Anomalous Higgs-boson coupling effects in $HW^+W^−$ production at the LHC.

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We study the LHC associated production of a Higgs boson and a $W^+W^-$ vector-boson pair at 14 TeV, in the Standard Model and beyond. We consider different signatures corresponding to the cleanest $H$ and $W$ decay channels, and discuss the potential of the high-luminosity phase of the LHC. In particular, we investigate the sensitivity of the $HW^+W^−$ production to possible anomalous Higgs couplings to vector bosons and fermions. Since the $b$-quark initiated partonic channel contributes significantly to this process, we find a moderate sensitivity to both the size and sign of an anomalous top-quark Yukawa coupling, because perturbative unitarity in the standard model implies a destructive interference in the $b\bar{b}$ subprocess. We show that a combination of various signatures can reach a $\sim 9$ standard-deviation sensitivity in the presently allowed negative region of the top-Higgs coupling, if not previously excluded.

I. INTRODUCTION

After the Higgs boson discovery [1,2] in 2012, a present and future major experimental task at the LHC is to test the detailed standard model (SM) predictions for the new-particle properties and couplings to known particles. Possible non-standard Higgs couplings to both known and speculated particles are to be taken into account in Higgs studies. In order to characterize the Higgs boson in the most accurate way, one should then scrutinize not only the main Higgs production channels, but also the rarest processes that can be sensitive to anomalous and/or new kinds of interactions. Here, we consider the associated production of a Higgs boson and a vector boson pair in the channel\(^1\)

$$pp \rightarrow HW^+W^-.$$ \hspace{1cm} (1)

The cross section for the process in Eq. (1) is of third order in the electroweak coupling, just as the dominant Higgs boson production in $WW$ fusion. On the other hand, the phase-space factor for the production of three massive objects depletes the total production rate at 14 TeV down to about 8 fb [at leading order (LO)] \cite{3,4}, to be compared with the $WW/ZZ$-fusion cross section of about 4 pb. Next-to-leading order (NLO) QCD corrections enhance the $HW^+W^−$ rates by about 50% \cite{5}. Similar considerations hold for the cross sections corresponding to the $HWZ$ and $HZZ$ final states, that are further depleted by SU(2) invariance down to about 4 fb and 2 fb at LO, respectively. The study of such relatively small cross-section processes then requires the large integrated luminosities expected in the high-luminosity phase of the LHC (HL-LHC), where one expects to collect about 3000 fb$^{-1}$ of data per experiment.

It is well-known that, in presence of anomalous Higgs couplings to vector bosons $V = W, Z$ and/or fermions $f$, there are processes which violate perturbative unitarity at high energies. In particular, any measured deviation from the SM $VVH$ and $ffH$ couplings results in new phenomena, since further unknown degrees of freedom are necessarily required in order to recover unitarity in $V_L V_L \rightarrow V_L V_L$ \cite{7} and $V_L V_L \rightarrow ff$ scatterings \cite{8}.

Presently, ATLAS \cite{9,10} and CMS \cite{11} data show a sign ambiguity in the Higgs couplings to fermions. The two dimensional fits of $C_V = g_{VVH}/g_{VVH}^{SM}$ and $C_f = g_{ffH}/g_{ffH}^{SM}$ (where $g_{VVV}$ and $g_{ffH}$ parametrize the Higgs couplings to gauge bosons and fermions, respectively) are both compatible within 2$\sigma$ with a SM coupling setup $C_V = C_f = 1$. On the other hand, a non-SM fit with $C_V \simeq -C_f \simeq 1$ is not yet excluded \cite{10}. The relative sign between the $VVH$ and $ffH$ couplings is predicted by the SM (being related to the SM Higgs mechanism for the fermion mass generation), and a flipped sign would spoil the unitarity and renormalizability of the theory. Nevertheless, there are theoretical frameworks that predict such a possibility \cite{12,13}.

A possible strategy to resolve the above sign degeneracy in the LHC data is to look at processes where two contributions to the scattering amplitude, depending separately on the $VVH$ and $ffH$ couplings, interfere. An example is given by the Higgs production in association with a single top in $pp \rightarrow t\bar{t}H$, whose total cross section gets largely enhanced by flipping the top Yukawa coupling sign in such interference contributions \cite{14,15}. This gives the process a considerable potential for constraining the negative $C_f \simeq -C_V$ coupling region \cite{17,18}.

\footnotesize

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1 The Higgs boson production in association with a pair of electroweak gauge bosons ($WW, ZZ, Z\gamma$) in $e^+e^-$ collisions has been considered in the SM framework in \cite{6}.

\normalsize
Indeed, even the present 7+8 TeV LHC data set could be sufficient to exclude the wrong-sign Yukawa solution in $pp \to tqH$ \cite{19}. The large enhancement (by about a factor of 13 at the LHC energies) resulting from the flipped Yukawa sign in the $pp \to tqH$ cross section points to unitarity breaking at large energies \cite{18}. Nevertheless, this cross section can be reliably computed at the LHC even in the anomalous coupling region, since perturbative unitarity breaks at energies of the $bW \to tH$ subprocess above 10 TeV \cite{18}.

The larger data sample on Higgs-boson production, expected at the LHC in forthcoming years, will have an enormous potential to check whether the actual couplings of the newly observed particle indeed approach the corresponding SM Higgs interactions, or show some deviation from them \cite{20, 21}.

In the present analysis, we aim also to analyze what the study of $pp \to HW^+W^-$ can add to the potential of other Higgs production processes characterized by higher cross section. This is motivated by the fact that, in $pp \to HW^+W^-$, the partonic contribution arising from the $b$-quark scattering $bb \to HW^+W^-$ (Figure 1) provides another example of process sensitive to the top Yukawa sign (and magnitude) through the interference between diagrams where the Higgs boson is radiated by a $W/Z$ boson and those ones where it is emitted by an internal top-quark line. Even in this case, anomalous Higgs couplings will induce perturbative unitarity violations. Nevertheless, the possible impact of such violations on the total cross section will be diluted by the dominant light-quark scattering contribution to the $pp \to HW^+W^-$ cross section, which is mostly insensitive to the Higgs Yukawa couplings. In the following, we will discuss the $pp \to HW^+W^-$ rate sensitivity to both Higgs Yukawa and gauge couplings, and analyze the corresponding unitarity bounds in presence of anomalous couplings.

The paper is organized as follows. In Section II, within the SM framework, we evaluate the $pp \to HW^+W^-$ total cross section for different c.m. energies, and compare it to the cross sections for other multi-boson final states. In Section III, we discuss signal versus background expectations at the HL-LHC, for the most robust $HW^+W^-$ signatures (i.e., multi-leptons final states, and di-photon resonances). Then, in Section IV, we discuss the sensitivity of the $HW^+W^-$ production to anomalous Higgs couplings to fermions and vector bosons. In Section V, we sum up and give our conclusions.

