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Searches for heavy Higgs bosons in two-Higgs-doublet models and for $t \to ch$ decay using multilepton and diphoton final states in pp collisions at 8 TeV

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Searches are presented for heavy scalar (H) and pseudoscalar (A) Higgs bosons posited in the two doublet model (2HDM) extensions of the standard model (SM). These searches are based on a data sample of pp collisions collected with the CMS experiment at the LHC at a center-of-mass energy of $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$. The decays $H \to hh$ and $A \to Zh$, where h denotes an SM-like Higgs boson, lead to events with three or more isolated charged leptons or with a photon pair accompanied by one or more isolated leptons. The search results are presented in terms of the H and A production cross sections times branching fractions and are further interpreted in terms of 2HDM parameters. We place 95% C.L. cross section upper limits of approximately 7 pb on $\sigma\mathcal{B}$ for $H \to hh$ and 2 pb for $A \to Zh$. Also presented are the results of a search for the rare decay of the top quark that results in a charm quark and an SM Higgs boson, $t \to ch$, the existence of which would indicate a nonzero flavor-changing Yukawa coupling of the top quark to the Higgs boson. We place a 95% C.L. upper limit of 0.56% on $\mathcal{B}(t \to ch)$.

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I. INTRODUCTION

The standard model (SM) has an outstanding record of consistency with experimental observations. It is not a complete theory, however, and since the recent discovery of a Higgs boson [1–3], attaining a better understanding of the mechanism responsible for electroweak symmetry breaking (EWSB) has become a central goal in particle physics. The experimental directions to pursue this goal include improved characterization of the Higgs boson properties, searches for new particles such as the members of an extended Higgs sector or the partners of the known elementary particles predicted by supersymmetric models, and searches for unusual processes such as rare decays of the top quark. Since the Higgs boson plays a critical role in EWSB, searches and studies of decays with the Higgs boson in the final state have become particularly attractive.

In many extensions of the SM, the Higgs sector includes two scalar doublets [4]. The two Higgs doublet model (2HDM) [5] is a specific example of such a SM extension. In this model five physical Higgs sector particles survive EWSB: two neutral CP-even scalars (h, H), one neutral CP-odd pseudoscalar (A), and two charged scalars (H^+, H^-) [6]. For masses at or below the 1 TeV scale these particles can be produced at the LHC. Both the heavy scalar H and the pseudoscalar A can decay into electroweak bosons, including the recently discovered Higgs boson. The branching fractions of H and A into final states containing one or more Higgs bosons h often dominate when kinematically accessible. For heavy scalars with masses below the top pair production threshold, the $H \to hh$ and $A \to Zh$ decays typically dominate over competing Yukawa decays to bottom quarks, while for heavy scalars with masses above the top pair production threshold, these decays are often comparable in rate to decays into top pairs and are potentially more distinctive.

We describe a search for two members of the extended Higgs sector, H and A, via their decays $H \to hh$ and $A \to Zh$, where h denotes the recently discovered SM-like Higgs boson [1–3]. The final states used in this search consist of three or more charged leptons or a resonant photon pair accompanied by at least one charged lepton. (In the remainder of this paper, "lepton" refers to a charged lepton, e, μ, or hadronic decay of the τ lepton, τ_h.) The $H \to hh$ and $A \to Zh$ decays can yield multileptonic final states when h decays to WW^*, ZZ^*, or $\tau\tau$. Similarly, the resonant decay $h \to \gamma\gamma$ can provide a final state that contains a photon pair and one or more leptons from the decay of the other daughter particle.

Using the same data set and technique, we also investigate the process $t \to ch$, namely the flavor-changing rare decay of the top quark to a Higgs boson accompanied by a charm quark in the $t\bar{t} \to (bW)(ch)$ decay. The $t \to ch$ process can occur at an observable rate for some parameters of the 2HDM [7]. Depending on how the h boson and t quark decay, both the multilepton and the lepton + diphoton final states can be produced. Both ATLAS [8]

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and CMS [9] have searched for this process using complementary techniques. The CMS upper limit for the branching fraction of 1.3% at 95% confidence level (C.L.) comes from an inclusive multilepton search that uses the data set analyzed here. We describe here a $t \to ch$ search using lepton + diphoton events and combine the results of the previously reported multilepton search with the present lepton + diphoton search. This combination results in a considerable improvement in the $t \to ch$ search sensitivity.

In this paper, we first briefly describe the CMS detector, data collection, and the detector simulation scheme in Sec. II. We then describe in Sec. III the selection of events that are relevant for the search signatures followed by the event classification in Sec. IV, which calls for the data sample to be subdivided in a number of mutually exclusive channels based on the number and flavor of leptons, the number of hadronically decaying τ leptons, photons, the tagged flavors of the jets, as well as the amount of missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). A description of the SM background estimation in Sec. V precedes the channel-by-channel comparison of the observed number of events with the background estimation in Sec. VI. We next interpret in Sec. VII these observations in terms of the stand-alone production and decay rates for H and A. Since these rates follow from the parameters of the 2HDM, we reexpress these results in terms of the appropriate 2HDM parameters. Finally, we selectively redeploy the H and A analysis procedure to search for the rare $t \to ch$ decay.

The multilepton component of this analysis closely follows the previously mentioned CMS inclusive multilepton analysis [9]. In particular, the lepton reconstruction, SM background estimation procedures as well as the data set used are identical in the two analyses and are therefore described minimally here.

