Higgs boson coupling sensitivity at the LHC using $H \to \tau \tau$ decays

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We investigate the potential for measuring the relative couplings of a low-mass Higgs boson at the Large Hadron Collider using $WH$, $ZH$, and $t\bar{t}H$ production, where the Higgs boson decays to tau-lepton pairs. With 100 fb$^{-1}$ of $\sqrt{s} = 14$ TeV $ pp$ collision data we find that these modes can improve sensitivity to coupling-ratio measurements of a Higgs boson with a mass of about 125 GeV/$c^2$.

I. INTRODUCTION

The recent discovery [1] of a resonance with a mass of about 125 GeV [2] in $ pp$ collisions at the Large Hadron Collider (LHC) could well correspond to the long-awaited observation of the Higgs boson [3] of the standard model (SM). If so, it would herald another long-awaited observation of the Higgs boson [3] of the Hadron Collider (LHC) could well correspond to the pre-existence of a Higgs boson with a mass less than 152 GeV at 95% confidence level (C.L.) [4] based on precision measurements of electroweak parameters such as the masses of the $W$ [5] and $Z$ [6] bosons, and of the top quark [7].

While the observed properties of the new resonance are consistent with those of the SM Higgs boson, further measurements are required to determine if it has one of the key properties predicted by the SM: couplings to fermions that are proportional to their SM couplings [12, 13].

The prospects for Higgs boson discovery and measurement have been studied extensively [14]; however, low-rate processes observable with the full LHC design luminosity have not been completely explored. We investigate the sensitivity of 100 fb$^{-1}$ of $\sqrt{s} = 14$ TeV LHC data to the Higgs boson production processes $WH$, $ZH$, and $t\bar{t}H$, followed by $H \to \tau \tau$ and at least one $W \to l\nu$ or $Z \to ll$ decay [15]. The potential measurement sensitivity to the $WH$ process has been considered only perfunctorily [16], though the CMS experiment has recently performed the first $WH$ search in the $H \to \tau \tau$ decay channel at the LHC [17]. Studies of $t\bar{t}H$ production have been performed in various top-quark and tau-lepton decay channels [18, 19]; we revisit $t\bar{t} + H(\to \tau \tau)$ production in light of the demonstrated performance of the ATLAS and CMS experiments in separating hadronic tau decays from the large hadronic jet background in data [20]. Combining the prospects for measurements of associated Higgs boson production in the $\tau \tau$ decay channel with those in the $b\bar{b}$ decay channel [8–10] improves the expected LHC sensitivity to the Yukawa coupling ratio $g_{Hbb}/g_{H\tau\tau}$. This ratio is determined at tree level by the bottom-quark and tau-lepton masses and is thus sensitive to differences in the source of mass for quarks and leptons [21]. The ratios of associated Higgs production measurements also directly provide the coupling ratios $g_{Htt}/g_{HWW}$ and $g_{HWW}/g_{HZZ}$.

This paper is structured as follows: Section II outlines the procedures for generating, simulating and selecting Higgs boson and background events; Section III describes the specific selection and expected signal and background yields for the $WH$, $ZH$, and $t\bar{t}H$ processes; Section IV presents the results of the fit to cross section in each channel and the uncertainties on partial-width ratios; and Section V summarizes our conclusions.

II. SIGNAL AND BACKGROUND SIMULATION

We simulate all signal and background processes using the SHERPA [22] event generator, except for $W + 6$ jets, which is simulated using ALPGEN [23] for the hard process and PYTHIA [24] for the hadronization and showering. The $W + 6$ jets and $t\bar{t} + 2$ jets cross sections are obtained from ALPGEN; all other processes are normalized to cross sections calculated at next-to-leading order in $\alpha_s$. Detector resolutions and efficiencies are modelled using the DELPHES simulation [25], with corrections based predominantly on ATLAS [26] performance projections; similar performance is expected with the CMS [27] detector. Events are selected using the reconstructed DELPHES objects.
A. Event generation and cross sections

We use CTEQ6M parton distribution functions for cross section calculations. Samples are generated with quark and gluon jets included to leading order at the matrix-element level, and additional jets modelled by parton showering. Tau leptons are decayed within SHERPA.