\section{Tri-Boson Cross Sections}

In order to provide a context for our study, we start by overviewing the tri-boson electroweak final states that involve at least one Higgs boson for the LHC energies and beyond. In particular, we compare the $pp \to HW^+W^-$ cross section to the ones for other tri-boson final states, including either one or two Higgs bosons, at different collision c.m. energies that could be of interest at future pp colliders \cite{22}. The $HH$ production cross sections are also presented here for comparative purposes. We postpone to the next section a detailed study of the cleanest $HW^+W^-$ production signatures versus the most relevant backgrounds, and a discussion of the potential of the HL-LHC to observe the $HW^+W^-$ process with an integrated luminosity of 3000 fb$^{-1}$.

In Table I we present the total cross sections for $HW^+W^-$, $HWZ$, $HZZ$, $HHW$, $HHZ$, and $HH$ production in proton-proton collisions for the LHC design energy of 14 TeV, and at possible future hadron colliders. From now on, we will assume $m_H = 125$ GeV.

The LO cross sections in Table I have been computed with MadGraph5 \cite{23}, by using the CTEQ6L1 parton distribution functions (PDF’s) \cite{24}. The $HHW$ and $HHZ$ cross sections have been calculated by retaining only the tree-level contribution of vector boson fusion (VBF) from quarks initiated processes, and by neglecting the next-to-leading contribution arising from $W/Z$ radiation by a $HH$ pair produced via gluon-gluon fusion. The dependence on the renormalization and factorization scales has been tested by varying the scale from a central value $\mu_0 = 265\text{GeV} \approx 2M_W + M_H$ to $2\mu_0$ and $\mu_0/2$. The corresponding scale uncertainty has been found in the range 1% - 2%. For comparison, we also include in Table I the NLO gluon fusion cross section for $HH$ production \cite{22}.

The $HW^+W^-$ production (from now on labeled just as $HWW$) turns out to have the largest cross section among all tri-boson channels involving Higgs bosons in the final state. Its production rate is almost a factor of 4, or 11, smaller than the double Higgs production at 14 TeV, or 100 TeV, respectively. Notice that the $HH$ cross section increases with energy faster than all tri-boson cross sections, as the latter acquire almost a common rescaling factor while growing with energy. This behavior reflects the different evolution in energy of the gluon PDF (that mainly influences the $HH$ production) versus the quark PDFs, which give the dominant contribution to the tri-boson cross sections.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
 & 14 TeV & 33 TeV & 40 TeV & 60 TeV & 80 TeV & 100 TeV \\
\hline
$HW^+W^-$ & 8.4 & 29 & 38 & 65 & 94 & 124 \\
$HWZ$ & 3.8 & 14 & 18 & 31 & 44 & 58 \\
$HZZ$ & 2.1 & 7.4 & 9.6 & 16 & 24 & 31 \\
$HHW$ & 0.43 & 1.6 & 2.1 & 3.6 & 5.2 & 7.0 \\
$HHZ$ & 0.27 & 1.0 & 1.3 & 2.2 & 3.3 & 4.4 \\
$HH$ & 33.8 & 207 & 298 & 609 & 980 & 1420 \\
\hline
\end{tabular}
\caption{LO electroweak tri-boson cross sections (including either one or two Higgs bosons in the final state), in $pp$ collisions (in fb) for $m_H = 125$ GeV, at different c.m. energies, and, for comparison, the NLO cross section for $gg \to HH$.}
\end{table}
III. HWW SIGNALS AND BACKGROUNDS

In this section, we detail our analysis of signatures and corresponding backgrounds for the cleanest HWW decay channels. Note that the present study partially overlaps with the analysis of the $HH \to HWW^*$ final state mediated by two Higgs-boson production [26], which has a slightly larger cross section ($\sigma_{HH} \times 2 \times BR(H \to WW^*) \sim 16$ fb at 14 TeV), but differs in the presence of one “less characterizing” off-shell $W$ in the final state.

Table II shows a list of the most relevant final states arising from the HWW system decays, as well as the corresponding event numbers at 14 TeV for 3000 fb$^{-1}$ (before applying any kinematical cut). One can see how multi-lepton and two-photon final states (that are the most robust against background) are in general characterized by lower rates.

In the following, both signal and background event numbers have been worked out by using MadGraph 5 [23], interfaced with Pythia 6.4 [25] for decays with large particle multiplicities. All event samples have been analyzed at parton level. The following set of basic kinematical cuts has been universally applied in this paper:

- for final state leptons ($e$, $\mu$) and photons, we require a pseudo-rapidity cut $|\eta| < 2.5$, and a transverse momentum cut $p_T > 10$ GeV;
- for final state quark and gluon jets, we impose $|\eta| < 2.5$ and $p_T > 20$ GeV. We disregard forward jets with $|\eta| > 2.5$ to ensure that b-jets can be more reliably identified, b-tagging algorithms being more efficient in the central part of the detector. We assumed a b-jet detection efficiency of 70%;
- for each pair of visible objects ($i,j$), we require an isolation cut $\Delta R_{ij} > 0.4$, where $\Delta R_{ij} = \sqrt{\eta_{ij}^2 + \phi_{ij}^2}$, and $\eta_{ij}(\phi_{ij})$ is their rapidity (azimuthal) separation.

In order to investigate hadronic tau decays, we have modified the Tauola code in MadGraph to assign a unique particle identifier to the hadronic tau decay products, $\tau_{\text{had}}$. We then applied to $\tau_{\text{had}}$ the same set of cuts as adopted for quark and gluon jets.

In our analysis, we do not include decay channels into $N$ jets plus two opposite-sign leptons, or one single lepton, or no leptons, which are dominated by QCD backgrounds such as top-pair production. This excludes the highest-rate (but challenging) channels with Higgs into $b\bar{b}$

