The measurement of Higgs couplings constitute an important part of present Standard Model precision tests at colliders. In this article, we show that modifications of Higgs couplings induce energy-growing effects in specific amplitudes involving longitudinally polarized vector bosons, and we initiate a novel program to study these very modifications of Higgs couplings off-shell and at high-energy, rather than on the Higgs resonance. Our analysis suggests that these channels are complementary and, at times, competitive with familiar on-shell measurements; moreover these high-energy probes offer endless opportunities for refinements and improvements.

I. INTRODUCTION

The precise measurement of the Higgs boson couplings to other Standard Model (SM) particles is an unquestionable priority in the future of particle physics. These measurements are important probes for our understanding of a relatively poorly measured sector of the SM; at the same time they offer a window into heavy dynamics Beyond the Standard Model (BSM). Indeed, it is well-known that the exchange of heavy states (with masses beyond the direct collider reach) leaves imprints in low-energy experiments, in a way that is systematically captured by an Effective Field Theory (EFT).

There are a number of similar ways in which one can parametrize modifications of Higgs couplings (HC): via partial widths \( \kappa_i^2 = \frac{\Gamma_{h\rightarrow ii}}{\Gamma_{SM_{h\rightarrow ii}}} \) [1], via Lagrangian couplings in the unitary gauge \( g_{ii} \) [2, 3], via pseudo observables [4], or via the effective field theory \( \mathcal{L} = \sum c_i \mathcal{O}_i / \Lambda^2 \), consisting of dimension-6 operators [3, 5]. In particular, the operators

\[
\begin{align*}
\mathcal{O}_r &= |H|^2 \partial_\mu H^\dagger \partial^\mu H \\
\mathcal{O}_{g_\psi} &= Y_\psi |H|^2 \psi_L H \psi_R \\
\mathcal{O}_{BB} &= g' |H|^2 B_\mu B^{\mu} \\
\mathcal{O}_{WW} &= g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu} \\
\mathcal{O}_{GG} &= g_s^2 |H|^2 G_\mu^a G^{\mu a} \\
\mathcal{O}_6 &= |H|^6
\end{align*}
\]

with \( Y_\psi \) the Yukawa for fermion \( \psi \), can be put in simple correspondence with the \( \kappa_s \), as they modify single-Higgs processes without inducing other electroweak symmetry breaking effects.

The well-established method for testing HC is, of course, to measure processes in which a Higgs boson is produced on-shell.

In this article we initiate a novel program to test the very same Higgs couplings, off-shell and at high-energy, via their contributions to the physics of longitudinally polarized gauge bosons. We will show that this program is potentially competitive with on-shell measurements, but it also offers endless opportunities of refinements and improvements. Indeed, the high-energy program can benefit maximally from accumulated statistics, from improved SM computations, from phenomenological analyses aimed at enhancing the signal-over-background (see, for instance, [6–11]), and from dedicated experimental analyses aimed at reducing the different backgrounds. Furthermore, given the complexity of the final states, advanced machine learning techniques [12–14] are expected to have a crucial role in improving on our simple cut and count analysis. In the context of a global precision program, the high-energy aspects that we discuss here will be the ones that benefit the most, not...
only from the long-term HL-LHC program, but also from potential future high energy colliders, such as the HE-LHC or CLIC.

Our leitmotiv is that any observable modification of a SM coupling will produce in some process a growth with energy (see table I). In some sense, this is obvious: since the SM is the only theory that can be extrapolated to arbitrarily high-energy, any departure from it can have only a finite range of validity, a fact that is made manifest by a disproportionate growth in some scattering amplitude. Theories with a finite range of validity are, by definition, EFTs; for this reason the best vehicle to communicate our message is the EFT language of Eq. (1). We stress nevertheless that at, tree level, the very same conclusions can be reached in the \( \kappa \) framework \cite{1} or in the unitary-gauge framework of Ref. \cite{2, 3}.

