Off-shell Higgs Couplings in $H^* \rightarrow ZZ \rightarrow \ell\ell\nu\nu$

Dorival Gonçalves

Department of Physics, Oklahoma State University, Stillwater, OK, 74078, USA

Tao Han, Sze Ching Iris Leung, and Han Qin

PITT PACC, Department of Physics and Astronomy,

University of Pittsburgh, 3941 O’Hara St., Pittsburgh, PA 15260, USA

We explore the new physics reach for the off-shell Higgs boson measurement in the $pp \rightarrow H^* \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ channel at the high-luminosity LHC. The new physics sensitivity is parametrized in terms of the Higgs boson width, effective field theory framework, and a non-local Higgs-top coupling form factor. Adopting Machine-learning techniques, we demonstrate that the combination of a large signal rate and a precise phenomenological probe for the process energy scale, due to the transverse $ZZ$ mass, leads to significant sensitivities beyond the existing results in the literature for the new physics scenarios considered.

I. INTRODUCTION

After the Higgs boson discovery at the Large Hadron Collider (LHC) Refs. [1–5], the study of the Higgs properties has been one of the top priorities in searching for new physics beyond the Standard Model (BSM). Indeed, the Higgs boson is a unique class in the SM particle spectrum and is most mysterious in many aspects. The puzzles associated with the Higgs boson include the mass hierarchy and is most mysterious in many aspects. The puzzles associated with the Higgs boson include the mass hierarchy and is most mysterious in many aspects. The puzzles associated with the Higgs boson include the mass hierarchy and is most mysterious in many aspects. The puzzles associated with the Higgs boson include the mass hierarchy and is most mysterious in many aspects.

So far, the measurements at the LHC based on the Higgs signal strength are in full agreement with the SM predictions. However, these measurements mostly focus on the on-shell Higgs boson production, exploring the Higgs properties at low energy scales of the order $v$. It has been argued that if we explore the Higgs physics at a higher scale $Q$, the sensitivity can be enhanced as $Q^2/\Lambda^2$. A particularly interesting option is to examine the Higgs sector across different energy scales, using the sizable off-shell Higgs boson rates at the LHC Refs. [6–10]. While the off-shell Higgs new physics sensitivity is typically derived at the LHC with the $H^* \rightarrow ZZ \rightarrow 4\ell$ channel Refs. [11–18], we demonstrate in this work that the extension to the channel $ZZ \rightarrow \ell\ell\nu\nu$ can significantly contribute to the potential discoveries. This channel provides two key ingredients to probe the high energy regime with enough statistics despite of the presence of two missing neutrinos in the final state. First, it displays a larger event rate by a factor of six than the four charged lepton channel. Second, the transverse mass for the $ZZ$ system sets the physical scale $Q^2$ and results in a precise phenomenological probe to the underlying physics.

In this paper, we extend the existing studies and carry out comprehensive analyses for an off-shell channel in the Higgs decay

$$pp \rightarrow H^* \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu},$$

where $\ell = e, \mu$ and $\nu = \nu_e, \nu_\mu, \nu_\tau$. Because of the rather clean decay modes, we focus on the leading production channel of the Higgs boson via the gluon fusion. First, we phenomenologically explore a theoretical scenario with additional unobserved Higgs decay channels leading to an increase in the Higgs boson width, $\Gamma_H/\Gamma_H^{SM} > 1$. The distinctive dependence for the on-shell and off-shell cross-sections with the Higgs boson width foster the conditions for a precise measurement for this key ingredient of the Higgs sector. We adopt the Machine-learning techniques in the form of Boosted Decision Tree (BDT) to enhance the signal sensitivity. This analysis sets the stage for our followup explorations. Second, we study the effective field theory framework, taking advantage of the characteristic energy-dependence from some of the operators. Finally, we address a more general hypothesis that features a non-local momentum-dependent Higgs-top interaction Refs. [19], namely, a form factor, that generically represents the composite substructure. Overall, the purpose of this paper is to highlight the complementarity across a multitude of frameworks Refs. [13–19] via the promising process at the LHC $H^* \rightarrow Z(\ell\ell)Z(\nu\nu)$, from models that predict invisible Higgs decays, passing by the effective field theory, and a non-local form-factor scenario. Our results demonstrate significant sensitivities at the High-Luminosity LHC (HL-LHC) to the new physics scenarios considered here beyond the existing literature.