2 The $WWb\bar{b}$ channel has been proposed as a signal channel for $HH$ production [26]. In this case the presence of two on-shell Higgs bosons (implying at least one very off-shell $W$) provides additional kinematic constraints to reject the top background.
| $H \rightarrow$ | final state | BR | $\text{ev}/3\,\text{ab}^{-1}$ | signature |
|---|---|---|---|---|
| $b\bar{b}$ | $b\bar{b} \ell\nu \ell\nu$ | 2.9% | 815 | $2\,b\,2\ell\,E_T$ |
| | $b\bar{b} \ell\nu jj$ | 18% | 4960 | $2\,b\,2\ell\,E_T$ |
| | $b\bar{b} jj jj$ | 27% | 7560 | $2\,b\,4\ell$ |
| $WW^*$ | $\ell\nu \ell\nu \ell\nu \ell\nu$ | 0.047% | 13 | $4\,\ell\,E_T$ |
| | $\ell\nu \ell\nu \ell\nu jj$ | 0.58% | 159 | $2\,\ell\,3\ell\,E_T$ |
| | $\ell\nu \ell\nu jj jj$ | 2.6% | 727 | $4\,\ell\,2\ell\,E_T$ |
| | $\ell\nu jj jj jj$ | 5.3% | 1480 | $6\,\ell\,E_T$ |
| | $jj jj jj jj$ | 4.1% | 1120 | $8\,\ell$ |
| $\tau^+\tau^-$ | $\ell\nu\ell\nu \ell\nu \ell\nu$ | 0.033% | 9 | $4\,\ell\,E_T$ |
| | $\ell\nu\ell\nu \ell\nu jj$ | 0.20% | 55 | $2\,\ell\,3\ell\,E_T$ |
| | $\ell\nu\ell\nu jj jj$ | 0.30% | 84 | $4\,\ell\,2\ell\,E_T$ |
| | $\ell\nu \tau_{\text{had}} \ell\nu \ell\nu$ | 0.13% | 37 | $\tau_{\text{had}}\,3\ell\,E_T$ |
| | $\ell\nu \tau_{\text{had}} \ell\nu jj$ | 0.81% | 223 | $2\,\tau_{\text{had}}\,2\ell\,E_T$ |
| | $\ell\nu \tau_{\text{had}} jj jj$ | 0.12% | 1240 | $4\,\tau_{\text{had}}\,\ell\,E_T$ |
| | $\tau_{\text{had}} \tau_{\text{had}} \ell\nu \ell\nu$ | 0.13% | 37 | $2\tau_{\text{had}}\,2\ell\,E_T$ |
| | $\tau_{\text{had}} \tau_{\text{had}} \ell\nu jj$ | 0.82% | 226 | $2\tau_{\text{had}}\,2\ell\,E_T$ |
| | $\tau_{\text{had}} \tau_{\text{had}} jj jj$ | 1.2% | 345 | $2\tau_{\text{had}}\,4\ell$ |
| $ZZ^*$ | $\ell\ell \ell\ell \ell\nu \ell\nu$ | 0.001% | 0 | $6\ell\,E_T$ |
| | $\ell\ell \ell\ell jj jj$ | 0.003% | 1 | $2\,\ell\,5\ell\,E_T$ |
| | $\ell\ell jj jj jj$ | 0.005% | 1 | $4\,\ell\,4\ell$ |
| | $\ell\ell jj jj \ell\nu$ | 0.006% | 2 | $2\,\ell\,4\ell\,E_T$ |
| | $\ell\ell jj jj jj$ | 0.017% | 5 | $4\,\ell\,3\ell\,E_T$ |
| | $\ell\ell jj jj jj$ | 0.053% | 5 | $8\,\ell\,E_T$ |
| | $jj jj jj \ell\nu$ | 0.059% | 16 | $4\,\ell\,2\ell\,E_T$ |
| | $jj jj jj jj$ | 0.16% | 200 | $6\,\ell\,E_T$ |
| | $jj jj jj jj$ | 0.36% | 100 | $6\,\ell\,E_T$ |
| | $jj jj jj jj$ | 0.55% | 152 | $8\,\ell$ |

| $\gamma\gamma$ | $\gamma\gamma \ell\nu \ell\nu$ | 0.011% | 3 | $2\gamma\,2\ell\,E_T$ |
| | $\gamma\gamma \ell\nu jj$ | 0.065% | 18 | $2\gamma\,2\ell\,E_T$ |
| | $\gamma\gamma jj jj$ | 0.099% | 27 | $2\gamma\,4\ell$ |

TABLE II: List of most relevant final states arising from the $HWW$ system decays, and the corresponding event numbers at 14 TeV for 3000 fb$^{-1}$, before applying any kinematical cut.

out the present analysis). The leptonic $Z$ decay via $\tau^+\tau^-$ (that we include) has lower rates, but is less characterized, and in general more overlapped with the Higgs signal into leptons:

- $ZZ$ pairs with the $Z$'s decaying into $e,\mu$ leptons or leptonically decaying taus; again the decays $Z \rightarrow \ell\ell\ell\ell$ can be cut away by reconstructing the $Z$ resonance;
- $ZH$ with $Z$ decaying into $e,\mu$ leptons or leptonically decaying taus, and $H$ decaying to leptons through $WW^*$ or taus pairs;
- $HH$ with both $H$'s going into $WW^*$, followed by leptonic decays of the $W$ bosons.

The corresponding signal and background rates are shown in Table III. We find that the most dangerous irreducible background, after our basic kinematic cuts, comes from $ZZ$ production, with both $Z$'s decaying into $\tau^+\tau^-$. In order to reduce this background, we cut on the scalar sum of the missing energy and the transverse momentum of the four leptons, $\sum_i p_T^\ell + E_T > 200$ GeV. Indeed, leptons from the indirect decays via $\tau \rightarrow l\nu\nu$ are typically produced with lower transverse energy. The total missing energy in the event is also lower for indirect decays, since the eight neutrinos in each event are on average emitted in random directions on the transverse plane, and their momenta partially cancel each other out. We find that, by applying a lower cut of 200 GeV on $\sum_i p_T^\ell + E_T$, the $ZZ$ background can be reduced by about a factor of 10, while the signal falls by 25% only.

After all the cuts described above, the signal to background ratio is close to 0.32, and the corresponding significance $(S/\sqrt{S+B} \, \text{in unity of standard deviation } \sigma_s)$ of the four-lepton channel for a dataset of 3000 fb$^{-1}$ is about 1.3 $\sigma_s$.

### B. Hadronic $W + 3$ leptons

We will now investigate the channel with one hadronic $W$ decay ($W_{\text{had}}$) plus three charged leptons in the final state. As in the previous channel, this signature can arise from the $HWW$ state in connection to two different Higgs decays. For the Higgs decaying into $WW^*$, compared to the four-lepton final state, the rate is enhanced by two effects:
the W branching ratio (BR) into hadrons is more than a factor 3 larger than the one into $e\nu + \mu\nu$;

- any of the three on-shell W’s can decay hadronically, giving a further factor of 3 from combinatorial enhancement.

On the other hand, when the signature arises from $H \rightarrow \tau\tau \rightarrow$ leptons, the W BR is again increased by a factor of 3, while the combinatorial factor is only 2. Altogether, after applying kinematical cuts, about 80% of the signal events originates from the $H \rightarrow WW^* \rightarrow \ell\ell \gamma\gamma$ decay mode (cf. Table IV).

