**Higgs self-coupling measurements at the LHC**

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Both the ATLAS and CMS collaborations have reported a Standard Model Higgs-like excess at around $m_h = 125$ GeV. If an SM-like Higgs particle is discovered in this particular mass range, an important additional test of the SM electroweak symmetry breaking sector is the measurement of the Higgs self-interactions. We investigate the prospects of measuring the Higgs self-coupling for $m_h = 125$ GeV in the dominant SM decay channels in boosted and unboosted kinematical regimes. We further enhance sensitivity by considering dihiggs systems recoiling against a hard jet. This configuration exhibits a large sensitivity to the Higgs self-coupling which can be accessed in subjet-based analyses. Combining our analyses allows constraints to be set on the Higgs self-coupling at the LHC.

I. INTRODUCTION

The Standard Model (SM) Higgs [1] has recently been excluded at the 95% confidence level from 129 (127.5) GeV to 539 (600) GeV by measurements performed by ATLAS (CMS) [2]. In addition, the Higgs mass bound from LEP2 was raised from 114.4 GeV [3] to 117.5 GeV by ATLAS. Both ATLAS and CMS have also observed tantalizing hints for a SM-like Higgs at a mass $m_h \simeq 125$ GeV with local significances of 2.5$\sigma$ and 2.8$\sigma$, respectively. In the same mass region, the D0 and CDF collaborations observe an excess with a local significance of 2.2$\sigma$ for the combination of their data sets [3].

Breaking down these results into the individual search channels has triggered some effort to pin down the properties of the observed excess in the SM and beyond [3]. These analyses are the first steps of a spectroscopy program which targets the properties of a newly discovered particle if the excess at 125 GeV becomes statistically significant. Strategies to determine spin- and CP quantum numbers, and the couplings to fermions and gauge bosons of a 125 GeV resonance with SM-like cross sections have been discussed in the literature [6, 7]. A determination of the Higgs self-interaction, however, which is crucial for a measurement of the symmetry breaking sector remains challenging in the context of the SM (this can change in BSM scenarios [8]). Even for scenarios where the Higgs is close to the $h \rightarrow W^+W^-$ threshold, statistics at the LHC in $pp \rightarrow hh + X$ is extremely limited [3, 11], so that formulating constraints on the Higgs self-coupling requires end-of-LHC-lifetime statistics if possible at all*.

The Higgs self-coupling in the SM follows from equating the Higgs potential after the Higgs doublet is expanded around the electroweak symmetry breaking vacuum expectation value, $H = (0, v + h)^T/\sqrt{2}$ in unitary gauge:

$$ V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2 $$

$$ \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\mu^2}{2}} m_h^2 h^2 + \frac{\eta}{4} h^4, \quad (1) $$

where $m_h^2 = \eta v^2/2$, and $v^2 = -\mu^2/\eta$. Since symmetry breaking in the SM relies on $\mu^2 < 0$ and $\eta > 0$, the partial experimental reconstruction of the Higgs potential via the measurement of the trilinear Higgs vertex and its comparison to SM quantities (e.g. $2\eta = g^2 m_h^2/m_W^2$) is necessary to verify symmetry breaking due to a SM-like Higgs sector. Strictly speaking, a similar program needs to be carried out for the quartic Higgs vertex to fully reconstruct the Higgs potential by measurements. This task is, however, even more challenging due to an even smaller cross section of triple Higgs production [13, 14].

A process at hadron colliders which is sensitive to the trilinear Higgs coupling is the previously mentioned Higgs pair production $pp \rightarrow hh + X$ via gluon fusion. Consequently, this process has already been studied in the literature in detail [14, 17]. From the known results it is clear that the LHC’s potential towards measuring the trilinear coupling only in a single channel is insufficient. Combining different Higgs decay final states improves the situation, but exhausting the entire LHC search potential requires also discussing the machine’s capability to constrain the trilinear Higgs coupling in different kinematical regimes.

Different properties of signal and background processes in e.g. boosted final states as compared to unboosted kinematics allows us to access Higgs decay channels which are impossible to isolate from the background in a more inclusive search. This has impressively been demonstrated in the context of subjet-based analysis techniques [18] which have proven successful during the 7 TeV LHC run [19]. In addition to that, initial state radiation can be an important effect when considering energetic final states. A dihiggs system recoiling against a hard hadronic jet accesses an entirely new kinematical

* A related analysis of Higgs physics at a future linear collider can be found in Ref. [22].
The phenomenology of such configurations can also be treated separately from radiative correction contributions to $pp \to hh + X$. Graphs of type (a) yield vanishing contributions due to color conservation.

The goal of this paper is to provide a comparative study of the prospects of the measurement of the trilinear Higgs coupling applying contemporary simulation and analysis techniques. In the light of recent LHC measurements, we focus on the context of a complete discussion of the sensitivity towards the trilinear Higgs coupling over the entire Higgs mass range $m_h \lesssim 1$ TeV. As we will see, $m_h \approx 125$ GeV is a rather special case. Since Higgs self-coupling measurements involve end-of-lifetime luminosities we base our analyses on a center-of-mass energy of 14 TeV.

We begin with a discussion of some general aspects of double Higgs production, before we review inclusive searches for $hh$ production, before we review inclusive analyses on a center-of-mass energy of 14 TeV.

We give our conclusions in Sec. IV.

II. HIGGS PAIR PRODUCTION AT THE LHC

A. General Remarks

Inclusive Higgs pair production has already been studied in Refs. [14–17], so we limit ourselves to the details that are relevant for our analysis.