The rest of the paper is organized as follows. In Sec. II, we derive the Higgs width limit at HL-LHC. Next, in Sec. III, we study the new physics sensitivity within effective field theory framework. In Sec. IV, we scrutinize the effects of a non-local Higgs-top form-factor. Finally, we present a summary in Sec. V.
II. HIGGS BOSON WIDTH

The combination of on-shell and off-shell Higgs boson rates addresses one of the major shortcomings of the LHC, namely the Higgs boson width measurement. This method breaks the degeneracy present on the on-shell Higgs boson rates addresses one of the major shortcomings of the LHC, namely the Higgs boson width measurement. The consistency of our event simulation and analysis setup is confirmed through a cross-check with the ATLAS study in Ref. [9].

In our calculations, the signal and background samples are generated with MadGraph5_aMC@NLO [20, 21]. The Drell-Yan background is generated at the NLO with the MC@NLO algorithm [22]. Higher order QCD effects to the loop-induced gluon fusion component are included via a universal K-factor [8, 23]. Spin correlation effects for the Z and W bosons decays are obtained in our simulations with the MADSPIN package [24]. The renormalization and factorization scales are set by the invariant mass of the gauge boson pair $Q = m_{VV}/2$, using the PDF set NN23LO [25]. Hadronization and underlying event effects are simulated with PYTHIA8 [26], and detector effects are accounted for with the DELPHES3 package [27].

We start our analysis with some basic lepton selections. We require two same-flavor and opposite sign leptons with $|\eta_\ell| < 2.5$ and $p_{T\ell} > 10$ GeV in the invariant mass window $76$ GeV < $m_{\ell\ell}$ < $106$ GeV. To suppress the SM backgrounds, it is required large missing energy selection $E_{T}^{\text{miss}} > 175$ GeV and a minimum transverse mass for the $ZZ$ system $m_{T}^{ZZ} > 250$ GeV, defined as

$$m_{T}^{ZZ} = \sqrt{\left(\sqrt{m_Z^2 + p_{T(\ell\ell)}^2} + \sqrt{m_Z^2 + (E_{T}^{\text{miss}})^2}\right)^2 - |\vec{p}_{TZ} + \vec{E}_{T}^{\text{miss}}|^2}.$$  

The consistency of our event simulation and analysis setup is confirmed through a cross-check with the ATLAS study in Ref. [9].

To further control the large Drell-Yan background, a Boosted Decision Tree (BDT) is implemented via the Toolkit for Multivariate Data Analysis with ROOT (TMVA) [28]. The BDT is trained to distinguish the full background events from the s-channel Higgs production. The variables used in the BDT are missing transverse energy, the momenta and rapidity for the leading and sub-leading leptons $(p_T^{j1}, \eta^{j1}, p_T^{j2}, \eta^{j2})$, the leading jet $(p_T^{j1}, \eta^{j1})$, the separation between the two charged leptons $\Delta R_{\ell\ell}$, the azimuthal angle difference between the di-lepton system and the missing transverse energy $\Delta \phi(p_T^{\ell\ell}, E_T^{\text{miss}})$, and the scalar sum of jets and lepton transverse momenta $H_T$. Finally, we also include the polar $\theta$ and azimuthal $\phi$ angles of the charged lepton $\ell^{-}$ in the Z rest frame [29, 30]. We choose the coordinate system for the Z rest frame following Collins and Soper (Collins-Soper frame) [31]. The signal and background distributions for these observables are illustrated in Fig. 2. We observe significant differences between the s-channel signal and background in the $(\theta, \phi)$ angle distributions. These kinematic features arise from the different Z boson polarizations for the signal and background components at the large di-boson invariant mass $m_{T}^{ZZ}$ [15, 32]. Whereas the s-channel Higgs tends to have $Z_1\mu$ dominance, the DY background is mostly $Z_T$ dominated.