We will now discuss the (mostly irreducible) backgrounds that can lead to the $W_{\text{had}} + 3 \ell + \not{E}_T$ final state, in order of relevance:

- 2 jets + $WZ$, where the Z decays via $\tau$’s to leptons. The total rate for this background after basic kinematic cuts is larger than 1 pb. On the other hand, by requiring the jet pair to reconstruct the $W$ mass, it falls down by a factor 20;

- $t\bar{t}W$ production, where the two b-jets from top decays are mis-tagged as light jets, and reconstruct the $W$ mass. By demanding the jets to reconstruct the $W$ mass within 5 GeV, the $t\bar{t}W$ background has been reduced by a factor $\sim 24$ (cf. Table IV). Similarly, the $t\bar{t}Z$ production, for $Z \rightarrow \ell\ell$, can contribute to the background whenever one of the charged leptons from the $Z$ decay falls outside the experimental acceptance (this actually occurs in about 1/6 of the events);

- further QCD backgrounds originate from $jjWWW$ and $jjWH$, but can similarly be reduced by requiring the jet-pair invariant mass to reconstruct $M_W$;

- purely electroweak backgrounds, which mainly originate from $4W$ and $WWZ$ production. For $WWZ$, we assume that the Z decays via $\tau$’s to leptons;

- $HH \rightarrow WW^*WW^*$ production. Note that $HH$ is more affected by previous cuts, since two out of four W’s are off-shell, and, for $W$ hadronic decays, do not reconstruct $M_W$, while, for $W$ leptonic decays, give reduced transverse momenta.

Then, in general, in addition to our basic kinematic cuts, we demand the two jets to reconstruct $M_W$ within a mass window of $\pm 5$ GeV. The effect of the above cuts on signal and background is shown in Table IV With 3000 fb$^{-1}$, we expect 69 signal and 477 background events. The $S/B$ ratio is 0.145 and the corresponding significance is 3.0 $\sigma$.

### C. Higgs decay into diphotons

We now examine the final states where the Higgs decays to two photons. The resonant $\gamma\gamma + WW$ signal is very clear, and the backgrounds are in general small, but the signal is penalized by the small Higgs BR to photons. The cleanest signature to look for would obviously be the full leptonic $WW$ final state, but the corresponding rate is highly suppressed, giving a total of about 3 events with 3000 fb$^{-1}$ (cf. Table II). Thus we concentrate on the larger-rate semi-leptonic $WW$ channel, resulting in the final state $jj\ell\nu\gamma\gamma$. The main irreducible backgrounds are

- $jjW\gamma\gamma$, with the W decaying into leptons, where the jets reconstruct the $W$ mass, and the photons reconstruct the Higgs mass;

- $jjWH$, that is $WH$ associated production with two extra jets faking a hadronic $W$ decay;

- $WW\gamma\gamma$, with one W decaying leptonically, and the other one hadronically, and two radiated photons that reconstruct the Higgs system;

- $HH$, with one of the Higgs bosons decaying into two photons and the other one into a semi-leptonic $W$ pair. One of the $W$’s from the Higgs decay being off-shell, this background will be reduced by a proper cut around $M_W$ on the hadronic $W^*$.

The two-jet and two-photon invariant masses are then required to be within the ranges $M_W \pm 5$ GeV, and $m_H \pm 2$ GeV, respectively. The main backgrounds contain radiated jets faking the $W$, and/or radiated photons faking the Higgs. The $p_T$ spectrum of the radiated objects is softer than the corresponding spectrum for the decay products of a real $W$ and Higgs, so we require additional cuts on the scalar $p_T$ sum of the two jets and the two photons, respectively, as $p_T^2 + p_T^2 > 70$ GeV and

| $HWW$ signal: | basic cuts | $m(W)$ |
|--------------|-----------|--------|
| via $H \rightarrow WW^*$ | 22.3 | 18.8 |
| via $H \rightarrow \tau\tau$ | 4.3 | 4.3 |
| $WWZ$ | 17.7 | 17.7 |
| $4W$ | 7.0 | 7.0 |
| $jjWWW$ | 74.0 | 29.4 |
| $jjWZ$ | 154.0 | 49.9 |
| $jjWH, H \rightarrow WW^*$ | 169 | 9.7 |
| $jjWH, H \rightarrow \tau\tau$ | 82.2 | 4.4 |
| $t\bar{t}W$ | 825 | 34.9 |
| $t\bar{t}Z$ | 11.7 | 0.5 |
| $HH \rightarrow WW^*WW^*$ | 10.3 | 5.4 |
| total signal | 26.6 | 23.1 |
| total background | 3400 | 159 |

TABLE IV: Signal and background cut flow in the $3\ell + W_{\text{had}}$ final states. All cross sections are in ab. The cut labeled $m(W)$ requires the invariant mass of the two jets to satisfy $75.4 \text{ GeV} < m^{jj} < 85.4 \text{ GeV}$. 
are events could lead to an observation. pressed in the SM, so that even a small number of signal channel since same-sign lepton events are very much sup-
tons, and one hadronic tau (τ). The signature is therefore two jets, two same-sign lep-
tons (one from a W and one from a τ). The signature is therefore two jets, two same-sign lep-
tons, and one hadronic tau (τ_{had}). We select the latter channel since same-sign lepton events are very much sup-
pressed in the SM, so that even a small number of signal events could lead to an observation.

The main irreducible backgrounds for this signature are:
- \( WWZ \), with \( Z \rightarrow ττ \). Because of the missing energy from neutrinos in tau decays, the mass of the particle decaying to tau cannot be reconstructed accurately, and the Z and Higgs signals will be in general quite overlapped;
- \( jjWH \), i.e., \( WH \) associated production with two extra jets, and \( H \rightarrow ττ; \)
- \( jjWZ \), with \( Z \rightarrow ττ \). This is the main background for this channel because of the large production cross section. Again, the Z and Higgs decay products via taus will be in general quite overlapped.

In addition to our basic kinematic cuts, we again demand the two-jet mass to be within the range \( M_W \pm 5 \) GeV, and assume 100% efficiency for hadronic tau identification. The effect of kinematical cuts on the signal and background is shown in Table VI. After all cuts, the same-sign lepton signal to background ratio for \( ℓνjjττ \) is about 0.034, and the significance for a data set of 3000 fb\(^{-1}\) is 0.74 \( σ_s \).