Higgs pairs are produced at hadron colliders such as the LHC via a range of partonic subprocesses, the most dominant of which are depicted in Fig. 1. An approximation which is often employed in phenomenological studies is the heavy top quark limit, which gives rise to effective $gg$ and $gghh$ interactions [20]

\[ \mathcal{L}_{\text{eff}} = \frac{1}{4 \pi} \frac{\alpha_s}{3} G_{\mu\nu}^a G^{a \mu\nu} \log(1 + h/v), \]

which upon expansion leads to

\[ \mathcal{L} \supset \frac{1}{3 \pi v} \frac{\alpha_s}{4} G_{\mu\nu}^a G^{a \mu\nu} h - \frac{1}{4 \pi v^2} \frac{\alpha_s}{3} G_{\mu\nu}^a G^{a \mu\nu} h^2. \]

Studying these operators in the $hh + X$ final state should in principle allow the Higgs self-coupling to be constrained via the relative contribution of trilinear and quartic interactions to the integrated cross section. Note that the operators in Eq. (3) have different signs which indicates important interference between the (nested) three- and four point contributions to $pp \to hh + X$ already at the effective theory level.

On the other hand, it is known that the effective theory of Eq. (3) insufficiently reproduces all kinematical properties of the full theory if the interactions are probed at momentum transfers $Q^2 \gtrsim m_t^2$ [11] and the massive quark loops are resolved. Since our analysis partly relies on boosted final states, we need to take into account the full one-loop contribution to dilihiggs production to realistically model the phenomenology.

B. Parton-level considerations

In order to properly take into account the full dynamics of Higgs pair production in the SM we have implemented the matrix element that follows from Fig. 1 in the VBFNLO framework [21] with the help of the FERMArts/FORMCalc/LOOPTools packages [22], with modifications such to include a non-SM trilinear Higgs coupling[. Our setup allows us to obtain event files according to the Les Houches standard [23], which can be straightforwardly interfaced to parton showers. Decay correlations are trivially incorporated due to the spin-0 nature of the SM Higgs boson.

†The signal Monte Carlo code underlying this study is planned to become part of the next update of VBFNLO and is available upon request until then.
Interference between the different non-zero contributions depicted in Fig. 3 becomes obvious for the differently chosen Higgs self-couplings. We also learn from Fig. 3 that the dihiggs cross section has a fairly large dependence on the particular value of the trilinear coupling for a $m_h = 125$ GeV Higgs boson. The qualitative Higgs mass dependence for different values of the trilinear self-coupling in Fig. 3 is easy to understand: The Higgs propagator in Fig. 1(c) is always probed off-shell at fairly large invariant masses; this renders the triangle contributions subdominant compared to the box contributions of Fig. 1(b). For Higgs masses close to the mass of the loop-dominating top quark, we have $s \simeq 4m_t^2$, which results in resonant contributions of the three-point functions of Fig. 1(c), well-known from one-loop $gg \rightarrow h$ production [27]. This ameliorates the $s$-channel suppression of the trilinear coupling-sensitive triangle graphs and causes the dependence of the cross section on the trilinear coupling to become large at around $m_h \lesssim m_t$.

To gain sensitivity beyond total event counts, it is important to isolate the region of phase space which is most sensitive to modifications of the trilinear coupling in order to set up an analysis strategy which targets the trilinear self-coupling most effectively. At the parton level, there is only a single phenomenologically relevant observable to $hh$ production, which can be chosen as the Higgs transverse momentum $p_{T,h}$. In Fig. 2 we show the differential $p_{T,h}$ distribution for different values of $\lambda$ and $m_h = 125$ GeV. The dip structure for $\lambda > \lambda_{SM}$ results again from phase space regions characterized by $s \sim 4m_t^2$, which are available if $m_h < m_t$, and the resulting maximally destructive interference with the box contributions.

The resulting inclusive hadronic cross sections are plotted in Fig. 3 where we also show results for non-SM trilinear couplings, varied around the SM value (see Eq. (1))

$$\lambda_{SM} = \sqrt{\frac{m_t}{2}m_h}.$$ (4)

Note that choosing a value different from $\lambda_{SM}$ does not yield a meaningful potential in terms of Eq. (1), but allows to constrain $\lambda$ in hypothesis tests using, e.g., the CLs method [24].

We also show the result of Ref. [15] for comparison and find excellent agreement in total, keeping in mind that the results of Ref. [15] were obtained using the GRV parametrizations of parton luminosities [25], which are different from the CTEQ6l1 [26] set that we employ for the remainder of this paper.

FIG. 2: Comparison of the (normalized) $p_{T,h}$ distributions in $pp \rightarrow hh + X$ at LO for different multiples of the trilinear Higgs coupling $\lambda$ ($m_t = 172.5$ GeV and $m_h = 4.5$ GeV using CTEQ6l1 parton densities).

FIG. 3: Comparison of $pp \rightarrow hh + X$ at LO. We choose $m_t = 175$ GeV as in Ref. [15], from which we also obtain the dashed blue reference line, and $m_h = 4.5$ GeV and we use the CTEQ6l1 parton distributions.

Using the integration-mode of FORMCALC/LOOPTOOLS with the CTEQ6l1 set we obtain perfect agreement.
are naturally boosted $p_{T,h} \gtrsim 100$ GeV,

- interference leads to an a priori $\lambda$-sensitive phenomenology for $m_h \simeq 125$ GeV,

- identical interference effects also cause the bulk of the sensitivity to $\lambda$ to follow from configurations with $p_{T,h} \sim 100$ GeV, while the $p_{T,h}$ shape at large values becomes similar for different values of $\lambda$ due to decoupling the triangle contributions at large partonic $\sqrt{s}$,

- the cross section shows a dependence on the trilinear coupling of $\Delta \sigma/\sigma_{SM} \simeq 50\%$ when varying $\lambda \in [0, 2\lambda_{SM}]$.