The operators of Eq. (1) have the form \( |H|^2 \times O_{SM} \), with \( O_{SM} \) a dimension-4 SM operator (i.e. kinetic terms, Higgs potential, and Yukawas) times

\[
|H|^2 = \frac{1}{2} \left( v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2 \right)
\]

where \( v = 246 \text{ GeV} \) is the Higgs vacuum expectation value (vev), \( h \) is the physical Higgs boson, and \( \phi^{+,-,0} \) are the would-be longitudinal polarizations of \( W^- \) and \( Z^- \) bosons. From the operators in Eq. (1), the piece \( \propto v^2 \) can be reabsorbed via a redefinition of the SM input parameters and is therefore unobservable \cite{15, 16}; the piece \( \propto vh \) constitutes instead the core of the HC measurements program, as it implies modifications to single-Higgs processes (triple Higgs processes for \( O_6 \)), and can be matched easily to the \( \kappa \) framework. The \( h^2 \) piece was discussed in \cite{17, 18} in the context of double Higgs production. In this article we focus on the last two terms in Eq. (2) and study processes with longitudinal gauge bosons instead of processes with an on-shell Higgs; we dub this search strategy “Higgs without Higgs” - HwH in short.

The high-energy avenue is potentially very promising: for \( E^2 \)-growing effects, a 1% sensitivity at the Higgs boson mass, corresponds to a \( O(1) \) sensitivity at \( E \sim 1 \text{ TeV} \). We will see that, in practice, High-E measurements are rather complex, so that this naive scaling is hardly achieved in the explorative analysis presented here. However, we envisage several strategies for improvement that outline a challenging and exciting collider program.

\[ \frac{A^O_{n}}{A_{SM}^n} \sim \frac{E^2}{\Lambda^2} \tag{3} \]

Table I shows the relevant processes that exhibit this behaviour; more explicitly, at hadron (lepton)
colliders,
\[
\begin{align*}
\kappa_t : pp &\to j t + V_L V'_L, \\
(e^+e^- &\to ll + \{tbW_L, tbZ_L, ttW_L, ttZ_L\}) \quad (4) \\
\kappa_\lambda : pp &\to j j h + V_L V'_L, \quad (e^+e^- \to llhV_LV'_L) \quad (5) \\
pp &\to jj + 4V_L, \quad (e^+e^- \to ll 4V_L) \quad (6) \\
\kappa_{\gamma,\gamma'} : pp &\to jj + V'V, \quad (e^+e^- \to llV'V) \quad (7) \\
\kappa_V : pp &\to jj + V_LV'_L, \quad (e^+e^- \to llV_LV'_L) \quad (8) \\
\kappa_g : pp &\to W_L^+W_L^-Z_LZ_L, \quad (e^+e^- \to lljj) \quad (9)
\end{align*}
\]
where \(V_LV'_L \equiv \{W_L^\pm W_L^\mp, W_L^\pm W_L^\mp, W_L^\pm Z_L, Z_LZ_L\}\) (similarly \(4V_L a generic generic longitudinally polarized final state) and \(V^{(t)}\) any (longitudinal or transverse) vector, including photons, while \(l\) denotes either a charged lepton \(\ell^\pm\) or a neutrino, depending on the final state. We also show in Fig. 1 a unitary-gauge diagram that exhibits E-growth and helps visualize our discussion in terms of HC. Notice that, for all processes, the amplitude associated with the modified couplings grows quadratically with the relevant energy scale of the process \(E^2\) (with the exception of Eq. (5), see later). In the following paragraphs we explore these processes in turn and provide a first estimate of the potential HwH reach at the HL-LHC in comparison with the reach from Higgs couplings measurements. This rhetoric of competitiveness has the sole scope of providing the reader with a quantitative feeling about the power of HwH processes; it is understood that, for practical purposes, the two search methods should be thought of as complementary. Our results are based on leading order (LO) MadGraph simulations [22], where the Higgs couplings have been modified using FeynRules [13] and checked against the model of Ref. [23].