### E. Same sign leptons from \( H \rightarrow W^+W^- \)

The same sign dilepton signal can also arise from \( W^+W^- H \rightarrow W^+W^-W^+W^- \), where the positively charged W’s decay to leptons and the negatively charged W’s into hadrons or vice versa. In this case the final state consists of two hadronic W systems, two same sign leptons and missing energy. The most relevant backgrounds are:

- \( 4jW^{±}W^{±} \), where the W’s decay into leptons, and the four jets fake the two hadronic W’s. Because of the valence-quark charge distribution, the cross section of the positively charged W pair production is about three times as large as the negative pair one.
- \( jjW^{±}W^{±}W^{±} \), where the same sign W’s decay into leptons, and the opposite sign W decays into hadrons, and the two jets reconstruct the remaining hadronic W.
- \( tW^{±} \rightarrow b\bar{b}W^{±}W^{±} \), where the same sign W’s decay into leptons and the opposite sign W decays into hadrons, and the two b-jets fake the hadronic W.
- \( tW^{+}W^{-}j \rightarrow W^{+}bW^{−}W^{−}j \), or the charge conjugate process, where the same sign W’s decay into leptons and the opposite sign W into hadrons, and the b-jet plus the light jet fake the hadronic W.
- \( W^+W^-W^-W^- \), that is electroweak production of four W bosons, with hadronic (leptonic) decays of the positively (negatively) charged W’s, or viceversa.
To extract the signal from the background we require the four jets in the final state to combine into two pairs with invariant mass within $+\pm 5$ GeV around $M_W$. To reduce the background from the $t\bar{t}W$ production, events with $b$-tagged jets are vetoed, (assuming a 70% tagging efficiency). The resulting signal and background rates are shown in Table VII for negatively charged leptons and in Table VIII for positively charged leptons. Because of the valence-quark charge distribution, the background cross sections are generally smaller for the negatively charged lepton pair, and hence this channel is more significant. After cuts, the signal to background ratio is 0.087 (0.042) for negative (positive) sign leptons, and the combined significance for 3000 fb$^{-1}$ is 0.98σ.

### F. Further relevant backgrounds

The associated production of a Higgs boson and a $t\bar{t}$ pair gives a common background for all final states investigated above, since the final state $Ht\bar{t} \rightarrow HWW\ell\ell$ can mimic the signal $HWW$ whenever the final $b$-jets are not reconstructed.

The LO cross section for the process $pp \rightarrow Ht\bar{t} \rightarrow HWW\ell\ell$ is about 360 fb at $\sqrt{s} = 14$ TeV. If we require, in a parton-level simulation, that the $b$-jets have transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 4.5$ to be reconstructed at least as further light jets, then both $b$-jets will be reconstructed in 91.9% of the events, and at least one $b$-jet will be reconstructed in 99.75% of the events. Thus the $Ht\bar{t}$ background can be effectively suppressed down to 0.25% of the original cross section by a veto on any additional jets with $p_T > 20$ GeV and $|\eta| < 4.5$. Then, the latter acceptance cuts reduce the cross section of the $t\bar{t}H$ background to about 0.9 fb, before applying the relevant BR's for the Higgs and $W$ bosons for each final state. On the other hand, the inclusion of extra QCD radiation and shower effects will in general impact the present conclusion.

A further potentially dangerous background for the $W_{\text{had}} + 3\ell$ signal is the $t\bar{t}j \rightarrow 2\ell 2\nu b\bar{b}j$ production, where a $b$-jet is mis-tagged as a light jet, and the corresponding $bj$ reconstruct a $W_{\text{had}}$, while the second $b$ is mis-tagged as a lepton [22]. Similarly for the $4\ell$ signal there is a potential background from $t\bar{t} \rightarrow 2\ell 2\nu b\bar{b}$ production, where both $b$'s are identified as leptons, although this background is suppressed by the square of the mis-tag rate.

The impact of the latter backgrounds critically depends on the actual detector performances. Although backgrounds of this type, originating from mis-tags, fakes and detector effects, are likely to be relevant for the actual experimental analysis of the $HWW$ production, their detailed analysis is beyond the scope of the present work.

### G. Combination

We now combine the potential of the six channels previously discussed, reported in Table IX. Here we combine

| basic cuts | $m(W)$ | final state | signal | backgr. | $S/\sqrt{S+B}$ |
|------------|--------|-------------|--------|---------|---------------|
| $HWW$ signal | 4.3 2.7 | $4\ell + \not{E}_T$ | 2.4 7.6 | 1.3 | |
| 4jWW | 828 2.5 | $3\ell + 2j$ | 23.1 159 | 3.0 | |
| 2jWWWW | 406 18.2 | $tH + j$ | 1.95 9.2 1.0 | | |
| $tW$ | 138 7.7 | $\ell^+\ell^- + 2j + \tau_{\text{had}}$ | 5.6 164 | 0.74 | |
| $tWWj$ | 112 2.5 | $\ell^-\ell^- + 4j$ | 2.7 31.2 0.80 | | |
| WWWWW | 0.3 0.3 | $\ell^+\ell^+ + 4j$ | 2.7 | 63.8 | 0.57 |
| total signal | 4.3 2.7 | | | | |
| total background | 4020 63.8 | | | | |

TABLE IX: Signal versus background rates (in ab) after all dedicated cuts for different final states, and the corresponding significance in unity of $\sigma_s (S/\sqrt{S+B})$ for 3000 fb$^{-1}$. The total significance of 3.6σ is the sum in quadrature of all individual significances.
the final rates, after the optimization procedure, for the signal and total background for each final state, and the corresponding significances. Significances are for 3000 fb$^{-1}$ of integrated luminosity. By summing in quadrature the significances of each individual channel, we get a total $HWW$ signal significance of 3.6$\sigma_S$ in the SM.

IV. ANOMALOUS HIGGS COUPLINGS

In this section we consider the possibility that the Higgs boson has non-SM couplings to $W,Z$ bosons and fermions. In order to parameterize any deviation from the SM expectations, we introduce the set of scaling coefficients $C_{W,Z,f}$ defined as

$$C_W = \frac{g_{WWW}}{g_{WWW}^{SM}}, \quad C_Z = \frac{g_{ZZH}}{g_{ZZH}^{SM}}, \quad C_f = \frac{g_{fHH}}{g_{fHH}^{SM}}, \quad (2)$$

where $g_{WWW}^{SM}, g_{ZZH}^{SM}$ and $g_{fHH}^{SM}$ stand for the corresponding SM couplings. The $C_Z$ and $C_W$ parameters are constrained to be positive, while $C_f$ can still assume negative values $^{13}$.

As discussed in Section I, anomalous Higgs couplings to SM weak gauge bosons and fermions can induce a violation of perturbative unitarity at some energy scale, which depends on the particular process considered. Perturbative unitarity can then be recovered by introducing new weakly coupled degrees of freedom with a mass spectrum at, or below, the unitarity breaking scale. In case no new elementary particle appear in the spectrum, the energy scale associated to the breaking of perturbative unitarity should be interpreted as the scale where interactions of the Higgs boson and longitudinal modes of vector gauge bosons become strong $^{29,30}$. Unitarity is then expected to be recovered in a non-perturbative regime, by the exchange of strongly-interacting composite resonances.

In case the Higgs couplings are modified without extending the SM content below the scale of the unitarity violation, total cross sections might increase with energy faster than the corresponding SM ones. A relevant example is provided by the single top production in association with a Higgs boson mediated by the sub-process $Wb \rightarrow Ht$ in $pp$ collisions $^{17,19}$. Its cross section is very sensitive not only to the magnitude of the ratio $C_t/C_W$, but also to its sign, because of the strong destructive interference between the diagrams involving the Higgs coupling to the $W$ and to the top-quark in the SM.