We conclude our parton-level discussion of dihiggs production by noting that the higher-order corrections \cite{16}, which result in a total $K$ factor of $\sigma^{NLO}/\sigma^{LO} \gtrsim 1.85$, result from a large contribution from real parton emission. This is a characteristic trait of processes involving color-singlet final states at leading order, for which plenty of phase space for extra parton emission in addition to new initial-state parton combinatorics becomes available at next-to-leading order (NLO). Similar observations have been made for $pp \to VV + X$, where $V = W^\pm, Z, \gamma$ \cite{29}. The discussed characteristics of $pp \to hh + X$ are therefore not distorted when including NLO precision, and the parton shower will capture the characteristic features of the cross section upon normalizing to the NLO inclusive rate.

### C. Inclusive Higgs Pair Searches

To measure $\lambda$ for a 125 GeV Higgs we need to isolate modifications of $pp \to hh + X$ cross sections around $\sigma^{NLO}(hh + X) = 28.4$ fb from the Higgses’ exclusive decay channels. Given the small total inclusive cross section\(^4\), it is clear that even for $\sqrt{s} = 14$ TeV and a target luminosity of $\mathcal{O}(10000 fb^{-1})$ we need to focus on the Higgs decay channels with the largest branching ratios to phenomenologically visible final states to observe $pp \to hh + X$. These are $31$ $h \to bb$ (59.48\%), $h \to W^+W^-$ (20.78\%), and $h \to \tau\tau$ (6.12\%). The decay $h \to ZZ$ (2.55\%) is limited by the decays of the $Z$ bosons to the clean leptonic final states $Z \to e^+e^-, \mu^+\mu^-$ (6.67\%) (yielding $\text{BR}(h \to e^+e^- + \mu^+\mu^-) = 0.013\%$). Hadronic $Z$ decay modes can only be accessed in the boosted regime, which is not feasible for $m_h = 125$ GeV \cite{22}. We do not consider the final state $hh \to \bar{b}\bar{b}\gamma\gamma$. A feasibility study for this particular channel was already presented in Ref. \cite{9}. A realistic assessment of the sensitivity in $\bar{b}\bar{b}\gamma\gamma$ depends on a realistic simulation of the diphoton fake rate due to multijet production, which is the dominant background to such an analysis, similar to Higgs searches in $h \to \gamma\gamma$. Details of the photon identification rely on the detector properties and the event selection approach, and we cannot address these issues in a realistic fashion. We focus in on $h \to \bar{b}b, W^+W^-, \tau^+\tau^-$ in the following.

We generate all (fully showered and hadronized) background samples with SHERPA \cite{32} or MadEvent \cite{34}. The signal events are interfaced to HERWIG++ \cite{35} for showering and hadronization.

1. $hh \to \bar{b}b\bar{b}\bar{b}$

The exclusive decay to two $\bar{b}b$ pairs is the most obvious channel to check for sensitivity due to its large branching ratio for $m_h = 125$ GeV. Using $b$-tagging, it also possible to access the intermediate invariant Higgs masses, for which the modifications due to $\lambda \neq \lambda_{SM}$ are well-pronounced.

Passing the trigger-level cuts is not a problem for the signal events: the Higgses are naturally boosted and the $p_T$-ordered $b$ jets typically pass the staggered cuts on the transverse momentum $p_T > 100$ GeV, $p_T > 80$ GeV, $p_T > 50$ GeV, $p_T > 40$ GeV. However, as already mentioned, there is only one relevant scale to dihiggs production, and therefore our options to compete with the gigantic QCD $pp \to \bar{b}b\bar{b}b + X$ background are highly limited. Note that both Higgs bosons need to be reconstructed in order to be sensitive to the modifications of the trilinear coupling.

In total, inclusive dihiggs production with decay to four $b$ quarks has a signal-over-background ratio $S/B$ which is too bad to be a suitable search channel, already when we focus only on the QCD-induced four $b$

\(^4\)The total inclusive single Higgs production cross section is 16.5 pb \cite{30} for comparison.

| cross section before cuts | $\xi = 0$ | $\xi = 1$ | $\xi = 2$ | $\bar{b}\bar{b}W\bar{W}$ | ratio to $\xi = 1$ |
|---------------------------|-----------|-----------|-----------|----------------|----------------|
|                           | 59.48%    | 28.34%    | 13.36%    | 877500        | 3.2 $\cdot 10^{-5}$ |
| 1 isolated lepton         | 7.96%     | 3.76%     | 1.74%     | 254897        | 1.5 $\cdot 10^{-5}$ |
| MET + jet cuts            | 1.54%     | 0.85%     | 0.44%     | 66595.7       | 1.2 $\cdot 10^{-5}$ |
| hadronic $W$ reconstruction | 0.59%    | 0.33%     | 0.17%     | 38153.3       | 0.9 $\cdot 10^{-5}$ |
| kinematic Higgs reconstruction | 0.028% | 0.017%    | 0.007%    | 205.1         | 8.3 $\cdot 10^{-5}$ |

TABLE I: Signal and background cross sections in fb for $hh \to \bar{b}\bar{b}W^+W^-$. The Higgs self-coupling is scaled in multiples of the Standard Model value $\lambda = \xi \times \lambda_{SM}$, Eq. \cite{4}. The background is $\bar{b}\bar{b}W^+W^-$ production discussed at NLO in Ref. \cite{25} ($K \simeq 1.5$).
1. **hh → bbarb** for boosted kinematics

To gain multiple phenomenological handles to deal with the contributing backgrounds while preserving a signal rate as large as possible we focus on $h → t\bar{t}$ and $h → (W → jj)(W → \nu l)$. The contributing background processes are $t\bar{t}$ and $b\bar{b}W^+W^−$ production and we can employ cuts on missing transverse energy (MET), lepton identification and $p_T$, and the reconstructed $W$ resonance to reduce them.