**The top Yukawa.** Modifications of the Yukawa coupling of the Higgs boson to top quarks is reputedly difficult to measure on the \(h\) resonance [24]; however, an anomalous top quark Yukawa induces a quadratic energy growth in the five point amplitude involving a bottom quark, a top, and three longitudinal bosons \(W_LV_LV'_L\). This amplitude leads to a process with a final state consisting of a top quark, a forward jet and two longitudinally polarized vector bosons in the final state, see Eq. (4) and Fig. 2.

The top carries a large transverse momentum \(p_T^t\) due to the hardness of the process, which makes it a good discriminator. We consider two categories, for \(p_T^t > 250(500)\) GeV. A forward jet with \(|\eta_j| > 2.5, p_T^j > 30\) GeV and \(E_j > 300\) GeV is required.

The signal is classified by counting the number of extra leptons reconstructed in the event. The following table shows the number of signal events at the 14 TeV HL-LHC with 3000 fb⁻¹, for \(p_T^t > 250\) GeV / \(p_T^t > 500\) GeV.

| Process | \(0\ell\) | \(1\ell\) | \(0\ell^+\ell^-\) | \(2\ell^+\ell^-\) | \(3\ell(4\ell)\) |
|---------|---------|---------|----------------|----------------|----------------|
| \(W^\pm W^\mp\) | 3449/567 | 1724/283 | 216/35 | - | - |
| \(W^\pm W^\pm\) | 2850/398 | 1425/199 | - | 178/25 | - |
| \(W^\pm Z\) | 3860/632 | 965/158 | 273/45 | - | 68/11 |
| \(ZZ\) | 2484/364 | - | 351/49 | - | (12/2) |

The categories with two or more leptons have small background. The largest source of background for the hadronic modes comes from \(t \bar{t}jj \to tWbjj\) where a \(bj\) pair is taken to reconstruct a \(W/Z\)-boson. The initial \(t \bar{t}jj\) cross section is approximately six orders of magnitude bigger than the ones we are interested in, but we have verified that simple cuts on the invariant mass of the \(bj\) pair, on the rapidity of the forward jet, on \(p_T^j\), and on the separation between the \(W\) and the \(b\), as well as vector boson tagging techniques [26], can reduce this background to a level that is comparable with the signal.

We broadly parametrize this and other backgrounds by a uniform rescaling \(B\) of the SM signal expectation in each bin (so that for \(B = 1\) we add an irreducible background equal to the SM signal in each channel), and show the estimated reach in the left panel of Fig. 3. The dashed grey lines compare our results with those from HC measurements [27]. For illustration we also show results that focus on channels with at least 2 leptons with a dashed purple line: here the backgrounds are much smaller. The

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2 See also Ref. [25] that studies \(tbj\) final states which exhibits linear \(E\)-growth with modifications of the top-Yukawa.
large number of events left in the zero and one lepton categories makes it possible to extend the analysis to higher energies, where not only the effects of the energy growth will be enhanced, but also the background reduced.

This mode of exploration also appears well-suited for high-energy lepton colliders like CLIC. Indeed, the processes in the second line of Eq. (4) have a lower threshold for production than the $t\bar{t}h$ final state that is usually considered to measure the top quark Yukawa. Moreover, the final state in Eq. (4) is produced in vector boson fusion, whose crosssection increases with energy, while $t\bar{t}h$ is produced in Drell-Yan, decreases with energy. We plan to study this in detail in the future.

**The Higgs self coupling.** Measurements of the Higgs self-coupling have received enormous attention in collider studies. In the di-Higgs channel at HL-LHC precision can reach $\delta\kappa_\lambda \in [-1.8, 6.7]$ at 95%C.L. [28] using the $b\bar{b}\gamma\gamma$ final state. Here we propose the processes of Eqs. (5, 6) with VBS scattering topology and a multitude of longitudinally polarized vector bosons, see second row of Tab. I and Fig. 1 where a unitary-gauge diagram is shown. The modified coupling $\delta\kappa_\lambda$, or the operator $\mathcal{O}_6$, induces a linear growth with energy w.r.t. the SM in processes with $jjV_LV_L$ final state (Tab. I), and a quadratic growth in processes with $jjV_LV_LV_L$. For the former, the same-sign $W^+W^-jj$ with leptonic $(e, \mu)$ decays is particularly favourable for its low background: two same-sign leptons (2ssl) and VBS topology offers a good discriminator against background, allowing for $h \rightarrow b\bar{b}$ decays. For illustration we focus on this channel in which the SM gives $N_{b\bar{b}} \approx 50$ events. Backgrounds from $ttjj$ enter with a misidentified lepton, but it can be shown that they can be kept under control with the efficiencies reported in [29] and with VBS cuts on the forward jets. A potentially larger background is expected to come from fake leptons, but the precise estimation of it is left for future work.