The cross sections and branching ratios for the Higgs boson production and decay processes are shown in Table I. We study Higgs boson masses in the 115-135 GeV range to investigate the dependence of the expected sensitivity on $m_H$. Cross sections for $W/Z + H$ production are calculated with v2hv and include QCD corrections at NLO. The next-to-next-to-leading order (NNLO) QCD and NLO electroweak corrections are $\lesssim 5\%$ relative to the v2hv calculation. Cross sections for $tH$ production include QCD corrections at NLO . The uncertainties on all signal cross sections are $O(10\%)$, while those on the branching ratios determined from hdecay are $O(1\%)$.

The dominant backgrounds to the $W/Z + H$ processes are the production of dibosons, where the bosons decay leptonically, and $W/Z +$ hadronic jet(s), $t\bar{t}$, and $tW$, where at least one jet is (mis)reconstructed as a lepton. Background production cross sections are obtained from MCFM and, for $t\bar{t}$, an NLO plus NLL calculation . For the $W/Z +$ jets backgrounds, we calculate cross sections requiring the boson mass to be between 20 and 200 GeV, the jets to have $p_T > 15$ GeV and $|\eta| < 3.5$, and, when there are two or more jets, $m_{jj} > 20$ GeV. The cross sections multiplied by SM branching ratios are shown in Table II.

The $tH$ process, with $H \rightarrow \tau\tau$, has relatively little background. The irreducible background $t\bar{t}Z$ has a cross section that is lower than the signal process. The background where hadronic jets are (mis)reconstructed as leptons results predominantly from $t\bar{t}$ production in association with 2 or 3 jets. We estimate this background using a leading-order cross section calculated with ALPGEN. The calculation requires jets with $p_T > 15$ GeV and $|\eta| < 3.5$, and $\Delta R > 0.7$ between jets. The potential background of $W + 6$ jets production is studied using an ALPGEN cross section with the above jet requirements and the $W$ boson mass between 50 and 120 GeV. We find it to be negligible.

B. Detector simulation

We model detector acceptance and response using the DELPHES simulation program . The detector consists of a charged particle tracker covering $|\eta| < 2.5$ surrounded by a calorimeter with coverage to $|\eta| = 4.9$. The calorimeter has a granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ and is divided into central ($|\eta| < 1.7$), forward ($1.7 < |\eta| < 3.2$), and endcap ($3.2 < |\eta| < 4.9$) regions with separate resolutions. Additional segmentation into electromagnetic (EM) and hadronic (Had) calorimeters provides improved resolution for electrons and photons relative to hadrons.

Detector resolutions are modelled by smearing the reconstructed momentum with a Gaussian resolution. Muon resolution is parameterized as $\sigma(p_T)/p_T = 1\%$, which is the approximate expected resolution of muons from weak boson decays . Calorimeter resolutions are parameterized as

$$\frac{\sigma_E}{E} = C \oplus \frac{S}{\sqrt{E}} \oplus \frac{N}{E},$$

where $E$ is expressed in units of GeV. In the central and forward EM calorimeters the only non-negligible term applied is a sampling term $S$ of about $10\%\sqrt{E}$. The resolution of the hadronic calorimeters is also dominated by the sampling term, which ranges from about 50% in the central region to $\approx 95\%$ in the endcap region. The constant terms $C$ provide small additional contributions of about 3% and 7.5% in the central and endcap regions respectively. The sampling and constant terms in the forward region are roughly in the middle of the corresponding central and endcap terms. The noise term $(N/E)$ is negligible for the final states we consider.