We require exactly one isolated lepton with $p_{T,l} > 10$ GeV in the central part of the detector $|y| < 2.5$, where isolation means an hadronic energy deposit of $E_{T,\text{had}} < 0.1 E_{T,l}$ within a cone of $R = 0.3$ around the identified light-flavor lepton. In the next step we reconstruct the missing transverse energy (MET) $E_T$ from all visible final state objects within the rapidity coverage $|y| < 4.5$ and require $E_T > 20$ GeV. Then, we use the anti-kT algorithm as implemented in FASTJET [38] (which we use throughout this paper) to reconstruct jets with $R = 0.6$ and $p_T > 40$ GeV, and require at least four jets in $|y| < 4.5$. Afterwards we reconstruct the $W$ boson by looping over all jet pairs. The jet pair that reconstructs the $W$ mass best within 60 GeV $≤ m_{jj} ≤ 100$ GeV is identified as the $W$ boson, and we subsequently remove these jets from the event. Analogous to the $W$ reconstruction we reconstruct the Higgs within 110 GeV $≤ m_{jj} ≤ 140$ GeV. To reduce the backgrounds and identify the signal contributions we use a double $b$-tag for the two jets which reconstruct the Higgs best. We use an efficiency of 60% with a fake rate of 2% in $|y| < 2.5$ [39]. Thus, if one of the Higgs jets is outside $|y| ≤ 2.5$ our reconstruction fails.

The results of this analysis flow can be found in Tab. II. While the cuts bring down the background by a factor of $4 \times 10^3$, they also reduce the signal by nearly the same amount $(1.5 \times 10^5)$. The requirement of two reconstructed Higgses has a strong effect on the background, however the initial cross-section (incrementally generated) is simply too large for these cuts to bring down the $S/B$ for this channel to a level for it to be useful in constraining the Higgs trilinear coupling.

### D. Boosted Higgs Pair Searches

Moving on to the discussion of boosted final states, we can potentially gain sensitivity in the dominant Higgs decay modes, *i.e.* in the $b\bar{b}$ channels [18]. The downside, however, is that we lose sensitivity to modifications of the trilinear couplings for harder Higgs bosons along the lines of Sec. III.B. Nonetheless, a measurement of the magnitude of the dihiggs cross section is already an important task in itself.

Recently, in the so-called BDRS analysis [13], it has been shown that applying jet substructure techniques on fatjets is a powerful tool to discriminate boosted electroweak-scale resonances from large QCD backgrounds. The BDRS approach proposes to recombine jets using the Cambridge-Aachen (C/A) algorithm [42, 43] with a large cone size to capture all decay products of the boosted resonance. Then one works backward through the jet clustering and stops when the clustering meets a so-called “mass-drop” condition: $m_{j_1} < \mu m_{j_2}$ with $\mu = 0.66$ and $\min(p_{T,j_1}^2, p_{T,j_2}^2)/m_2^2 \Delta R_{j_1,j_2}^2 > y_{cut}$ using $y_{cut} = 0.09$. If this condition is not met the softer subject $j_2$ is removed and the subjects of $j_1$ are tested for a mass drop. As soon as this condition is met browsing backward through the cluster history the algorithm stops. In a step called “filtering” the constituents of the two subjects which meet the mass drop condition are recombined using the (C/A) algorithm with $R_{filt} = \min(0.3, R_{bb}/2)$. Only the three hardest filtered subjects are kept to reconstruct the Higgs boson and the two hardest filtered subjects are $b$-tagged. The filtering step reduces the active area of the jet tremendously and makes the Higgs-mass reconstruction largely insensitive to underlying event and pileup.

For the reconstruction of the boosted Higgs bosons in Sec. III.D1 and Sec. III.D2 we adopt this approach without modifications. It is worth noting that other techniques, possibly in combination with the BDRS approach, can improve on the Higgs reconstruction effi-
TABLE III: Signal and background cross sections in fb for $hh \rightarrow b\bar{b}τ^+τ^−$ for boosted kinematics. The Higgs self-coupling is scaled in multiples of the Standard Model value $λ = ξ × λ_{SM}$, Eq. (11). The background comprises $tt$ with decays to $t \rightarrow bτν_τ$, and $b\bar{b}τ^+τ^−$ for pure electroweak and mixed QCD-electroweak production, normalized to the respective NLO rates. The $b\bar{b}W^+W^−$ NLO cross sections are provided in [28] ($K \approx 1.5$), for the mixed and the purely electroweak contributions we infer the corrections from $Zb$ ($K \approx 1.4$) and $ZZ$ ($K \approx 1.6$) production using MCfM [40, 41].

| $ξ = 0$ | $ξ = 1$ | $ξ = 2$ | $b\bar{b}ττ$ | $b\bar{b}ττ$ [ELW] | $b\bar{b}W^+W^−$ | ratio to $ξ = 1$ |
|----------|----------|----------|---------------|----------------|----------------|----------------|
| cross section before cuts | 59.48 28.34 13.36 | 67.48 | 8.73 | 873000 | 3.2 $\cdot 10^{-5}$ |
| reconstructed Higgs from $τs$ | 4.05 1.94 0.91 | 2.51 | 1.10 | 1507.99 | 1.9 $\cdot 10^{-3}$ |
| fatjet cuts | 2.27 1.09 0.65 | 1.29 | 0.84 | 223.21 | 4.8 $\cdot 10^{-3}$ |
| kinematic Higgs reconstruction ($m_{bb}$) | 0.41 0.26 0.15 | 0.104 | 0.047 | 9.50 | 2.3 $\cdot 10^{-2}$ |
| Higgs with double $b$-tag | 0.148 0.095 0.053 | 0.028 | 0.020 | 0.15 | 0.48 |

1. $hh \rightarrow b\bar{b}ττ$

As already pointed out, the Higgs bosons are naturally boosted, and requiring two fatjets subject to BDRS tagging can improve the very bad $S/B$ in the conventional $pp \rightarrow b\bar{b}ττ + X$ search without losing too much of the dihiggs signal cross section.

