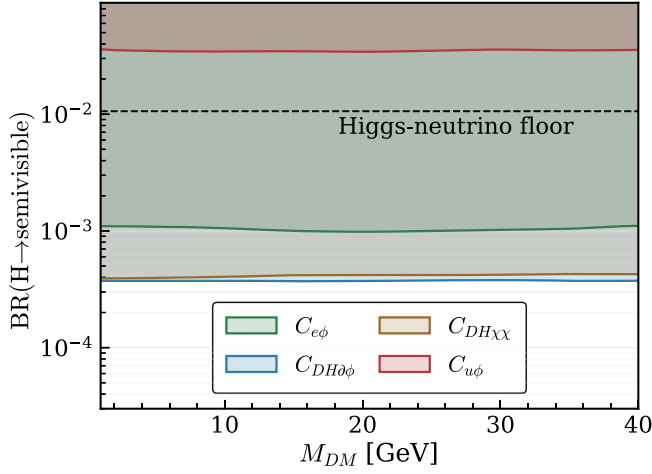


FIG. 10. Level of the branching fraction $\text{BR}(H \rightarrow \text{semivisible})$: $\text{BR}(H \rightarrow \ell^+ \ell^- \text{DMDM})$ or $\text{BR}(H \rightarrow jj \text{DMDM})$ depending on the operator-type, where $\text{DM} = \phi$ or χ , that can be probed at 3σ sensitivity for different values of M_{DM} and different choices of operators at the HL-LHC with luminosity $\mathcal{L} = 3000 \text{ fb}^{-1}$ and $\sqrt{s} = 14 \text{ TeV}$. The Higgs-neutrino-floor curve (shown as the dashed black line) corresponds to $\text{BR}(H \rightarrow \ell^+ \ell^- \nu \bar{\nu})_{\text{SM}} = 1.06 \times 10^{-2}$, and it would be about 30% lower for $\text{BR}(H \rightarrow qq \nu \bar{\nu})_{\text{SM}}$ [72], which is relevant for $C_{u\phi}$. The sensitivities for $\mathcal{O}_{DH\chi\chi 2}$ and $\mathcal{O}_{d\phi}$ are the same as those for $\mathcal{O}_{DH\chi\chi}$ and $\mathcal{O}_{u\phi}$, respectively, and are therefore not shown separately.

$\mathcal{O}_{d\phi}$ operators, on the other hand, the sensitivity of a semivisible Higgs-decay analysis is comparatively much weaker. Although, nominally below the Higgs-neutrino floor, these bounds are observable as we have shown that this background is reducible in our case.

VII. SUMMARY AND CONCLUSION

We have considered the set of dimension-six effective operators that can give rise to semivisible Higgs decays, through the production of pairs of new invisible scalars or fermions. Perturbative unitarity bounds on the coefficients of the effective operators, as well as constraints from the Z-invisible width, limit the size of the allowed interactions. We presented a framework for studying the semivisible Higgs decays, utilizing simple kinematical cuts and contrasting with the results from a BDT.

The main results are shown in Figs. 9 and 10. The invisible Z width provides the strongest constraints on

$C_{DH\phi\phi}$, $C_{DH\chi\chi}$, and $C_{DH\chi\chi 2}$, whereas semivisible Higgs decays are the most restrictive for $C_{e\phi}$. Requiring perturbative unitarity to hold up to 1 TeV provides the strongest bound on $C_{u\phi}$, indicating that the processes we study are not sensitive to the types of BSM physics parametrized by $\mathcal{O}_{u\phi}$ at scales above a few TeV. As Fig. 9 also indicates, semivisible Higgs decays constrain other scenarios where perturbative unitarity is satisfied for a narrow region with scale $\sim 1 \text{ TeV}$, and almost everywhere for $\sqrt{s} \sim 0.3 \text{ TeV}$, the scale probed by this decay. A BSM scenario described by these conditions is consistent with new degrees of freedom (which can be visible or invisible) appearing at around 0.5 TeV. In Fig. 10, we display the results in a different form, showing the Higgs branching fraction into the semivisible channels that can be probed by HL-LHC. The figure also demonstrates that the region accessible to HL-LHC is below the Higgs-neutrino floor.

If the invisible final state is interpreted as thermal dark matter [73–75], the semivisible Higgs sensitivities are weaker than the limits from direct detection for hadronic operators [76–79] and from indirect detection for leptonic operators [80]. Nonetheless, they are complementary—especially for different dark matter scenarios such as asymmetric dark matter, where indirect detection bounds are absent [81–84] (see Ref. [42] for recent limits), or for coannihilating dark matter, where both direct and indirect detection signals can be suppressed [15]. A quantitative study of semivisible Higgs decay using DSMEFT for these scenarios will be the subject of future work.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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