For the $pp \rightarrow HWW$ production, the cross section receives the largest contribution from the $HWW$ coupling, and has a milder dependence on the $HZZ$ and $Htt$ couplings$^3$. In particular, the top-Yukawa coupling $g_{ttH}$ enters through the subprocess $b\bar{b} \rightarrow HWW$ (see Figure 1), which moderately contributes to the cross section with respect to the light-quark initiated sub-process $q\bar{q} \rightarrow HWW$. As for the $HZZ$ coupling, it enters only through the $s$-channel in all the sub-processes, and its impact is therefore sub-dominant with respect to the $HWW$-coupling one.

When assuming anomalous couplings, the energy scale of the partonic process must be held below the characteristic scale of unitarity violation in order to keep the cross section within the perturbative regime. In the!p!pp!→!HWW case, this scale will mostly depend on the coefficients $C_{W,Z,t}$, and should tend to infinity for $C_{W,Z,t} \rightarrow 1$, which recovers the SM case.

In order to determine the $pp \rightarrow HWW$ sensitivity to anomalous $C_{W,Z,t}$ coefficients in a perturbative regime, the effective partonic c.m. energy of the $HWW$ system ($\lesssim$ TeV at the LHC) must be kept below the energy scale of unitarity violations. To this purpose, we analyze below the relevant unitarity bounds associated to the partonic processes contributing to $pp \rightarrow HWW$ as a function of the anomalous Higgs couplings.

A. Analytical unitarity bounds

We now analyze the contribution to the $pp \rightarrow HWW$ cross section that comes from the $b$-quark initiated process

$$b(p_b) \bar{b}(p_{\bar{b}}) \rightarrow H(p_H) W^+(p_+) W^-(p_-), \quad (3)$$

where the quantities in parenthesis label the corresponding particle momenta. A representative set of Feynman diagrams for the $b\bar{b} \rightarrow HWW$ is given in Figure 1. This sub-process receives a large contribution from the top-quark Yukawa coupling (see Figure 1(b)), and is also sensitive to anomalous Higgs couplings in both the $W,Z$ and top-quark sectors. In the following, we will retain only the contribution from top-quark exchange diagrams, setting to zero the Yukawa couplings of lighter quarks since their effect does not significantly affect the present results.

The breaking of perturbative unitarity in the process in Eq. (3) is induced by the contributions of the vector-boson longitudinal polarizations. At high energy, the corresponding polarization vectors are approximated by

$$e_L^{\mu}(p_{\pm}) \approx \frac{p_{\pm}^{\mu}}{M_W}. \quad (4)$$

By retaining only the contribution of $W^\pm$ longitudinal polarizations in the relevant amplitude (labelled as

---

3 We neglect any contribution from light-quark transitions to a top-quark ($d,s \rightarrow t$) via $W$ exchange, the latter being strongly suppressed by off-diagonal terms of the Cabibbo-Kobayashi-Maskawa matrix.
\( M_{LL} \), one gets the asymptotic expression

\[
i M_{LL} = \frac{2m_b^2}{v^3} (C_t - C_W) \times \\
\frac{\bar{v}_b}{v^3} \left( \frac{\hat{p}_- - \frac{\hat{p}_+}{s}}{(p_b - p_+ - m_t^2 - m_b^2)} \right) P_L u_b + \\
2 \frac{M_Z^2}{v^3} (C_Z - C_W) \frac{\bar{v}_b}{v^3} \left( \frac{\hat{p}_+ - \frac{\hat{p}_-}{s}}{2q_b s_w^2 + P_L} \right) u_b, \tag{5}
\]

where \( u_b \) and \( \bar{v}_b \) are the spinors of the \( b \) and \( \bar{b} \) quarks, respectively, \( v \) is the Higgs vacuum expectation value, \( q_b = -1/3 \) is the bottom-quark electromagnetic charge, and \( P_L = (1 - \gamma_5)/2 \) is the left-handed chirality projector. \( M_Z \) and \( m_t \) are the \( Z \) and top-quark mass, respectively, while the \( b \)-quark is assumed massless.

In the high energy limit the kinematics is simplified by treating all the external particles as massless. Under this assumption, the phase space of the final state can be parametrized by the following dimensionless variables evaluated in the c.m. frame

\[
(p_+ + p_-)^2 \approx s - 2 \sqrt{s} E_H \equiv s y_+ \ , \\
(p_H + p_+)^2 \approx s - 2 \sqrt{s} E_- \equiv s y_- \ , \\
(p_H + p_-)^2 \approx s - 2 \sqrt{s} E_+ \equiv s y_+ , \tag{6}
\]

(with \( y_+ + y_- + y_H = 1 \)) and three angular variables, \( E_i \) denotes the energy of the particle \( i \). The r.h.s of Eq. (6) is explicitly evaluated by assuming the massless approximation.

The differential phase space, \( d\Phi_3 \), is then expressed as

\[
d\Phi_3 = \frac{s}{32(2\pi)^3} \delta(1 - y_+ - y_- - y_H) dy_+ dy_- dy_H dz, \tag{7}
\]

with \(-1 \leq z \leq 1, 0 \leq y_i \leq 1\), and \( z \) being the cosine of an angle between the initial (anti)particle and the final particle three-momenta. Two angular degrees of freedom have been integrated out. The asymptotic cross section is consequently

\[
\sigma = \frac{2 \log(s/m_t^2) - 1}{64(2\pi)^3 v^2} \delta_t^2 + 2 \delta_t \delta_Z + \frac{3}{2} \delta_Z^2, \tag{8}
\]

where, for left-handed fermions,

\[
\delta_t = \frac{2m_t^2}{v^2} (C_t - C_W) \approx 0.99 (C_t - C_W) , \hspace{1cm} \\
\delta_Z = \frac{2M_Z^2}{v^2} (2q_b s_w^2 + 1) (C_Z - C_W) \approx 0.23 (C_Z - C_W) , \tag{9}
\]

while for right-handed fermions \( \delta_t = 0 \), and in \( \delta_Z \) the expression \( 2q_b s_w^2 + 1 \) is replaced by \( 2q_b s_w^2 \). The dominant contribution arises from the \( \delta_t \) terms.

Given the above cross section, the unitarity bound can now be obtained by requiring \( \sigma \leq \frac{4\pi}{s} \), that holds under the assumption that the \( s \)-wave contribution dominates the elastic \( b \bar{b} \to b \bar{b} \) scattering. The above inequality provides the tightest bound that perturbative unitarity can cast.

In order to simplify the analysis, we consider now two different scenarios for Higgs anomalous couplings. We first assume a universal rescaling of the Higgs couplings to weak gauge bosons by imposing \( C_Z = C_W = C_V \). Secondly, we assume \( C_f = C_W \) for the Higgs fermion couplings, and vary the relative strength of \( C_Z \) and \( C_W \), inducing in this way an explicitly breaking of the custodial symmetry.