The detector acceptance for electrons, taus, and charged-particle tracks is assumed to be $|\eta| < 2.5$. Muon coverage is assumed to extend to $|\eta| < 2.7$. Because of the potential challenges in reconstructing jets in the forward region at high luminosity, we conservatively assume a jet acceptance of $|\eta| < 3.5$. Jets are reconstructed with the anti-$k_t$ algorithm with cone radius 0.4 and, if $|\eta| < 2.5$, are identified as originating from either a $b$ quark or a lighter quark or gluon. Hadronic tau decays are identified as jets with $> 90\%$ of their energy within a cone of $\Delta R < 0.15$ and only one reconstructed track with $p_T > 2$ GeV and $\Delta R < 0.4$ from the jet axis. Electrons and muons are identified if no additional track with $p_T > 2$ GeV lies within a cone of $\Delta R < 0.2$ from the $e$ or $\mu$. Finally, the $p_T$ imbalance in the event is $p_T$ is derived by summing over the momentum of each calorimeter.
The performance of \( \tau_\beta \) identification at \( \sqrt{s} = 14 \) TeV in the presence of 25 additional interactions is difficult to predict. In addition to our nominal efficiency of 30\%, we study an optimistic scenario where the efficiency is increased to 40\% for the same misidentification rate. The two scenarios give an indication of the effect of the performance of tau identification on the results.

### III. EVENT SELECTION

Each of the three production channels (\( WH, ZH \) and \( t\bar{t}H \)) is subdivided according to the decay of the tau leptons originating from the Higgs boson. The general strategy is to define a simple cut-based selection for each decay channel and then to perform a one-dimensional likelihood fit to a mass-based distribution. The simple selection limits the number of assumptions on the detector performance; the key assumptions are relatively low jet-to-\( \tau_\beta \) misidentification rates and reasonable \( p_T \) resolution. The fit reduces the effect of normalization uncertainties on the background. We assume that the dominant uncertainties will result from extrapolations of control regions in data, and will not significantly affect the sensitivity.
A. WH selection

Considering only the leptonic W-boson decays, the WH final state contains one lepton, $p_T$, from the neutrino, and two tau leptons from the Higgs boson decay. Events where at least two $\tau$ leptons decay hadronically are not included in this study because the $\approx 1\%$ jet-to-$\tau$ misidentification rate leads to overwhelming background from $W +$ jets production. Events where all tau leptons decay leptonically are also not included because the relatively low branching ratio results in marginal sensitivity in the corresponding final state; adding it to the final state with one $\tau_H$ would reduce the uncertainty on the $WH$ cross section by $\approx 20\%$. We study the final state $l_W \tau\tau_H p_T$, where $l_W$ is an $e$ or $\mu$ assumed to come from a W-boson decay and $\tau$ is an $e$ or $\mu$ assumed to come from a tau-lepton decay. We define $l_W$ by $p_{TlW}^T > p_{T\tau}^T$; in more than 80% of signal events the lepton from the W boson decay has higher $p_T$ than that from the tau lepton decay.

There are several background contributions to the $l_W \tau\tau_H p_T$ final state. Production of $W$ and $Z$ bosons in association with hadronic jets, as well as $t\bar{t}$ and $tW$ decays, contribute when at least one hadronic jet is misreconstructed as a lepton. We model these backgrounds by applying the hadronic misidentification rates listed in Table III to all jets in the events. Production of $WZ$ background and $WH$ signal are modelled using MC acceptances, with corrections for trigger and identification efficiencies (Table III).

The presence of neutrinos from the $\tau$-lepton and W-boson decays prevents a full reconstruction of the Higgs boson mass. However, the “visible mass,” defined as the invariant mass of the $\tau\tau_H$ pair, is correlated with the Higgs boson mass. We perform a likelihood fit to the visible mass distribution to extract the signal yield.

Event selection begins with the reconstructed objects in the final state. For the signal process, an $e$ or $\mu$ from the W-boson decay typically has the highest $p_T$ of the three charged leptons, with a $p_T$ distribution that peaks around 40 GeV. We therefore require $p_{TlW}^T > 25$ GeV. The unobserved neutrinos in tau-lepton decays reduce the $p_T$ of the reconstructed objects, so a $p_T$ threshold of 15 GeV is applied to $\tau_l$ and $\tau_H$. Background from $W+\text{jets}$ is suppressed by requiring the charges of the leptons ($q_l$) to sum to $\pm 1$. Events are required to have no jet with $p_T > 25$ GeV and $|y| < 3.5$, reducing both top-quark and $W/Z + \text{jet(s)}$ backgrounds. A requirement of $p_T > 30$ GeV reduces background from $Z+$ jet production, and an upper bound of $p_T < 80$ GeV reduces top-quark background.