In the analysis, we veto events with light leptons $p_T,l > 10$ GeV in $|y| < 2.5$ to reduce $tt$, where the leptons are again assumed isolated if $E_{T,had} < 0.1E_{T,l}$ within $R < 0.3$. We need to make sure that the events we want to isolate pass the trigger level. For this reason, we recombine final state hadrons to jets with $R = 0.4$ and $p_T > 40$ GeV and require at least four jets and the following staggered cuts: $p_{T,j1} > 100$ GeV, $p_{T,j2} > 70$ GeV, $p_{T,j3} > 50$ GeV. All jets have to be within detector coverage $|y| < 4.5$.

For the events that pass the trigger cuts, we apply a “fatjet” analysis, i.e. require at least two jets with $p_{T,j} > 150$ GeV and $R = 1.5$ in the event. We apply the BDRS approach to both of these fatjets using $µ_{cut} = 0.66$ and $y_{cut} = 0.09$. The reconstructed Higgs jets need to reproduce the Higgs mass within a 20 GeV window: $115$ GeV $≤ m_h ≤ 135$ GeV, and we additionally require that the two hardest filtered subjects are $b$-tagged.

We generate the backgrounds with exclusive cuts to make our cut-analysis efficient, yet inclusive enough to avoid a bias. More precisely we demand two pairs of $b$ quarks to obey $R_{bb} < 1.5$, $p_{T}(bb) ≥ 100$ GeV, $m(bb) ≥ 50$ GeV, while $p_{T,b} ≥ 20$ GeV, and $|y_b| ≤ 2.5$. The (anti-) $b$s are generated with $R_{bb} ≥ 0.2$.

The results are collected in Tab. III. Again, while the cuts allow an improvement in $S/B$ by an nearly an order of magnitude, we are still left with a small signal rate on top of a very large background so that this channel is in the end also not promising.

2. $hh \rightarrow b\bar{b}τ^+τ^−$

A promising channel is dihiggs production with one Higgs decaying to a pair of $τ$ leptons. This decay channel in association with two jets is one of the main search channels for single light Higgs production [42, 43] and has recently been used to put bounds on Higgs production by CMS [49]. The reconstruction of $τ$ leptons is delicate from an experimental point of view, and current analysis strategies mostly rely on semi-hadronic $τ$ pair decays in the context of Higgs searches (see e.g. Ref. [49]). The $τ$ identification is performed using likelihood methods which do not allow a straightforward interpretation in terms of rectangular cuts used in e.g. Ref. [48]. Consequently, with likelihood $τ$ taggers unavailable to the public, a reliable and realistic estimate is hard to obtain. For this reason, we choose a $τ$ reconstruction efficiency of $80%$ with a negligible fake rate. This is not too optimistic in the light of the likelihood approaches of Ref. [50], bearing in mind that our analyses are based on end-of-lifetime luminosities, for which we may expect a significant improved $τ$ reconstruction when data is better understood. We choose a large enough Higgs mass window for the reconstruction, in order to avoid a too large systematic pollution due to our assumption (in Ref. [49] CMS quotes a $O(20%)$ of the reconstructed Higgs mass).

In more detail, we require two $τ$ jets with $p_T ≥ 20$ GeV, reproducing the Higgs mass window within $50$ GeV, $m_{ττ} = m_h ± 25$ GeV. Then we use the C/A algorithm to reconstruct fatjets with $R = 1.5$ and $p_{T,j} > 150$ GeV and require at least one fatjet in the event. Thereby we demand the fatjets to be sufficiently isolated from the $τ$s. We subsequently apply the BDRS approach to the fatjet with $µ_{cut} = 0.66$ and $y_{cut} = 0.09$. The two hardest filtered subjets need to pass $b$ tags and the reconstructed Higgs jet has to be in $m_h ± 10$ GeV. $B$-tagging is performed for $|y| < 2.5$ and we assume an efficiency of $70%$ and a fake rate of $1%$ following Ref. [51].

We generate the $b\bar{b}ττ$ and pure electroweak $b\bar{b}ττ$ backgrounds with exclusive cuts to make our cut-analysis reasonably efficient, yet inclusive enough to avoid a bias. More precisely we demand the two $b$ quarks to obey $R_{bb} < 1.5$, $p_{T}(bb, ττ) ≥ 100$ GeV, $m(bb, ττ) ≥ 50$ GeV, while $p_{T,b,τ} ≥ 20$ GeV, and $|y_{b,τ}| ≤ 2.5$. The $b$s and
\( \tau \)s are generated with \( R_{bb, \tau \tau} \geq 0.2 \). On the other hand, the \( bbW^-W^+ \) sample is generated inclusively, and is the same sample used in the unboosted \( bbW^-W^+ \) analysis in the previous section.

The results are shown in Tab. III. The initial background cross-section looks very large due to it being inclusively generated. However, once we take into account the small branching ratio of \( W \rightarrow \tau \nu \) this drops dramatically. After requiring two \( b \)-tagged jets which reconstruct the Higgs mass we are left with an \( S/B \) of nearly half for the \( \xi = 1 \) case (and nearly one in for \( \xi = 0 \)). The cross-section is also reasonable, corresponding to 95 events for 1000 inverse femtobarns of luminosity. This channel is hence very promising indeed.

**III. HIGGS PAIR PRODUCTION IN ASSOCIATION WITH A HARD HADRONIC JET**

**A. Parton-Level considerations**

The qualitatively poor agreement of the effective theory of Eq. (3) with the full theory persists if additional jet radiation is included. Naively we could have expected that accessing smaller invariant masses in the Higgs system due to significant initial state radiation might result in a better agreement with the effective theory of Eq. (3). However, especially for hard jet emission, which allows the Higgs pairs to access large invariant masses in a new collinear kinematical configuration compared to \( pp \rightarrow hh + X \), the disagreement of full and effective theories is large (Fig. 5).