We would like to illustrate the power of the imple-
mented BDT analysis to separate the s-channel Higgs from the background contributions in Fig. 3. The BDT discriminator is defined in the range $[-1,1]$. The events with discriminant close to $-1$ are classified as background-like and those close to 1 are signal-like. The optimal BDT score selection has been performed with TMVA. To estimate the effectiveness of the BDT treatment, we note that one can reach $O(88\%)$ signal efficiency and $34\%$ background rejection by requiring $\text{BDT}_\text{response} > -0.26$. Now that we have tamed the dominant backgrounds $q\bar{q}\rightarrow ZZ, ZW$, we move on to the new physics sensitivity study.

To maximize the sensitivity of the Higgs width measurement, we explore the most sensitive variable, $m_{ZZ}$ distribution, and perform a binned log-likelihood ratio analysis. In Fig. 4 we display the 95% CL on the Higgs width $\Gamma_H/\Gamma_H^{SM}$ as a function of the $\sqrt{s} = 14$ TeV LHC luminosity. To infer the relevance of the multivariate analysis, that particularly explore the observables ($E_T^{\text{miss}}, \theta, \phi$) depicted in Fig. 2 we display the results in two analysis scenarios: in blue we show the cut-based analysis and in red the results accounting for the BDT-based framework. The significant sensitivity enhancement due to the BDT highlights the importance of accounting for the full kinematic dependence, including the $Z$-boson spin correlation effects. Whereas the Higgs width can be constrained to $\Gamma_H/\Gamma_H^{SM} < 1.35$ at 95% CL level following the cut-based analysis, $\Gamma_H/\Gamma_H^{SM} < 1.31$ in the BDT-based study assuming $L = 3$ ab$^{-1}$ of data. Hence, the BDT limits result in an improvement of $O(5\%)$ on the final Higgs width sensitivity. These results are competitive to the HL-LHC estimates for the four charged lepton final state derived by ATLAS and CMS, where the respective limits are $\Gamma_H/\Gamma_H^{SM} < O(1.3)$ and $O(1.5)$ at 68% CL [33][34].

![Figure 2](image2.png)

Figure 2. Normalized distributions for the missing transverse momentum $E_T^{\text{miss}}$ (left panel), azimuthal $\phi$ (central panel) and polar $\theta$ angles (right panel) of the charged lepton $\ell^-$ in the $Z$ boson rest frame.

![Figure 3](image3.png)

Figure 3. BDT distribution for the s-channel Higgs signal (red) and background (blue).

![Figure 4](image4.png)

Figure 4. 95% CL bound on the Higgs width $\Gamma_H/\Gamma_H^{SM}$ as a function of the $\sqrt{s} = 14$ TeV LHC luminosity. We display the results for the cut-based study (blue) and BDT-based analysis (red).
III. EFFECTIVE FIELD THEORY

The Effective Field Theory (EFT) provides a consistent framework to parametrize beyond the SM effects in the presence of a mass gap between the SM and new physics states. In this context, the new physics states can be integrated out and parametrized in terms of higher dimension operators [35]. In this section we parametrize the new physics effects in terms of the EFT framework [36 37]. Instead of performing a global coupling fit, we will focus on a relevant subset of higher dimension operators that affect the Higgs production via gluon fusion. This will shed light on the new physics sensitivity for the off-shell $pp \to H^* \to Z(\ell \ell)Z(\nu\nu)$ channel. Our effective Lagrangian can be written as

$$\mathcal{L} \supset \frac{\alpha_s}{12\pi v^2} |H|^2 G_{\mu\nu}^\mu G_{\nu}^{\mu} + c_{g,t} \frac{v}{2} |H|^2 Q_L \tilde{H} t_R + \text{h.c.},$$

(5)

where $H$ is the SM Higgs doublet and $v = 246$ GeV is the vacuum expectation value of the SM Higgs field. The couplings are normalized in such a way for future convenience. If we wish to make connection with the new physics scale $\Lambda$, we would have the scaling as $c_g, c_t = v^2/\Lambda^2$. After electroweak symmetry breaking, Eq. (5) renders into the following interaction terms with a single Higgs boson

$$\mathcal{L} \supset \kappa_g \frac{\alpha_s}{12\pi v^2} H G_{\mu\nu}^\mu G_{\nu}^{\mu} - \kappa_t \frac{m_t}{v} H (\tilde{t} R I + \text{h.c.}),$$

(6)

where the coupling modifiers $\kappa_g,t$ and the Wilson coefficients $c_g,t$ are related by $\kappa_g = c_g$ and $\kappa_t = 1 - \text{Re}(c_t)$. We depict in Fig. 5 the $gg \to ZZ$ Feynman diagrams that account for these new physics effects.