Then we obtain

- if \( C_Z = C_W = C_V \) (i.e., \( \delta_Z = 0 \) in Eq. (8)), the bound in Eq. (4) is given by

\[
\frac{4\pi}{s} \geq \frac{m_t^4 (C_t - C_W)^2}{(2\pi)^6 v^6} \left( 2 \log \left( \frac{s}{m_t^2} \right) - 1 \right) ; \tag{10}
\]

- if \( C_f = C_W \) (which sets \( \delta_t = 0 \) in Eq. (8)), breaking the custodial symmetry by setting \( C_Z \neq C_W \) yields

\[
\frac{4\pi}{s} \geq \frac{m_t^4 (C_Z - C_W)^2}{64(2\pi)^6 v^6} (2q_b s_w^2 + 1)^2 . \tag{11}
\]

By defining now the unitarity breaking (UB) energy scale, \( E_{UB} \), as the specific value of \( \sqrt{s} \) for which equalities hold in the above equations, we can see that in the first case \( E_{UB} \) is minimal when \( C_t < 0 \). In particular, setting \( C_t = -C_V = -1 \) we obtain

\[
E_{UB} \approx 14 \text{ TeV} . \tag{12}
\]

For comparison, a similar value (namely \( E_{UB} \approx 9.3 \text{ TeV} \)) was found in [18] for the \( Wb \to tH \) partonic process in single-top production in association with a Higgs boson, for \( C_W = 1 \) and \( C_t = -1 \). In the second case, given the actual bounds on the ratio \( C_Z/C_W [19] \), we can assume at most \( |C_Z - C_W| \approx 0.2 \). Correspondingly, the scale of unitarity violation brought by a maximal explicit custodial-symmetry breaking is

\[
E_{UB} \approx 4700 \text{ TeV} , \tag{13}
\]

that is more than two orders of magnitude higher than the one induced by \( C_t = -C_V = 1 \).

In conclusion, we checked that all relevant unitarity bounds are well above the effective \( HWW \) partonic c.m. energies for \( O(1) \) (or less) variations of the \( C_{W,Z,f} \) parameters. The partonic cross section for the \( HWW \) production at the LHC collision energies falls indeed in the perturbative regime (and therefore it is safely computable) for the \( C_{W,Z,f} \) parameters within currently allowed experimental ranges [9,11].

### B. Signal strengths and significances

We now discuss the sensitivity of the different \( pp \to HWW \) channels analyzed in Section III to presently allowed variations of the \( C_{W,Z,f} \) parameters.
FIG. 2: Higgs boson BR’s, normalized to their SM value, as a function of $C_F$, where $F = t, b, c, \tau \ldots$, for $C_V = 1$ (upper left panel), $C_V$, where $V = W, Z$, for $C_F = 1$ (upper right panel), $C_W$, for $C_Z = 1$ (lower left panel), and $C_Z$, for $C_W = 1$ (lower right panel). Here, $R_i = BR_i/BR_i^{SM}$, where $BR_i = \Gamma(H \rightarrow i)/\Gamma(H)_{tot}$. The normalized BR’s for $H \rightarrow W^+W^−, H \rightarrow \tau\tau$ and $H \rightarrow \gamma\gamma$ are shown by the magenta, yellow and brown lines, respectively. In the upper plots, the blue and green areas show the regions allowed at 95% confidence level by the CMS and ATLAS experiments, respectively.

We first review the impact of such variations on the Higgs BR’s. Then, we combine the latter information with the $pp \rightarrow HWW$ cross-section dependence on $C_{W,Z,f}$, obtaining in this way the sensitivity of production rates and significances to anomalous Higgs couplings for different $HWW$ signatures.

In the following analysis, we assume that Higgs couplings to all fermions are modified by a universal rescaling coefficient $C_F$, defined as $C_F = C_f$ for all fermions $f$. As above, $C_V$ is defined as a common rescaling factor for $g_{WWH}$ and $g_{ZZH}$, namely $C_V = C_W = C_Z$.

In Figure 2 we plot the Higgs BR’s normalized to their SM values ($R_i = BR_i/BR_i^{SM}$), for the decay channels relevant to our analysis, namely $H \rightarrow \gamma\gamma$, $H \rightarrow WW^*$, $H \rightarrow \tau\tau$, as a function of anomalous couplings in the range

$$-2 < C_F < 2, \quad 0.3 < C_{W,Z,V} < 1.5.$$  \hspace{1cm} (14)

In particular, in the top panels of Figure 2 we plot the normalized BR’s, $R_i$, versus $C_F$, for $C_V = 1$ (left), and $C_V$, for $C_F = 1$ (right), while in the bottom panels, the same quantities are plotted versus $C_W$, for $C_Z = C_F = 1$ (left), and $C_Z$, for $C_W = C_F = 1$ (right). The blue and light-green areas, in the top panel plots, label the regions
FIG. 3: The $pp \rightarrow WH$ cross section, normalized to its SM value, $R_\sigma = \sigma/\sigma_{SM}$ at 14 TeV (black solid line), and the combined signal significance (red solid line), corresponding to an integrated luminosity of 3000 fb$^{-1}$, as a function of $C_F$, for $C_V = 1$ (upper left panel), $C_V$, where $V = W, Z$, for $C_F = 1$ (upper right panel), $C_W$, for $C_{Z,F} = 1$ (lower left panel), and $C_Z$, for $C_{W,F} = 1$ (lower right panel). In the upper plots, the blue and green areas show the regions allowed at 95% confidence level by the CMS and ATLAS experiments, respectively. The individual significances of the five final states [$4\ell, 3\ell, \gamma\gamma, 2\ell(\tau\tau), 2\ell(WW^*)$], in units of standard deviations $\sigma_s$, are shown by the dashed magenta, cyan, brown, yellow and gray lines, respectively. The horizontal red dot-dashed line shows for reference the combined signal significance in the SM.

allowed at 95% C.L. by the present CMS and ATLAS analysis, respectively, where the darker-green areas stand for their overlaps$^4$ [9,11].

$^4$ In the bottom plots of Figure 2 we do not report the experimental allowed regions, since these correspond to a different hypothesis with respect to the one used for the exclusion regions of couplings in the $C_F/C_V$ plane adopted by CMS and ATLAS analysis.