FIG. 1: The $p_T$ (top), $m_T$ (middle) and $m(\tau\tau)$ distributions after all $l_W \tau\tau_H p_T$ selection requirements, except for requirements on the plotted distribution. The selected regions are between the arrows in the $p_T$ plot and above the arrow in the $m_T$ plot. Shown are the $WH$ signal (dashed line) and the following backgrounds: top-quark (diagonal-hatched region), $Z + \text{jet}$ (tilted-hatched region), $WZ$ (tilted-lined region), and $W + \text{jet}$ (horizontal-lined region) production.
a similar transverse mass requirement on the excess of signal events over background in 100 fb^{-1} and $m_H = 125$ GeV. Also shown is the signal over the square root of background, a measure of the statistical sensitivity to the signal. Additional sensitivity is gained from a fit to the visible mass distribution.

TABLE IV: The numbers of $WH$ signal and background events passing each set of requirements, for an integrated luminosity of 100 fb^{-1} and $m_H = 125$ GeV. Also shown is the signal over the square root of background, a measure of the statistical sensitivity to the signal. Additional sensitivity is gained from a fit to the visible mass distribution.

| Selection                                      | $N_{WH}^s$ | $N_{b}^W$ | $N_{WH}^s/N_{b}^W$ |
|-----------------------------------------------|------------|-----------|---------------------|
| $p_T^W > 25$ GeV, $p_T^{l_h} > 15$ GeV; $\sum q_i = \pm 1$ and no jet | 233        | 171408    | 0.6                 |
| $30 < \not{p}_T < 80$ GeV                     | 137        | 19124     | 1.0                 |
| $m_T > 50$ GeV                               | 103        | 1582      | 2.6                 |
| No opposite-sign same-flavour $l_W \tau$     | 92         | 1177      | 2.7                 |

TABLE V: The contribution of each background to the $l_W \tau \tau l_T$ final state for an integrated luminosity of 100 fb^{-1}.

| Process                                      | Number of events |
|----------------------------------------------|------------------|
| $t\bar{t}(\rightarrow l\ell b\bar{b})$      | 573              |
| $Z/\gamma^*(\rightarrow l\ell) + 1$ jet      | 330              |
| $tW(\rightarrow l\nu b\bar{b})$             | 112              |
| $W(\rightarrow l\nu)Z/\gamma^*(\rightarrow \tau\tau)$ | 81               |
| $W(\rightarrow l\nu) + 2$ jets              | 52               |
| $W(\rightarrow l\nu)Z/\gamma^*(\rightarrow ee/\mu\mu)$ | 30             |
| Total                                        | 1177             |

TABLE VI: The number of $WH$ signal events for $m_H$ in the range 115-135 GeV, and the statistical significance of the excess of signal events over background in 100 fb^{-1} of integrated luminosity.

| $m_H$ (GeV) | $N_{WH}^s$ | $N_{WH}^s/N_{b}^W$ |
|-------------|------------|---------------------|
| 115         | 122        | 3.6                 |
| 120         | 109        | 3.2                 |
| 125         | 92         | 2.7                 |
| 130         | 70         | 2.0                 |
| 135         | 52         | 1.5                 |

The significant background from $Z(\rightarrow \tau\tau) +$ jet production contributes primarily when the tau leptons decay leptonically and the jet is misreconstructed as a $\tau_h$. The tau lepton from the $Z$ boson decay is highly boosted and its decay products are nearly collinear. In a class of $Z +$ jet events, the reconstructed $\not{p}_T$ is aligned with $l_W$, while in signal events the $\not{p}_T$ is rarely aligned with $l_W$. Defining the transverse mass as $m_T = \sqrt{2(p_T^W \not{p}_T - p_T^W \not{p}_x - p_T^W \not{p}_y)}$, we suppress $Z +$ jet events with the requirement $m_T > 50$ GeV. Additional background rejection could be achieved with a similar transverse mass requirement on $\tau$ and $\not{p}_T$; however, there would be larger reduction in signal since there are neutrinos collinear with $\tau_l$ in signal events.