Whereas Eq. (5) represents only a sub-set of high dimensional operators affecting the Higgs interactions [36 37], we focus on it to highlight the effectiveness for the off-shell Higgs measurements to resolve a notorious degeneracy involving these terms. The gluon fusion Higgs production at low energy regime can be well approximated by the Higgs Low Energy Theorem [38 39], where the total Higgs production cross-section scales as $\sigma_{GF} \propto |\kappa_t + \kappa_g|^2$. Therefore, low energy measurements, such as on-shell and non-boosted Higgs production [13 15 20 40], are unable to resolve the $|\kappa_t + \kappa_g| = \text{constant}$ degeneracy. While the combination between the $t\bar{t}H$ and gluon fusion Higgs production have the potential to break this blind direction [47], we will illustrate that the Higgs production at the off-shell regime can also result into relevant contributions to resolve this degeneracy.

Since the Higgs boson decays mostly to longitudinal gauge bosons at the high energy regime, it is enlightening to inspect the signal amplitude for the longitudinal components. The amplitudes associated to each contribution presented in Fig. 5 can be approximated at

$$m_{ZZ} \gg m_t, m_H, m_Z$$

by [13 15 48]

$$M_t^{++00} \approx \frac{m_t^2}{2m_Z^2} \log^2 \frac{m_{ZZ}^2}{m_t^2},$$

$$M_g^{++00} \approx -\frac{m_g^2}{2m_Z^2},$$

$$M_c^{++00} \approx -\frac{m_c^2}{2m_Z^2} \log^2 \frac{m_{ZZ}^2}{m_c^2}. \quad (7)$$

Two comments are in order. First, both the $s$-channel top loop $M_t$ and the continuum $M_c$ amplitudes display logarithmic dependence on $m_{ZZ}/m_t$ at the far off-shell regime. In the SM scenario the ultraviolet logarithm between these two amplitudes cancel, ensuring a proper high energy behavior when calculating the full amplitude. Second, it is worth noting the difference in sign between the $s$-channel contributions $M_t$ and $M_c$. This results into a destructive interference between $M_t$ and $M_c$, contrasting to a constructive interference between

Figure 5. Feynman diagrams for the GF $gg \to ZZ$ process. The new physics effects from Eq. (6) display deviations on the coefficients $\kappa_t$ and $\kappa_g$ from the SM point $(\kappa_t, \kappa_g) = (1,0)$.

Figure 6. Transverse mass distributions $m_T^{ZZ}$ for the DY and GF $Z(\ell\ell)Z(\nu\nu)$ processes. The new physics effects are parametrized by deviations from SM point $(\kappa_t, \kappa_g) = (1,0)$. We follow the benchmark analysis defined in Sec [1].
In the following, we will explore these phenomenological effects pinning down the new physics sensitivity with a higher precision.

Exploiting the larger rate for $ZZ \rightarrow \ell\ell\nu\nu$ than that for $ZZ \rightarrow 4\ell$ [13,14], we explore the off-shell Higgs physics at the HL-LHC. To simulate the full loop-induced effects, we implemented Eq. (4) into FeynRules/NLOCT [49,50] through a new fermion state, and adjusting its parameters to match the low-energy Higgs interaction $Hg_{\mu\nu}G^{\mu\nu}$ [35,39]. Feynman rules are exported to a Universal FeynRules Output (UFO) [51] and the Monte Carlo event generation is performed with MadGraph5aMC@NLO [20].

In Fig. 6, we present the Drell-Yan (DY) and the gluon-fusion (GF) $m_{TZZ}$ distributions for different signal hypotheses. In the bottom panel, we display the ratio between the GF beyond the SM (BSM) scenarios with respect to the GF SM. In agreement with Eq. (7), we observe a suppression for the full process when accounting for the $s$-channel top loop contributions and an enhancement when including the new physics terms associated to $\mathcal{M}_g$ at high energies.