The results—shown in the center panel of Fig. 3—are very encouraging: this simple analysis can match the precision of the by-now very elaborate di-Higgs studies. There are many directions in which this approach can be further refined: i) including the many other final states in Eq. (5), both for the vector decays and for the Higgs decay ii) including the $E^2$-growing $jjV_LV_LV_L$ topologies of Eq. (6), iii) taking into account differential information. Moreover, the process of Tab. I grows only linearly with energy w.r.t. the SM amplitude with transverse vectors in the final state, but it grows quadratically w.r.t. the SM final states; iv) measurements of the polarization fraction can improve this measurement. We leave all this for a future detailed study.

**Higgs to $\gamma\gamma, Z\gamma$.** These decay rates are loop-level and small in the SM: their measurement implies therefore tight constraints on possible large (tree-level) BSM effects, which in the EFT language are...
captured by the operators $O_{WW, BB}$ from Eq. (1).\(^3\) These also enter in high-energy VBS Eq. (7), and they represent a beautiful additional motivation (together with $\kappa_V$, see below) to study these processes, which at present are often interpreted in the context of anomalous quartic gauge couplings (QGC) \([30]\), corresponding to dimension-8 operators.

We perform a simple analysis of vector boson scattering (VBS) with $W^\pm W^\pm, ZZ, WZ, Z\gamma$ final states. For the first three we use the usual cuts on the forward jets: $|\delta_{jj}| > 2.5, p_T^j > 30$ GeV and $m_{jj} > 500$ GeV \([31]\). A kinematic variable that captures the hardness of the 2 → 2 process is the scalar sum of the $p_T^V$ of the vector bosons, and therefore we bin the distribution in bins of 250 GeV up to 2 TeV. For the $Z\gamma$ final state, we follow the analysis for aQGC of \([32]\).

The combined results are displayed in the right panel of Fig. 3, for fully leptonic, semileptonic and fully hadronic decays, for backgrounds $B = 0.1$ where, as explained above, $B = 1$ corresponds to an additional background of the same order as the SM. Note that we translated the constraints on $c_{BB}, c_{WW}$ to the $\kappa_{V, 0}$. We find that the $ZZ, Z\gamma$ final states provide the best reach. For comparison, the individual reach from HL-LHC measurements of HC \([27]\) is shown by the black error bars. These clearly offer an unbeatable sensitivity in the $h\gamma\gamma$ direction; the $hZ\gamma$ direction is however less tested, and our simple analysis of high-energy probes shows promising results.

**Higgs to $W^+ W^−, ZZ$.** It is known that modifications of the tree-level $hZZ$ and $hW^+ W^−$ SM couplings (assumed here to be controlled by a unique parameter, corresponding for instance to $O_H$ in the SILH basis \([33]\)) imply a quadratic $E$-growth in longitudinal VBS. This is discussed in detail in Ref. \([34]\) (and \([35]\) for linear colliders), where it is pointed out that, in the SM, the longitudinal component is suppressed by an accidental factor $\sim 2000$, which is equivalent to a very large irreducible background. This motivated studies of VBS $hh$ pair production instead, see \([17]\), finding at 1$\sigma$, $\delta\kappa_V \lesssim 8\%$, comparable to $\delta\kappa_V \lesssim 5\%$ from HC \([27]\).\(^4\)