A final selection requirement of no opposite-charge, same-flavor $l_W \tau$ further reduces background from $Z +$ jet production, removing most events with $Z$ bosons decaying to $e$ or $\mu$ pairs. Decays of $Z$ bosons to tau-lepton pairs are also reduced with this requirement, and could be further reduced by removing events with an oppositely charged electron and muon. However, the loss of signal from such a requirement would be relatively large, and the statistical sensitivity would degrade.

Figure 1 shows the $\not{p}_T$, $m_T$ and $m(\tau_h \tau_l)$ distributions with all selection requirements applied, except those on the plotted quantity. The numbers of signal ($N_{WH}^s$) and background ($N_{b}^W$) events, as well as $N_{WH}^s/N_{b}^W$, are given in Table IV after each selection requirement. The detailed contribution of each background and the dependence of the signal yield on $m_H$ are shown after all selection in Tables V and VI respectively.

The selection gives modest statistical sensitivity to $WH$ production, but the sensitivity is improved with a fit to the visible mass distribution. Normalization uncertainties will be mitigated by this fit, though uncertainties on the shape of the visible mass distribution are also relevant; we assume the systematic uncertainties can be sufficiently constrained by studying independent kinematic regions (for example, the high-$\not{p}_T$ region for top production, and the low-$m_T$ region for $Z +$ jet production).

B. $ZH$ selection

In contrast to $WH$ production, $ZH \rightarrow ll\tau\tau$ production is dominated by an irreducible background ($ZZ$), with relatively low signal statistics in 100 fb^{-1} of integrated luminosity. Thus, the selection strategy is to apply few requirements and to combine the $l_Zl_Z\gamma\tau_h\bar{\tau}_l$ and $l_Zl_Z\gamma\tau_l\bar{\tau}_h$ decay channels, where $l_Z$ is an $e$ or $\mu$. The $l_Zl_Z\gamma\tau_l\bar{\tau}_h$ channel adds only marginal sensitivity because of the small branching ratio and the
increased $ZZ$ background.

In addition to the irreducible $ZZ \rightarrow ll\tau\tau$ background, reducible backgrounds from $Z +$ jets and $tt \rightarrow l\nu\ell\nu b\bar{b}$ contribute when two jets are misreconstructed as hadronic tau(s) and/or light-flavor lepton(s). These backgrounds are modelled by applying the hadronic misidentification rates in Table III to MC-generated events. Production of $ZZ$ background and $ZH$ signal are modelled using trigger and identification-corrected MC acceptances (Table III).

The irreducible $ZZ$ background can be separated using the invariant mass of the tau-lepton pair. Since the tau leptons from the Higgs boson decay are highly boosted, their decay products are nearly collinear. Assuming collinear tau-lepton decays, the net neutrino momentum from each decay can be resolved. The resulting invariant mass of the tau-lepton pair, or “collinear mass”, can be expressed in the $ll\tau\tau$ decay channel as $m(\tau_h, \tau_l)/\sqrt{\chi_h\chi_l}$, where $\chi_{h(l)}$ is the fraction of tau-lepton energy taken by $\tau_h (\tau_l)$. The fractions $\chi_h$ and $\chi_l$ can be solved in terms of measured quantities,

$$
\chi_h = \frac{p_T^h p_T^{\tau_h} - p_T^\ell p_T^{\tau_\ell}}{p_T^h p_T^{\ell} + p_T^{\tau_h} p_T^{\tau_\ell} - p_T^{\tau_h} p_T^{\ell}},
$$

$$
\chi_l = \frac{p_T^l p_T^{\tau_l} - p_T^\ell p_T^{\tau_\ell}}{p_T^h p_T^{\ell} + p_T^{\tau_h} p_T^{\tau_\ell} - p_T^{\tau_h} p_T^{\ell}}.
$$

(1)

For the $ll\tau\tau\ell\ell$ channel, $\tau_l$ is replaced by the other $\tau_h$. We fit the collinear mass distribution to extract the $ZH$ signal yield after initial selection requirements.