We follow the benchmark analysis defined in Sec. [11]. After the BDT study, the resulting events are used in a binned log-likelihood analysis with the $m_{TZZ}$ distribution. This approach explores the characteristic high energy behavior for the new physics terms highlighted in Eq. (7) and illustrated in Fig. 6. We present in Fig. 7 the resulting 95% CL sensitivity to the $(\kappa_{t}, \kappa_{g})$ new physics parameters at the high-luminosity LHC. In particular, we observe that the LHC can bound the top Yukawa within $\kappa_{t} \approx [0.4, 1.1]$ at 95% CL, using this single off-shell channel. The observed asymmetry in the limit, in respect to the SM point, arises from the large and negative interference term between the $s$-channel and the continuum amplitudes. The upper bound on $\kappa_{t}$ is complementary to the direct Yukawa measurement via $ttH$ [52] and can be further improved through a combination with the additional relevant off-shell Higgs final states. The results derived in this section are competitive to the CMS HL-LHC prediction that considers the boosted Higgs production combining the $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels [34]. The CMS projection results into an upper bound on the top Yukawa of $\kappa_{t} \lesssim 1.2$ at 95% CL.

IV. HIGGS-TOPO FORM FACTOR

The fact that the observed Higgs boson mass is much lighter than the Planck scale implies that there is an unnatural cancellation between the bare mass and the quantum corrections. Since the mass of the Higgs particle is not protected from quantum corrections, it is well-motivated to consider that it may not be fundamental, but composite in nature [53,56]. In such a scenario, the Higgs boson is proposed as a bound state of a strongly interacting sector with a composite scale $\Lambda^2$. It is challenging to find a general construction for such form factor without knowing the underlying dynamics. Here, we will adopt a phenomenological ansatz motivated by the nucleon form factor [67]. It is defined

![Figure 7. 95% CL bound on the coupling modifiers $\kappa_t$ and $\kappa_g$ when accounting for the off-shell Higgs measurement in the $Z(\ell\ell)Z(\nu\nu)$ channel. We assume the 14 TeV LHC with 3 ab$^{-1}$ of data.](image)

![Figure 8. Transverse mass distribution $m_{TZZ}$ for $gg(\rightarrow H^*) \rightarrow Z(2\ell)Z(2\nu)$ in the Standard Model (black) and with a new physics form factor (red). We assume $n = 2, 3$ and $\Lambda = 1.5$ TeV for the form factor scenario.](image)
Table I. Comparison of the sensitivity reaches between $H^* \to ZZ \to \ell\ell\nu\nu$ in this study and $H^* \to ZZ \to 4\ell$ in the literature as quoted. All results are presented at 95% CL except for the Higgs width projection derived by ATLAS with 68% CL [33]. We assume that the Wilson coefficient for the EFT framework is given by $c_1 = \nu^2 / \Lambda_{EFT}^2$. Besides the $H \to 4\ell$ channel, Ref. [34] also accounts for the $H \to \gamma\gamma$ final state with a boosted Higgs analysis.

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
   & $\Gamma_H / \Gamma_{SM}^{HM}$ & $\Lambda_{EFT}$ & $\Lambda_{EFT}^{5\nu}$ \tabularnewline
\hline
$H^* \to ZZ \to \ell\ell\nu\nu$ & 1.31 & 0.8 TeV & 1.5 TeV \tabularnewline
$H^* \to ZZ \to 4\ell$ & 1.3 (68% CL) & 0.55 TeV & 0.8 TeV \tabularnewline
\hline
\end{tabular}
\end{center}

limits on the new physics scale are $\Lambda = 0.8$ TeV for $n = 2$ and $\Lambda = 1.1$ TeV for $n = 3$ at 95% CL [18].

\section{Summary}

We have systematically studied the off-shell Higgs production in the $pp \to H^* \to Z(\ell\ell)Z(\nu\nu)$ channel at the high-luminosity LHC. We showed that this signature is crucial to probe the Higgs couplings across different energy scales potentially shedding light on new physics at the ultraviolet regime. To illustrate its physics potential, we derived the LHC sensitivity to three BSM benchmark scenarios where the new physics effects are parametrized in terms of the Higgs boson width, the effective field theory framework, and a non-local Higgs-top coupling form factor.