**Higgs to $gg$.** This coupling modifies the main production mode at hadron colliders and is, therefore, very well measured. The most interesting high-energy process that can be associated with this coupling is $gg \rightarrow ZZ$, which has been discussed in Refs. \([36\text{-}38]\). Using the results from Ref. \([36]\) we estimate $HwH$ versus HC reach at the end of the HL-LHC, in particular we have considered a scenario with and one without the background and three different decay channels. We find that

\begin{align}
&\text{HC: } |\kappa_g| \lesssim 0.025 \\
&\text{HwH: } |\kappa_g| \lesssim 0.24 / 0.06 / 0.01 \\
&\text{HwH (no } \bar{q}q \rightarrow Z_T Z_T \text{): } |\kappa_g| \lesssim 0.09 / 0.02 / 0.005
\end{align}

where the numbers stand for the fully leptonic / semileptonic / fully hadronic channels. The partonic $\bar{q}q \rightarrow Z_T Z_T$ process represents here the main irreducible background, as it does not interfere with our $gg \rightarrow Z_L Z_L$ amplitude with longitudinal polarization. Its reduction would constitute an important aspect of $HwH$ analyses. Notice that, unfortunately, in the SM the $gg \rightarrow Z_L Z_L$ process is extremely suppressed at high-$E$, to the benefit of the transverse $TT$ one, see Ref. \([39]\). This implies that the SM – BSM interference is also suppressed.

Despite these difficulties, which might be overcome in more refined analyses (along the lines of \([9,10]\)), the high-$E$ results remain competitive in the semileptonic and fully hadronic channels, assuming that the background from $\bar{q}q \rightarrow Z_T Z_T$ can be efficiently suppressed.

The amplitude we propose can also find a beautiful implementation in the context of future lepton colliders, in the form of $ZZ, WW \rightarrow gg$ in VBS. There, the possibility to polarize the initial electron positron beams could offer an additional handle to enhance the longitudinal polarizations. This would offer a new potential for ILC or CLIC to improve upon Higgs coupling measurements.

\(^3\) The same operators also affect the $h$ couplings to $Z_T Z_T$ and $WW \gamma T$. The same qualitative analysis can be performed with focus on the $hA_{\mu\nu} A^{\mu\nu}$ and $hA_{\mu\nu} Z^{\mu\nu}$ vertices, but we prefer to work here with the gauge invariant $O_{WW, BB}$ operators. See also comments in section III.

\(^4\) The authors of \([17]\) assume separate couplings of the vector bosons to $h$ or $h^2$; when the Higgs is part of a doublet, these are proportional. Moreover, the numbers we report here are indicative: both HC measurements and the di-higgs analysis have optimistic and pessimistic scenarios in which these numbers might differ.
III. COMMENTS

In a generic EFT fit there can be other operators that enter in the observables we propose. On general grounds, assuming the Higgs is part of a doublet, we expect these operators to be better constrained by other measurements, so that their impact on our study is small. Dividing operators by the number of fields they contain, equivalent to the number of legs $n$ of the first amplitude to which they contribute as $\sim E^2/\Lambda^2$, we have [5],

| $n$ | HC | No HC |
|-----|-----|-------|
| 6   | $h^6$ |       |
| 5   | $\psi^2 h^3$ |       |
| 4   | $F^2 h^2, h^4 D^2$ | $F\psi^2 h, \psi^2 h^2 D, h^4 D^2$ |
| 3   |       |       |

where $F, \psi, h$ denote field strengths, spinor and scalar (Higgs) fields, and $D$ denotes derivatives, and we have divided operators that modify HC from those that do not. In the latter category, the majority contributes to $2 \rightarrow 2$ partonic processes, where they are expected to be better measured than in processes with more legs. So we expect our studies of the $n = 6, 5$ processes in Eqs. (4,5)—targeting $\kappa_\psi \sim \psi^2 h^3$ and $\kappa_\lambda \sim h^6$—to be rather robust against the presence of other operators.

On the same lines, in our analysis of $gg \rightarrow ZZ$ targeting $\kappa_g \sim O_{GG}$, there are no other dimension-6 operators that enter with $E^2$-growing effects; this would not have been true for the $W^+ W^-$ final state (also modified by $O_{GG}$).