The selection requires two opposite-charge same-flavor leptons from the $Z$ boson decay. If an event has multiple candidate pairs, we define the pair with invariant mass closest to $m_Z$ as the $Z$ boson candidate decay. The highest (lowest) $p_T$ lepton from the decay is required to have $p_T > 25$ (15) GeV. We then require two opposite-charge tau-lepton decay candidates with $p_T > 25$ GeV (or $p_T > 15$ GeV for $\tau_l$). Table VII shows the numbers of signal ($N_s^{ZH}$) and background ($N_b^{ZH}$) events, as well as $N_s^{ZH}/N_b^{ZH}$, in each channel after this initial selection. The collinear mass requirement reduces the signal yield by nearly 30%; recovering these events with an alternative mass variable would improve the measurement.

Figure 2 shows the collinear mass distribution with all selection requirements. The detailed contribution of each background and the dependence of the signal yield on $m_H$ are shown after all selection requirements in Tables VIII and IX, respectively. The relatively small background and the discrimination given by the collinear mass make the $ZH$ channel particularly promising for measuring Higgs boson decays to tau leptons.

C. $t\bar{t}H$ selection

The cross section for $t\bar{t}H$ production, with the Higgs boson decaying to tau leptons, is relatively low. We focus on the decays with the highest branching ratios, excluding fully hadronic $t\bar{t}$ decays because of the potentially large multijet background. Thus we consider $t\bar{t} \rightarrow l_Wq\bar{q}b\bar{b}$ and either $H \rightarrow \tau_h\tau_h$ or $H \rightarrow \tau_h\tau_l$, with $l_W$ defined by $p_T^{l_W} > p_T^{\tau_l}$. These final states are the same as in $WH$ production but with the addition of four jets.

For the detector performance assumed in Sec. , the background is a roughly equal mix of irreducible $t\bar{t}Z$ production and reducible $t\bar{t} +$ jets production. The dominant reducible background is $t\bar{t}(\rightarrow l_W\nu\ell\nu b\bar{b}) + 3$ jets, where one jet is misreconstructed as a $\tau_h$, and $l$ is identified as either $\tau_h$ or $\tau_l$. The generation of $t\bar{t} + 3$ jets at tree-level is computationally intensive; we therefore model this background using the SHERPA $t\bar{t} + 2$ jets process, with additional jets modelled by the SHERPA parton-showering algorithm.

Since the reducible background consists of $t\bar{t} +$ jets, the sensitivity depends predominantly on tau identification and the broadly peaking visible mass distribution of the tau-lepton pair. The irreducible $t\bar{t}Z$ background is suppressed by requiring opposite-sign same-flavor $l_W\tau$ pairs to have an invariant mass outside the 75 – 105 GeV peak of resonant $Z$-boson production. Other selection requirements are $p_T^{l_W} > 25$ GeV.
luminosity of \(100 \text{ fb}^{-1}\) and Higgs boson mass of 125 GeV. Also shown is the signal over the square root of background, a measure of the statistical sensitivity to the signal. Additional sensitivity is gained from a fit to the collinear mass distribution.

Table VII: The numbers of \(ZH\) signal and background events passing each set of requirements, for an integrated luminosity of \(100 \text{ fb}^{-1}\) and Higgs boson mass of 125 GeV. Also shown is the signal over the square root of background, a measure of the statistical sensitivity to the signal. Additional sensitivity is gained from a fit to the collinear mass distribution.

| Process                                      | Number of events | \(N^ZH\) | \(N^ZH/\sqrt{N^ZH}\) |
|----------------------------------------------|------------------|----------|---------------------|
| \(Z/\gamma^*(\rightarrow t\bar{t})Z/\gamma^*(\rightarrow \tau\tau)\) | 305              |          |                     |
| \(Z/\gamma^*(\rightarrow t\bar{t}) + 2 \text{ jets}\)   | 25               |          |                     |
| \(t\bar{t}(\rightarrow l\nu l\nu b\bar{b})\)          | 2                |          |                     |
| Total                                        | 332              |          |                     |