The combination of a large signal rate and a precise phenomenological probe for the process energy scale, due to the transverse $ZZ$ mass, renders strong limits for all considered BSM scenarios. A summary table and comparison with the existing results in the literature are provided in Table I. Adopting Machine-learning techniques, we demonstrated in the form of BDT that the HL-LHC, with $L = 3$ ab$^{-1}$ of data, will display large sensitivity to the Higgs boson width, $\Gamma_H / \Gamma_{SM}^{HM} < 1.31$. In addition, the characteristic high energy behavior for the new physics terms within the EFT framework results in relevant bounds on the $(\kappa_t, \kappa_g)$ new physics parameters, resolving the low energy degeneracy in the gluon fusion Higgs production. In particular, we observe that the LHC can bound the top Yukawa within $\kappa_t \approx [0.4, 1.1]$ at 95% CL. The upper bound on $\kappa_t$ is complementary to the direct Yukawa measurement via $ttH$ and can be further improved in conjunction with additional relevant off-shell Higgs channels. Finally, when considering a more general hypothesis that features a non-local momentum-dependent Higgs-top interaction, we obtain that the HL-LHC is sensitive to new physics effects at large energies with $\Lambda = 1.5$ TeV for $n = 2$ and $\Lambda = 2.1$ TeV for $n = 3$ at 95% CL. We conclude that, utilizing the promising $H^* \to Z(\ell^+\ell^-)Z(\nu\nu)$ channel at the HL-LHC and adopting the Machine-Learning techniques, the combination of a large signal rate and a precise phenomenological probe for the process energy scale renders improved sensitivities beyond the existing literature, to all the three BSM scenarios considered in this work.
ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under grant No. DE-FG02-95ER40896 and by the PITT PACC. DG was supported by the U.S. Department of Energy under grant number DE-SC 0016013.