The structure $h^4 D^2$ appears in two combinations (e.g. $O_{HD}, O_{H\Box}$ in the Warsaw basis). The combination that cannot be associated with Higgs couplings enters in the $T$ parameter; this is very well measured from LEP [42, 43], so that we can associate $V_L V_L$ scattering almost entirely with modifications of the Higgs coupling to vectors $\kappa_V \sim O_r$.

For the other effects that enter VBS, the situation is more complex and requires a detailed study. Nevertheless, the majority of $n = 4$ operators that do not modify HC contain fermions (and $W^\mu \nu$ modifies amplitudes $A(\psi \psi \rightarrow VV')$ involving fermions), so that these operators can be measured also in other processes. For this reason we expect that $HwH$ observables will remain important also in the context of a global fit.

An important aspect of the high-$E$ exploration is the question of EFT validity, which questions the truncation of the EFT expansion when a measurement is performed in regions with poor sensitivity, in a way that it relies on the quadratic $O(1/\Lambda^2)$ terms in the cross section. In light of this there are different ways in which our analysis can be taken: i) we believe it will be possible to refine and redesign our analyses, along the lines of [6–11] (see also comments in the hgg paragraph), in order to make it more precise and sensitive to the linear terms $O(1/\Lambda^2)$ in the expansion, ii) in strongly coupled theories the inclusion of $O(1/\Lambda^4)$ does not imply a breakdown of the expansion [44–46], so that unrefined high-energy measurements can always be interpreted in this context, iii) a breakdown of the EFT implies generically the discovery of on-shell modes within the kinematic collider reach; given that the sensitivity we find here is comparable to that of HC, our analysis implies that the question of EFT validity should be discussed also in the context of HC measurements.

IV. CONCLUSIONS

In this article we have proposed a novel way of testing Higgs couplings at colliders, based on high-energy processes rather than processes involving an on-shell Higgs resonance. Exploiting the fact that anomalous modifications of the SM necessarily induce $E$-growth in some process, we identified and initiated an explorative study of the potential reach of these high-energy probes, which we have compared with Higgs coupling measurements in the context of the HL-LHC.

The preliminary results are very positive, especially given the potential of improvements that we foresee. Simple cut-and-count analyses were shown, in some cases, to match the precision of sophisticated Higgs Coupling measurements. For instance, the $j j W^\pm W^{\mp} h$ channel with leptonic decays, allows a precision comparable to di-Higgs production in measuring the Higgs self-coupling. Similarly, modifications of the top Yukawa can be measured in the many $jt + V_L V_L'$ final states to a precision in the ballpark of Higgs coupling measurements. VBS processes and $ZZ$ at high-energy offer further alternative possibilities to test the Higgs coupling to electroweak gauge

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5 Non-interference arguments [40] can lead to processes with more legs providing better measurements [9, 41]. For electroweak processes, however, this is superseded by measurements of azimuthal angles from the decay of vector bosons [9, 10].

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bosons and to gluons, respectively.

There are many directions in which our analysis can be extended and refined. Our signals center on the presence of longitudinally polarized vector bosons. An important irreducible background in this context is the SM fraction of transversely polarized states which, in many cases, is much larger than the longitudinal signal [34]. So, from a phenomenological perspective, important progress could come from a better understanding of the kinematics of the various helicity amplitudes, aimed at improving the signal/background ratio, along the lines of [9, 10, 41], or other techniques aimed at accessing information about vector-boson polarization [47–49].

A more refined understanding of the relevant scales and BSM-sensitive distributions in the problem, along the lines of [25], or complemented with more advanced machine learning techniques, in the direction of [12–14], would also increase the sensitivity of our analysis. A more realistic analysis would also include QCD corrections (our discussion here has been at leading order), which tend to increase the relevant cross sections, but also complicate their helicity structure. Finally, it would be interesting to include our observables in the context of a global fit (see e.g. [50]) to understand whether, even in situations where they cannot directly compete with individual HC measurements, they can still provide valuable global information.

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