Given these shortcomings of the effective theory, we implement the full matrix element in the VBFLNLO framework using FeynArts/FormCalc/LoopTools. We
\[ \lambda = 2 \times \lambda_{\text{SM}} \]
\[ \lambda = 1 \times \lambda_{\text{SM}} \]
\[ \lambda = 0 \times \lambda_{\text{SM}} \]
\[ \lambda = -1 \times \lambda_{\text{SM}} \]

FIG. 6: Comparison of the (normalized) leading order max \( p_{T,h} \) distributions in \( pp \rightarrow hh + j + X \) for different multiples of the trilinear Higgs coupling \( \lambda \) (\( m_t = 172.5 \text{ GeV} \) and \( m_h = 4.5 \text{ GeV} \) using CTEQ6l1 parton densities), and \( p_{T,j} \geq 20 \) (100) GeV in the upper (lower) row, respectively. Factorization and renormalization scales are chosen \( \mu_F = \mu_R = p_{T,j} + 2m_h \).

FIG. 7: Comparison of the (normalized) dihiggs lego plot separation in \( pp \rightarrow hh + j + X \) at LO for different multiples of the trilinear Higgs coupling \( \lambda \) (\( m_t = 172.5 \text{ GeV} \) and \( m_h = 4.5 \text{ GeV} \) using CTEQ6l1 parton densities), and \( p_{T,j} \geq 100 \) GeV in the upper (lower) row, respectively. Factorization and renormalization scales are chosen \( \mu_F = \mu_R = p_{T,j} + 2m_h \).
have checked our phase space implementation for the effective theory’s matrix element against MadEvent. Some of the contributing Feynman graphs to the dominant $gg$-initiated subprocess are shown in Fig. 4; note that again only a subset of the contributing diagrams is sensitive to non-standard $hhh$ couplings. Interference between these and the remaining contributions is again obvious from Fig. 8 especially at around $m_h \lesssim m_t$, which can again be explained along the lines of Sec. II.B.

In comparison to $pp \to hh + X$, we find sizably larger dependence on $\lambda$ of the total cross section, Fig. 8. For $p_{T,j} \geq 20$ GeV we have $\Delta \sigma/\sigma_{SM} \simeq 100\%$ for a variation $0 \leq \lambda \leq 2 \lambda_{SM}$. This is due to the larger available phase space for the dihiggs system. The intermediate $s$ channel Higgs in Fig. 4(a), (c) is probed at smaller values compared to Fig. 4(c), suppression is ameliorated and (destructive) interference becomes more pronounced.

With a dihiggs system that becomes less back-to-back for increasingly harder jet emission, the characteristic dip structure encountered in the $p_{T,h}$ spectrum of $pp \to hh + X$ is washed out (Fig. 6). Characteristic imprints can still be observed in the dihiggs invariant mass or, equivalently, in the dihiggs separation in the azimuthal-angle—pseudorapidity plane, Fig. 7.

Let us summarize a few points relevant to the analysis of $pp \to bbbb + j + X$ production for $p_{T,j} \gtrsim 100$ GeV:

- The dihiggs+jet cross section has a comparably large dependence on the value of the trilinear couplings as compared to $pp \to hh + X$ ($\Delta \sigma/\sigma_{SM} \simeq 45\%$ when varying $\lambda \in [0, 2 \lambda_{SM}]$),

- the sensitivity to non-standard values of the trilinear coupling arises from phase space configurations where the two Higgs bosons are close to each other in the central part of the detector, i.e. for rather small values of the invariant masses,

- as a consequence, the hadronic Higgs decay products are likely to overlap, and to fully reconstruct the busy $hh$ decay system we need to rely on jet-substructure techniques.

Let us again comment on the impact of higher order QCD contributions. A full NLO QCD computation for $pp \to hh + j + X$ is yet missing, but most $pp \to VV + j + X$ ($V = W^\pm, Z, \gamma$) production cross sections, which have similar properties from a QCD point of view, are known to NLO QCD precision [52]. Also, the NLO QCD cross sections for $pp \to V h + j + X$ ($V = W^\pm, Z$) have been provided in Ref. [53]. Given that the QCD sector is largely agnostic about the matrix elements’ precise electroweak properties (taken apart the partonic composition of the initial state), it is not a big surprise that all these production cross sections exhibit a rather similar phenomenology at NLO QCD. The total inclusive $K$ factors range around $K \sim 1.3$ and result from unsuppressed parton emission. It is hence reasonable to expect the QCD corrections to $pp \to hh + j + X$ to be of similar size, and parton shower Monte Carlo programs to reasonably reproduce the dominant kinematical properties.

For the remainder of this paper we do not include the weak boson fusion component [54] to one-jet inclusive production. This the second largest contribution to inclusive dihiggs production, but it is still smaller than $hh + j$ production from gluon fusion in the phase space region we are interested in. For $max p_{T,j} \geq 80$ GeV we have $\sigma_{WBF}(hh + 2j) \simeq 0.5$ fb in the SM, so this amounts to a $\mathcal{O}(+10\%)$ correction to our inclusive signal estimate (well inside the perturbative uncertainty of $pp \to hh + j + X$).
### B. Boosted Higgs searches in association with a jet

From Fig. 6 we see that the Higgs bosons are again naturally boosted. Events of this signature possess an hadronically more active final state. The pure BDRS approach works very well if there is no other hard radiation inside the fatjet except the decay products of the Higgs boson. Here it is likely that the additional hard jet ends up in one of the fatjets challenging a good reconstruction of the Higgs. Therefore, we modify the tagger similar to the Higgs tagger in [55]: The last clustering of the jet 3 is undone, giving two subjets j1, j2, ordered such that m_{j1} > m_{j2}. If m_{j1} > 0.8m_j we discard j2 and keep j1, otherwise both j1 and j2 are kept. For each subjet j_i that is kept, we either add it to the list of relevant substructures (if m_i < 30 GeV) or further decompose it recursively. After performing this declustering procedure (we do not stop after observing a mass drop but continue to decluster the jets until we obtain a set of hard subjets inside the fatjet) we recombine the constituents of every two-subjet combination with the C/A algorithm using R_{6th} = min(0.3, ∆R_{j1,j2}/2). For each combination we keep the three hardest filtered subjets and call it a Higgs candidate. The two hardest filtered subjets of the Higgs candidate with the mass closest to the true Higgs mass of 125 GeV we require to be b-tagged. We find that this tagger recovers roughly 40% more of the signal events while keeping S/B constant.