[1] Peter W. Higgs. Broken symmetries, massless particles and gauge fields. Phys. Lett., 12:132–133, 1964.
[2] Peter W. Higgs. Broken symmetries and the masses of gauge bosons. Phys. Rev. Lett., 13:508–509, Oct 1964.
[3] F. Englert and R. Brout. Broken symmetry and the mass of gauge vector mesons. Phys. Rev. Lett., 13:321–323, Aug 1964.
[4] G. Aad, T. Abajyan, B. Abbott, J. Abdallah, S. Abdel Khalek, A.A. Abdelalim, O. Abdinov, R. Aben, B. Abi, M. Abolins, and et al. Observation of a new particle in the search for the standard model Higgs boson with the atlas detector at the lhc. Physics Letters B, 716(1):1–29, Sep 2012.
[5] S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan, W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, and et al. Observation of a new boson at a mass of 125 gev with the cms experiment at the lhc. Physics Letters B, 716(1):30–61, Sep 2012.
[6] Nicolas Kauer and Giampiero Passarino. Inadequacy of zero-width approximation for a light Higgs boson signal. JHEP, 08:116, 2012.
[7] Fabrizio Caola and Kirill Melnikov. Constraining the Higgs boson width with ZZ production at the LHC. Phys. Rev., D88:054024, 2013.
[8] John M. Campbell, R. Keith Ellis, and Ciaran Williams. Bounding the Higgs width at the LHC using full analytic results for gg → e+e−μ+μ−. JHEP, 04:060, 2014.
[9] Morad Aaboud et al. Constraints on off-shell Higgs boson production and the Higgs boson total width in ZZ → 4ℓ and ZZ → 2ℓ2ν final states with the ATLAS detector. Phys. Lett. B, 786:223–244, 2018.
[10] Albert M Sirunyan et al. Measurements of the Higgs boson width and anomalous HVV couplings from on-shell and off-shell production in the four-lepton final state. Phys. Rev. D, 99(11):121103, 2019.
[11] James S. Gainer, Joseph Lykken, Konstantin T. Matchev, Stephen Mrenna, and Myeonghun Park. Beyond Geolocating: Constraining Higher Dimensional Operators in H → 4ℓ with Off-Shell Production and More. Phys. Rev. D, 91(3):035011, 2015.
[12] Giacomo Cacciapaglia, Aldo Deandrea, Guillaume Drieu La Rochelle, and Jean-Baptiste Flament. Higgs couplings: disentangling New Physics with off-shell measurements. Phys. Rev. Lett., 113(20):201802, 2014.
[13] Aleksandr Azatov, Christophe Grojean, Ayan Paul, and Emnio Salvioni. Taming the off-shell Higgs boson. Zh. Eksp. Teor. Fiz., 147:410–425, 2015.
[14] Christoph Englert and Michael Spannowsky. Limitations and Opportunities of Off-Shell Coupling Measurements. Phys. Rev. D, 90:053003, 2014.
[15] Malte Buschmann, Dorival Goncalves, Silvan Kuttimalai, Marek Schonherr, Frank Krauss, and Tilman Plehn. Mass Effects in the Higgs-Gluon Coupling: Boosted vs Off-Shell Production. JHEP, 02:038, 2015.
[16] Tyler Corbett, Oscar J. P. Eboli, Dorival Goncalves, J. Gonzalez-Fraile, Tilman Plehn, and Michael Rauch. The Higgs Legacy of the LHC Run I. JHEP, 08:156, 2015.
[17] Dorival Goncalves, Tao Han, and Satyanarayan Mukhopadhyay. Off-Shell Higgs Probes of Naturalness. Phys. Rev. Lett., 120(11):111801, 2018. [Erratum: Phys.Rev.Lett. 121, 079902 (2018)].
[18] Dorival Goncalves, Tao Han, and Satyanarayan Mukhopadhyay. Higgs Couplings at High Scales. Phys. Rev., D98(1):015023, 2018.
[19] Christoph Englert, Yotam Soreq, and Michael Spannowsky. Off-Shell Higgs Coupling Measurements in BSM scenarios. JHEP, 05:145, 2015.
[20] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. JHEP, 07:079, 2014.
[21] Valentin Hirschi and Olivier Mattelaer. Automated event generation for loop-induced processes. JHEP, 10:146, 2015.
[22] Stefano Frixione and Bryan R. Webber. Matching NLO QCD computations and parton shower simulations. JHEP, 06:029, 2002.
[23] Marco Bonvini, Fabrizio Caola, Stefano Forte, Kirill Melnikov, and Giovanni Ridolfi. Signal-background interference effects for gg → H → W+W− beyond leading order. Phys. Rev., D88(3):034032, 2013.
[24] Pierre Artoisenet, Rikkert Frederix, Olivier Mattelaer, and Robbert Rietkerk. Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations. JHEP, 03:015, 2013.
[25] Richard D. Ball, Valerio Bertone, Luigi Del Debbio, Stefano Forte, Alberto Guffanti, Nathan P. Hartland, and Juan Rojo. Parton distributions with QED corrections. Nucl. Phys., B877:290–320, 2013.
[26] Torbjörn Sjöstrand, Stefan Ask, Jesper R. Christiansen, Richard Corke, Nishita Desai, Philip Iten, Stephen Mrenna, Stefan Prestel, Christine O. Rasmussen, and Peter Z. Skands. An Introduction to PYTHIA 8.2. Comput. Commun., 191:159–177, 2015.
[27] S. Ovyn, X. Roudy, and V. Lemaitre. DELPHES, a framework for fast simulation of a generic collider experiment. 2009.
[28] Andreas Hoecker, Peter Speckmayer, Joerg Stelzer, Jan Therhaag, Eckhard von Toerne, and Helge Voss. TMVA: Toolkit for Multivariate Data Analysis. PoS, ACAT:040, 2007.
[29] Dorival Goncalves and Junya Nakamura. Role of the Z polarization in the H → b¯b measurement. Phys. Rev., D98(9):093005, 2018.
[30] Dorival Goncalves and Junya Nakamura. Boosting the H → invisibles searches with Z boson polarization. Phys. Rev., D99(5):055021, 2019.
[31] John C. Collins and Davison E. Soper. Angular Distribution of Dileptons in High-Energy Hadron Collisions. Phys. Rev., D16:2219, 1977.

[32] Dorival Goncalves, Tilman Plehn, and Jennifer M. Thompson. Weak boson fusion at 100 TeV. Phys. Rev., D95(9):095011, 2017.

[33] Off-shell Higgs boson couplings measurement using $H \rightarrow ZZ \rightarrow 4l$ events at High Luminosity LHC. 2015.

[34] Sensitivity projections for Higgs boson properties measurements at the HL-LHC. 2018.