Table VIII: The contribution of each background to the \(ZH\) final state for an integrated luminosity of \(100 \text{ fb}^{-1}\).

| \(m_H\) (GeV) | \(N^ZH\) | \(N^ZH/\sqrt{N^ZH}\) |
|---------------|----------|---------------------|
| 115           | 77       | 4.2                 |
| 120           | 71       | 3.9                 |
| 125           | 56       | 3.1                 |
| 130           | 45       | 2.4                 |
| 135           | 33       | 1.8                 |

Table IX: The number of \(ZH\) signal events for \(m_H\) in the range 115-135 GeV, and the statistical significance of the excess of signal events over background in \(100 \text{ fb}^{-1}\) of integrated luminosity.

| Process                                      | \(t\bar{t} + \tau_\ell \tau_\ell\) channel | \(t\bar{t} + \tau_\ell \tau_\ell\) channel |
|----------------------------------------------|-------------------------------------------|-------------------------------------------|
| \(t\bar{t}(\rightarrow l\nu l\nu b\bar{b}) + 3 \text{ jets}\)   | 52                                        | 20                                        |
| \(t\bar{t}(\rightarrow l\nu q\bar{q}\bar{b}b) \pm Z/\gamma^*(\rightarrow ee/\mu\mu)\) | 32                                        | 2                                         |
| \(t\bar{t}(\rightarrow l\nu q\bar{q}\bar{b}b) \pm Z/\gamma^*(\rightarrow \tau\tau)\) | 13                                        | 5                                         |
| \(t\bar{t}(\rightarrow l\nu q\bar{q}\bar{b}b) + 2 \text{ jets}\)          | 2                                         | 15                                        |
| Total                                        | 99                                        | 42                                        |

Table X: The contribution of each background to the \(tH\) final states for an integrated luminosity of \(100 \text{ fb}^{-1}\).

Tables XI: The number of \(ttH\) signal events in each channel for \(m_H\) in the range 115-135 GeV, and the statistical significance of the excess of signal events over background in \(100 \text{ fb}^{-1}\) of integrated luminosity. The \(t\bar{t}\) pair is selected in the \(l\nu l\nu b\bar{b}\) final state.

Table XI: The number of \(ttH\) signal events in each channel for \(m_H\) in the range 115-135 GeV, and the statistical significance of the excess of signal events over background in \(100 \text{ fb}^{-1}\) of integrated luminosity. The \(t\bar{t}\) pair is selected in the \(l\nu l\nu b\bar{b}\) final state.

| \(m_H\) (GeV) | \(N^{ttH}_{s}\) | \(N^{ttH}_{s}/\sqrt{N^{ttH}_{b}}\) |
|---------------|----------------|---------------------|
| 115           | 47             | 4.8                 |
| 120           | 47             | 4.8                 |
| 125           | 37             | 3.7                 |
| 130           | 30             | 3.0                 |
| 135           | 22             | 2.2                 |
| \(t\bar{t} + \tau_\ell \tau_\ell\) | 7              | 1.1                 |

Table XII: The number of \(ttH\) signal events in each channel for \(m_H\) in the range 115-135 GeV, and the statistical significance of the excess of signal events over background in \(100 \text{ fb}^{-1}\) of integrated luminosity. The \(t\bar{t}\) pair is selected in the \(l\nu l\nu b\bar{b}\) final state.

Table XII: The number of \(ttH\) signal events in each channel for \(m_H\) in the range 115-135 GeV, and the statistical significance of the excess of signal events over background in \(100 \text{ fb}^{-1}\) of integrated luminosity. The \(t\bar{t}\) pair is selected in the \(l\nu l\nu b\bar{b}\) final state.

For \(p_T^{\tau_\ell} > 15\) GeV, \(\tau_\ell\) have \(\sum q_\ell = \pm 1\), and at least 4 jets.