#### 1. hh + j → bbbb + j

We proceed in a similar manner to the analysis outlined in Sec. IIIA but with modifications of the Higgs tagger in order to preserve a larger signal cross section.

We generate the backgrounds with the following parton-level cuts, yet inclusive enough to avoid a bias. We require that two bb combinations obey p_T(b) ≥ 100 GeV and m(bb) ≥ 100 GeV, while |y_b| ≤ 2.5 and p_T_b ≥ 20 GeV. The bs are separated by R_{bb} ≥ 0.2. The additional jet is generated with p_T ≥ 80 GeV in |y_j| ≤ 4.5 and is separated from the bs by ∆R ≥ 0.7. Signal events are generated with p_T,j ≥ 80 GeV.

In the analysis, we again veto events with isolated leptons in |y| < 2.5 for p_T,l > 10 GeV and E_T,had < 0.1 E_T,l with R < 0.3. To assure the trigger requirements we ask for at least five jets and the following staggered cuts on the transverse momentum: p_T,j_1 > 120 GeV, p_T,j_2 > 100 GeV, p_T,j_3 > 70 GeV, p_T,j_4 > 40 GeV. All jets have to fall inside the detector |y| < 4.5. The events which pass these trigger criteria are again analyzed in a subjet approach: We reconstruct fatjets with p_T,j > 150 GeV and R = 1.5. At least one fatjet has to be present which fulfills the mass-drop condition [13] with an invariant mass of m_j > 110 GeV. The reconstructed Higgs has to be double b-tagged and have p_T_H > 150 GeV.

The hardest of these fatjets is declustered with a tagger which is inspired by the Higgs tagger of Ref. [55]. The reconstructed Higgs has to be double b-tagged with p_T_H > 150 GeV. We subsequently remove the reconstructed Higgs’ constituents from the event.

The remaining constituents are reclustered using the anti-kT algorithm with R = 0.4 and p_T,j > 30 GeV. The two jets which reconstruct the Higgs mass best within m_h = 125 ± 10 GeV are b-tagged with 60% tagging efficiency and 2% fake rate; b-tagging is again performed in |y| < 2.5. Then, the two jets are again removed from the event. For the two reconstructed Higgs jets we require an invariant mass (p_T_H + p_T_L)² > 400² GeV² and the last remaining jet needs to be hard p_T > 100 GeV. In total, this corresponds to a signal signature discussed in Sec. IIIA.

The results of this analysis flow can be found in Tab. IV. For the numbers quoted there it is clear that we can reduce the background contributions, but the QCD-induced cross sections have a too large initial value. In the QCD background, while the bbbb was predominantly gluon initiated, the bbbb + j receives large contributions from gg initial states, leading to final states with a large invariant mass. This in turn increases the amount of background in searches for boosted resonances. The QCD backgrounds can be reduced by a factor O(1000) while the signal rate is decreased by a factor ∼ 100. In total, this does not leave a large enough S/B to be relevant from the point of systematics, and we conclude that pp → hh + j → bbbb + j is not a sensitive channel.

### Table IV: Signal and background cross sections in fb for hh + j → bbbb + j for boosted kinematics. The Higgs self-coupling is scaled in multiples of the Standard Model value λ = ξ × λ_{SM}, Eq. (4). None of the contributing backgrounds’ normalization is known to NLO QCD precision. We therefore include a conservative correction factor of K = 2.

| TABLE IV: Signal and background cross sections in fb for hh + j → bbbb + j for boosted kinematics. The Higgs self-coupling is scaled in multiples of the Standard Model value λ = ξ × λ_{SM}, Eq. (4). None of the contributing backgrounds’ normalization is known to NLO QCD precision. We therefore include a conservative correction factor of K = 2. |
|---|---|---|---|---|---|---|---|---|
| cross section before cuts | ξ = 0 | ξ = 1 | ξ = 2 | bbbb [QCD] | bbbb [QCD/ELW] | bbbb [ELW] | ratio to ξ = 1 |
| trigger+fatjet cuts | 6.45 | 3.24 | 1.81 | 29400 | 513.36 | 10.0 | 1.1 · 10^{-4} |
| first kinematical Higgs rec (new tagger) + 2b | 1.82 | 1.08 | 0.69 | 10579.8 | 211.04 | 4.16 | 1.0 · 10^{-4} |
| sec kinematical Higgs rec + 2b | 0.30 | 0.20 | 0.13 | 331.84 | 10.82 | 0.54 | 0.5 · 10^{-3} |
| invariant mass + p_T,j cut | 0.09 | 0.05 | 0.039 | 54.1 | 2.46 | 0.066 | 1.0 · 10^{-3} |
| | 0.049 | 0.031 | 0.022 | 36.06 | 0.92 | 0.030 | 0.9 · 10^{-3} |
| $\xi = 0$ | $\xi = 1$ | $\xi = 2$ | $b\bar{b}\tau^+\tau^-j$ | $b\bar{b}\tau^+\tau^-j$ | $t\bar{t}j$ | ratio to $\xi = 1$ |
|---|---|---|---|---|---|---|
| cross section before cuts | 6.45 | 3.24 | 1.81 | 66.0 | 1.67 | 106.7 | $1.9 \times 10^{-2}$ |
| $2\, \tau$s | 0.44 | 0.22 | 0.12 | 37.0 | 0.94 | 7.44 | $4.8 \times 10^{-3}$ |
| Higgs rec. from taus + fatjet cuts | 0.29 | 0.16 | 0.10 | 2.00 | 0.150 | 0.947 | $5.1 \times 10^{-2}$ |
| kinematic Higgs rec. | 0.07 | 0.04 | 0.02 | 0.042 | 0.018 | 0.093 | 0.26 |
| $2\beta + hh$ invariant mass + $p_{T,j}$ cut | 0.010 | 0.006 | 0.004 | $<0.0001$ | 0.0022 | 0.0014 | 1.54 |