[35] Thomas Appelquist and J. Carazzone. Infrared Singularities and Massive Fields. Phys. Rev. D, 11:2856, 1975.

[36] W. Buchmuller and D. Wyler. Effective Lagrangian Analysis of New Interactions and Flavor Conservation. Nucl. Phys. B, 268:621–653, 1986.

[37] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek. Dimension-Six Terms in the Standard Model Lagrangian. JHEP, 10:085, 2010.

[38] Mikhail A. Shifman, A.I. Vainshtein, M.B. Voloshin, and Valentin I. Zakharov. Low-Energy Theorems for Higgs Boson Couplings to Photons. Sov. J. Nucl. Phys., 30:711–716, 1979.

[39] Bernd A. Kniehl and Michael Spira. Low-energy theorems in Higgs physics. Z. Phys. C, 60:77–88, 1995.

[40] U. Baur and E.W.Nigel Glover. Higgs Boson Production at Large Transverse Momentum in Hadronic Collisions. Nucl. Phys. B, 339:38–66, 1990.

[41] Robert V. Harlander and Tobias Neumann. Probing the nature of the Higgs-gluon coupling. Phys. Rev. D, 88:074015, 2013.

[42] Andrea Banfi, Adam Martin, and Veronica Sanz. Probing top-partners in Higgs+jets. JHEP, 08:053, 2014.

[43] Aleksandr Azatov and Ayan Paul. Probing Higgs couplings with high pr Higgs production. JHEP, 01:014, 2014.

[44] Christophe Grojean, Ennio Salvioni, Matthias Schlafer, and Andreas Weiler. Very boosted Higgs in gluon fusion. JHEP, 05:022, 2014.

[45] Malte Buschmann, Christoph Englert, Dorival Goncalves, Tilman Plehn, and Michael Spannowsky. Resolving the Higgs-Gluon Coupling with Jets. Phys. Rev. D, 90(1):013010, 2014.

[46] Aleksandr Azatov, Christophe Grojean, Ayan Paul, and Ennio Salvioni. Resolving gluon fusion loops at current and future hadron colliders. JHEP, 09:123, 2016.

[47] Michelangelo L. Mangano, Tilman Plehn, Peter Reimitz, Torben Schell, and Hua-Sheng Shao. Measuring the Top Yukawa Coupling at 100 TeV. J. Phys. G, 43(3):035001, 2016.

[48] E.W.Nigel Glover and J.J. van der Bij. Z BOSON PAIR PRODUCTION VIA GLUON FUSION. Nucl. Phys. B, 321:561–590, 1989.

[49] Adam Alloul, Neil D. Christensen, Céline Degrande, Claude Duhr, and Benjamin Fuks. FeynRules 2.0 - A complete toolbox for tree-level phenomenology. Comput. Phys. Commun., 185:2250–2300, 2014.

[50] Céline Degrande. Automatic evaluation of UV and R2 terms for beyond the Standard Model Lagrangians: a proof-of-principle. Comput. Phys. Commun., 197:239–262, 2015.

[51] Céline Degrande, Claude Duhr, Benjamin Fuks, David Grellscheid, Olivier Mattelaer, and Thomas Reiter. Ufo – the universal feynrules output. Computer Physics Communications, 183(6):1201–1214, Jun 2012.

[52] M. Cepeda et al. Report from Working Group 2: Higgs Physics at the HL-LHC and HE-LHC. CERN Yellow Rep. Monogr., 7:221–584, 2019.

[53] Alex Pomarol and Francesco Riva. The Composite Higgs and Light Resonance Connection. JHEP, 08:135, 2012.

[54] Giuliano Panico and Andrea Wulzer. The Discrete Composite Higgs Model. JHEP, 09:135, 2011.

[55] Giuliano Panico and Andrea Wulzer. The Composite Nambu-Goldstone Higgs. Lect. Notes Phys., 913:pp.1–316, 2016.

[56] Da Liu, Ian Low, and Carlos E. M. Wagner. Modification of Higgs Couplings in Minimal Composite Models. Phys. Rev., D96(3):035013, 2017.

[57] V. Punjabi, C. F. Perdrisat, M. K. Jones, E. J. Brash, and C. E. Carlson. The Structure of the Nucleon: Elastic Electromagnetic Form Factors. Eur. Phys. J., A51:79, 2015.