Figure \(\text{X}\) shows the mass distribution of opposite-sign same-flavor \(l_W\) pairs and the visible mass distributions of the tau-lepton pairs in the two decay channels \(t\bar{t} + \tau_\ell \tau_\ell tH + \tau_\ell \tau_\ell\). Tables \(\text{X}\) and \(\text{XI}\) respectively show the contribution of each background and the dependence of the signal yield on \(m_H\) after all selection for both channels. With basic object selection, reasonable sensitivity to \(ttH\) production can be obtained if tau leptons are identified with a similar efficiency and jet rejection rate to that achieved by ATLAS and CMS with \(\sqrt{s} = 7\) TeV LHC data.

IV. RESULTS

e determine the expected sensitivity to the cross section of a given process using pseudoexperiments \(\text{[15]}\). In each pseudoexperiment, data are produced according to a Poisson distribution in each bin of the relevant mass-based fit distribution, where the mean of the Poisson is equal to the combined signal and background in that bin. The number of signal
events is determined by minimizing the negative log likelihood of the fit distribution. This procedure is performed for $10^4$ pseudoexperiments for each process, and the uncertainty is taken to be the root-mean square of the resulting signal-yield distribution. The relative statistical uncertainties on $\sigma \times \text{BR}$ of the signal processes are shown in Fig. 4.

The cross section of a given signal process includes the product of partial widths for the production and decay vertices of the Higgs boson. Individual partial widths can be determined by taking cross-section ratios, providing direct access to the individual couplings of the Higgs boson to SM particles. We expect this procedure to provide the additional benefit of cancelling many experimental uncertainties. From the ratios of cross-section measurements studied in this paper, and from the expected uncertainties on the measurements of associated Higgs production in its decays to bottom quarks (Table XII), we obtain the expected sensitivity to partial width ratios shown in Fig. 5.

V. CONCLUSIONS

With the recent discovery of a resonance with cross sections consistent with that of the SM Higgs boson, tests of the specific SM predictions of the Higgs boson couplings are a high priority. A Higgs boson with a mass of 125 GeV can be measured in a wealth of production and decay channels. We have performed a detailed study of channels that have not been investigated in this context, or that have not been considered promising because of the expected large jet-to-$\tau$ background. Assuming the experiments can achieve $\approx 20\%$ precision with 100 fb$^{-1}$ of integrated luminosity.

| $m_H$ (GeV) | $VH$ | $tH$ |
|------------|------|------|
| 115        | 10%  | 19%  |
| 120        | 12%  | 22%  |
| 130        | 17%  | 34%  |

TABLE XII: The assumed relative uncertainties on $V(H \rightarrow b\bar{b})$ and $tt(H \rightarrow b\bar{b})$ cross section measurements in data corresponding to 100 fb$^{-1}$ of integrated luminosity.
FIG. 4: The expected relative statistical uncertainties on $\sigma \times \text{BR}$ of $VH$ (left, $V = W, Z$) and $t\bar{t}H$ (right) production for the nominal (top) and optimistic (bottom) tau identification performance scenarios.

more data the sensitivity to $ZH$ and $t\bar{t}H$ production should improve, while sensitivity to $WH$ production is unlikely to improve significantly due to systematic uncertainties on the background. If the assumed $\tau$ identification efficiency or $p_T$ resolution cannot be achieved, targeted background rejection through e.g. a multivariate analysis or improved mass reconstruction could compensate. Including additional decays of the tau leptons or top quarks would also improve sensitivity. By combining the associated production measurements in $H \to \tau\tau$ decays with measurements of the same production mechanisms in $H \to b\bar{b}$ decays, a precision of $\approx 20\%$ on the ratio of partial widths $\Gamma_\tau/\Gamma_b$ is achievable. We expect associated Higgs production with $H \to \tau\tau$ to provide an important contribution to Higgs coupling measurements with 100 fb$^{-1}$ of integrated luminosity at $\sqrt{s} = 14$ TeV.

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FIG. 5: The expected relative statistical uncertainties on ratios of partial widths using measurements of associated Higgs boson production and decays to tau-lepton or bottom-quark pairs. Each partial width $\Gamma_i$ corresponds to the trilinear interaction of a Higgs boson to another particle $i$. Shown are the nominal (top) and optimistic (bottom) detector performance scenarios.