TABLE V: Signal and background cross sections in fb for $hh+j \rightarrow b\bar{b}\tau^+\tau^-j$ for boosted kinematics. The Higgs self-coupling is scaled in multiples of the Standard Model value $\lambda = \xi \times \lambda_{SM}$, Eq. (4). The QCD corrections to $t\bar{t}+j$ have been discussed in Ref. [57] ($K \approx 1.1$). For the pure electroweak production we take the results of [52] as a reference value ($K \approx 1.3$). The corrections to mixed production are unknown and we conservatively use a total inclusive QCD correction $K = 2$.

2. $hhj \rightarrow b\bar{b}\tau^+\tau^-j$

We generate the backgrounds with the following parton-level cuts to have a reasonably efficient analysis, yet inclusive enough to avoid a bias. We require $p_T(b\bar{b}, \tau \tau) \geq 100$ GeV and $m(b\bar{b}, \tau \tau) \geq 90$ GeV (100 GeV in case of $t\bar{t} + j$), while $|y_{b,\tau}| \leq 2.5$ and $p_{T,b,\tau} \geq 20$ GeV. The $b$s and $\tau$s are separated by $R_{b,\tau} \geq 0.2$. The additional jet is generated with $p_T \geq 80$ GeV in $|y_j| \leq 4.5$ and is separated from the $b$s by $\Delta R \geq 0.7$. Signal events are generated with $p_{T,j} \geq 80$ GeV.

We require exactly two $\tau$ jets in an event in $|y_{\tau}| < 2.5$ with $p_T \geq 20$ GeV and assume an identification efficiency of 80% each. The $\tau$s have to reconstruct to an invariant mass of $m_\tau \pm 25$ GeV. Then we use the C/A algorithm to reconstruct fatjets with $R = 1.5$ and $p_{T,j} > 150$ GeV and require at least 1 fatjet in the event which is sufficiently isolated from the $\tau$s. Then we apply the Higgs tagger described in Sec. II[B] and require the reconstructed Higgs jet have a mass of $m_H \pm 10$ GeV and $p_{T,H} > 150$ GeV. To suppress the large $t\bar{t}$ background we reject events where the invariant mass of the two reconstructed Higgs bosons is below 400 GeV. After removing the constituents of the reconstructed Higgs bosons from the final state we cluster the remaining final state constituents using the anti-kT algorithm $R = 0.4$ and $p_{T,j} > 30$ GeV. Finally, we require at least one jet with $p_T > 100$ GeV.

We find that these cuts can suppress the backgrounds significantly as long as the $\tau$ fake rate is sufficiently small. Due to the large invariant mass of the final state, several high-$p_T$ jets and possibly leptons from the $\tau$ decays we expect that these events can be triggered on easily. The full analysis flow can be found in Tab. V. The initial background contributions are significantly lower, as this final state does not have a dominant purely QCD-induced component. In total we end up with an estimate on $S/B \approx 1.5$. This means that with a target luminosity of 1000 fb$^{-1}$, constraints can be put on $\lambda$ in this channel.

IV. SUMMARY

We have studied the prospects to constrain the trilinear Higgs coupling by direct measurements at the LHC in several channels, focussing on $m_h = 125$ GeV. This is also the mass region which is preferred by electroweak precision data, and where we currently observe excesses in data both at the LHC and the Tevatron. Depending on the particular decay channel, we find a promising signal-to-background ratio at the price of a very small event rate.

Higgs self-coupling measurements for a SM Higgs in this particular mass range are typically afflicted with large backgrounds, so that achieving maximal sensitivity requires the combination of as many channels as possible. For dedicated selection cuts we obtain signal cross sections in Higgs pair production of the order of 0.01 to 0.1 fb and measurements will therefore involve large data sets of the 14 TeV run with a good understanding of the involved experimental systematics.

Searches for unboosted kinematics of the Higgs bosons do not allow any constraint on the trilinear coupling or total cross-section to be made. However, requiring the two Higgses to be boosted and applying subjet methods to boosted $pp \rightarrow hh+X$ and $pp \rightarrow hh+j+X$ production, we find a sensitive $S/B$ particularly for final states involving decays into $\tau$s. A necessary condition for sensitivity in these channels is a sufficiently good $\tau$ reconstruction, but more importantly, a small fake rate. Unfortunately, while boosting the Higgses increases $S/B$, it leads us into a region of phase space which lacks sensitivity to the trilinear coupling.

In addition to inclusive dihiggs production we find that dihiggs production in association with a hard jet shows an improved sensitivity to the trilinear Higgs coupling. However to exploit this scenario still requires the use of boosted techniques which require thorough evaluation on data.

Assuming the efficiency for $\tau$-tagging and the hadronic Higgs reconstruction as outlined in this work are confirmed using data, the $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\tau^+\tau^-j$ channels can be used to constrain the Higgs self-coupling in the SM at the LHC with a data set of several hundred inverse femtobarns. The analysis strategies developed in this paper will also help to improve bounds on dihiggs...
production in scenarios with strong electroweak symmetry breaking and related models, which also predict enhanced dihiggs production cross sections.\textsuperscript{8, 57}

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