One can see from the upper-left plot in Figure 2 that the BR’s for $H \rightarrow \gamma\gamma$ and $WW^*$ ($H \rightarrow \tau\tau$) reach their maximum (minimum) at $C_F = 0$, which makes the Higgs total width minimal. Notice that the maximum of $R_{\gamma\gamma}$ is not set exactly at $C_F = 0$, since the corresponding decay width is not symmetric under a change in the $C_t$...
sign. This is due to the destructive (constructive) interference between the W- and top-quark contributions in the $H \rightarrow \gamma\gamma$ loop amplitude for positive (negative) values of $C_F/C_W$. On the other hand, the positive (negative) slope of $R_\gamma$ for $H \rightarrow WW^*, \gamma\gamma (H \rightarrow \tau\tau)$, versus $C_V$ and $C_W$ (in the upper-right and lower-left plots of Figure 2 respectively) is just due to the rescaling property of the $H \rightarrow WW^*, \gamma\gamma$ decay widths versus the $C_{V/W}$ coupling. In the lower-left plot, we can see that all BR’s plotted versus $C_Z$ are degenerate, since the dependence on $C_Z$ mainly affects the total Higgs width (i.e., a common normalization factor) in this case.

We now combine the latter results with the $pp \rightarrow HWW$ cross-section and signal-rate dependence on Higgs couplings, working out the potential of the individual five channels analyzed in Section III and their combination.

Figure 3 shows, as a function of anomalous $C_{f,V,W,Z}$, the $pp \rightarrow WWH$ total cross section $R_\gamma$, normalized to its SM value (continuous black line), the corresponding significance $S_i$, expressed in standard deviations ($\sigma_i$), for the five signatures considered in section III A,B,C,D,E (dashed colored lines), and their combined effect (continuous red line). The horizontal dashed-dot line corresponds to the SM combined significance for the five channels. All the significances reported in Figure 3 are for a (14 TeV) LHC integrated luminosity of 3000 fb$^{-1}$.

We checked that in general the $pp \rightarrow HWW$ cross sections grow faster with energy when $C_{f,V}$ depart from the SM set-up, matching the expected unitarity-violation pattern. The most pronounced effect is obtained for negative top-Yukawa couplings, $C_t = C_F < 0$, that are more sensitive to the unitarity breaking regime than anomalous $C_Z$, as shown by Eqs. (10) and (11).

On the other hand, the cross section dependence on $C_W$ (lower-left plot in Figure 3) is mostly a consequence of the overall $C_W^0$ rescaling of the total cross sections, since Higgs radiation from a $W$ boson gives the dominant contribution to the $HWW$ production. Analogous conclusions hold (upper-right plot) for the cross section dependence on a common $C_V$ rescaling factor. Quite large variations (up to 50%) of the total cross sections are expected for anomalous couplings in the 95% C.L. range allowed by present experiments.

We then combine in quadrature the expected $HWW$ significances in different channels, versus $C_{V,F}$. Large enhancements can be obtained with respect to the SM signal sensitivity, for $C_{V,F}$ values presently allowed by LHC experiments (see Figure 4), thanks to the combined effect of the cross section and BR’s dependence on anomalous couplings. In particular, the significance versus $C_F$ for the combined channels is maximal for $C_F \simeq 0$, reaching values up to $\sim 12 \sigma$, as a consequence of the corresponding enhancements in the ratios $R_{\gamma\gamma,WW}$ (upper-left plot in Figure 2). For $C_F \sim 0$, the most sensitive final states are three-leptons, and $\gamma\gamma$, followed by two-same-sign leptons. Within the allowed 95% C.L. regions, the highest combined significance, corresponding to $C_F \sim -0.5$, is about $\sim 9\sigma$.

For $C_F = 1$, upper-right and lower-left plots in Figure 3 give different-channel significances versus $C_V$ and $C_W$, respectively. The $C_V$ and $C_W$ dependence is mainly due to the naive rescaling property of the signal cross section and BR’s with $C_V$ and $C_W$. In particular, the maximum effect, corresponding to the largest allowed value $C_V \sim 1.3$, gives a $\sim 8\sigma$ significance for the combined channels. Analogous conclusions hold for the dependence on $C_W$ (with $C_{Z,F} = 1$).

Finally, in Figure 3 lower-right plot, we show the significance versus $C_Z$ (with $C_{V,F} = 1$). The maximum enhancement in this case is obtained for the lower-edge $C_Z \sim 0.3$, with a significance $\sim 4\sigma$, and a modest 10% enhancement over the SM value, that falls down to a few per-cent for $0.8 \lesssim C_Z \lesssim 1.2$.

V. SUMMARY AND CONCLUSIONS

The discovery of the Higgs boson started a new phase in the experimental test of the electroweak symmetry breaking mechanism of the SM. Now it is indeed of utmost importance not only to study with high accuracy the Higgs production through the basic discovery channels, but also to explore lower-cross-section processes that can be sensitive to multi-boson interactions. A typical example is given by the Higgs-boson pair production, which is the lowest-order process that probes at tree-level the trilinear term of the Higgs potential, and yet has a cross section of just 34 fb at the (14 TeV) LHC. Here we considered the largest-rate among the electroweak triboson production processes involving a Higgs boson in the final state, that is the associated production of a $W$ pair and a Higgs boson. We analyzed (in a tree-level study) the cleanest experimental signatures corresponding to the $HWW$ final state, that are either multi-lepton or di-photon resonances. The main backgrounds have been scrutinized. The most sensitive signature turns out to be a three lepton plus hadronic $W$ final state that reaches a $3\sigma$ significance at the HL-LHC with 3000 fb$^{-1}$. Including other channels, we obtain a total $3.6\sigma$ significance in the SM.

We then carried out a first study of the $pp \rightarrow HWW$ sensitivity to possible Higgs anomalous couplings to vector bosons and fermions. We assumed a simple framework where a change in the fermion Higgs coupling sector is universal in fermion flavor. Regarding couplings to vector bosons, we assumed both a universal change in the $W/Z$ coupling and the possibility of custodial symmetry breaking.

While the sensitivity to $C_V$ in the cross section is driven by an approximate multiplicative factor $C_V^2$, in the total cross section, the dependence on $C_F$ is mainly restricted to the $bb \rightarrow HWW$ subprocess, whose amplitude presents, in the SM, non-trivial cancelation effects between the $W$ and $t$ quark radiation of a Higgs boson.

We also studied unitarity-breaking effects induced by anomalous Higgs couplings in the $q\bar{q} \rightarrow HWW$ ampli-
tude behavior with c.m. scattering energy, and checked that the corresponding cross section can be reliably computed at the LHC in the experimentally allowed range of Higgs anomalous couplings.

Note that, by the time the high-luminosity run of the LHC will start, our knowledge of Higgs boson couplings will have widely been enlarged with respect to the present one [20, 21]. In case some deviation from the SM expectations in the Yukawa and/or vector boson sectors will have been observed by then, our preliminary study shows that the $HWW$ production mode could be an extra valuable channel to clarify the emerging picture. Furthermore, even in a scenario where the SM picture is apparently confirmed, the $HWW$ production could probe higher-dimensional operators by which higher-cross-section processes are moderately affected. We leave to further work the assessment of the $HWW$ potential in this case.

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