II. DETECTOR, DATA COLLECTION, AND SIMULATION

The central feature of the CMS detector is a superconducting solenoidal magnet of field strength 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead tungstate crystal calorimeter, and a brass-and-scintillator hadron calorimeter. The tracking detector covers the pseudorapidity region $|\eta| < 2.5$ and the calorimeters $|\eta| < 3.0$. Muon detectors based on gas-ionization detectors lie outside the solenoid, covering $|\eta| < 2.4$. A steel-and-quartz-fiber forward calorimeter provides additional coverage between $3 < |\eta| < 5.0$. A detailed description of the detector as well as a description of the coordinate system and relevant kinematical variables can be found in Ref. [10].

The data sample used in this search corresponds to an integrated luminosity of 19.5 fb^{-1} recorded in 2012 with the CMS detector at the LHC. Dilepton triggers (dielectron, dimuon, muon electron) and diphoton triggers are used for data collection. The transverse momentum (p_{T}) threshold for dilepton triggers is 17 GeV for the leading lepton and 8 GeV for the subleading lepton. Similarly, the p_{T} thresholds for the diphoton trigger are 36 and 22 GeV.

The dominant SM backgrounds for this analysis such as $t\bar{t}$ quark pairs and diboson production are simulated using the MadGraph (version 5.1.3.30) [11] generator. We use the CTEQ6L1 leading-order parton distribution function (PDF) set [12]. For the diboson + jets simulation, up to two jets are selected at the matrix element level in MadGraph. The detector simulation is performed with GEANT4 [13]. The generation of signal events is performed using both the MadGraph and PYTHIA generators, with the description of detector response based on the CMS fast simulation program [14].

III. PARTICLE RECONSTRUCTION AND PRELIMINARY EVENT SELECTION

The CMS experiment uses a particle-flow (PF) based event reconstruction [15,16], which takes into account information from all subdetectors, including charged-particle tracks from the tracking system and deposited energy from the electromagnetic and hadronic calorimeters. All particles in the event are classified into mutually exclusive types: electrons, muons, τ leptons, photons, charged hadrons, and neutral hadrons.

Electron and muon candidates used in this search are reconstructed from the tracker, calorimeter, and muon system measurements. Details of reconstruction and identification can be found in Refs. [17,18] for electrons and in Refs. [19,20] for muons. The electron and muon candidates are required to have $p_{\mathrm{T}} \geq 10$ GeV and $|\eta| < 2.4$. For events triggered by the dilepton trigger, the leading electron or muon must have $p_{\mathrm{T}} > 20$ GeV in order to ensure maximal efficiency of the dilepton trigger. Hadronic decays of the τ lepton (τ_{h}) are reconstructed using the hadron-plus-strips method [21] and must have the measured jet p_{T} of the jet tagged as a τ_{h} candidate to be greater than 20 GeV and $|\eta| \leq 2.3$.

Photon candidates are reconstructed using the energy deposit clusters in the electromagnetic calorimeter [18,22]. Candidate photons are required to satisfy shower shape requirements. In order to reject electrons misidentified as photons, the photon candidate must not match any of the tracks reconstructed with the pixel detector. Photon candidates are required to have $p_{\mathrm{T}} \geq 20$ GeV and $|\eta| < 2.5$. For events triggered by the diphoton trigger, the leading (subleading) photon must have $p_{\mathrm{T}} > 40(25)$ GeV.

Jets are reconstructed by clustering PF particles using the anti-k_{T} algorithm [23] with a distance parameter of 0.5 and are required to have $|\eta| \leq 2.5$. Jets are further characterized as being "b tagged" using the medium working point of the CMS combined secondary-vertex algorithm [24]. They typically result from the decays of the b quark. The total hadronic transverse energy, H_{T}, is the scalar sum of the p_{T}

of all jets with $p_T > 30$ GeV. The E_T^{miss} in an event is defined to be the magnitude of the vectorial p_T sum of all the PF candidates.

The primary vertex for a candidate event is defined as the reconstructed collision vertex with the highest p_T^2 sum of the associated tracks. It also must be within 24 cm from the center of the detector, along the beam axis (z direction), and within 2 cm in a direction transverse to the beam line [25]. We require the candidate leptons to originate from within 0.5 cm in z of the primary vertex and that their impact parameters d_{xy} between the track and the primary vertex in the plane transverse to the beam axis be at most 0.02 cm.

For electrons and muons, we define the relative isolation I_{rel} of the candidate leptons to be the ratio of the p_T sum of all other PF candidates that are reconstructed in a cone defined by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the candidate to the p_T of the candidate, and require $I_{\text{rel}} < 0.15$. The photon isolation requirement is similar, but varies as a function of the candidate p_T and η [26]. For the isolation of the τ_h candidates, we require that the p_T sum of all other particles in a cone of $\Delta R < 0.5$ be less than 2 GeV. The isolation variable for leptons and photons is corrected for the contributions from pileup interactions [27]. The combined efficiency for trigger, reconstruction, and identification are approximately 75% for electrons and 80% for muons. The identification and isolation efficiency for prompt leptons is measured in data using a "tag-and-probe" method based on an inclusive sample of $Z+$ jets events [28]. The ratio of the efficiency in data and simulation parametrized by the different p_T and η values of the probed lepton is used to correct the selection efficiency in the simulated samples.

A leptonically decaying Z boson can lead to a trilepton event when the final-state radiation undergoes (internal or external) conversion and one of the leptons escapes detection. Therefore, we reject trilepton events with low missing transverse energy ($E_T^{\text{miss}} < 30$ GeV) when their three body invariant mass is consistent with the Z mass (i.e. $m_{\ell^+\ell^-\ell'^\pm}$ or $m_{\ell^+\ell^-\ell^\pm}$ is between 75 and 105 GeV), even if $m_{\ell^+\ell^-}$ is not ($\ell = e, \mu$). Finally, SM background from abundant low-mass Drell-Yan production and low-mass resonances like J/ψ and Υ is suppressed by rejecting an event if it contains a dilepton pair with $m_{\ell^+\ell^-}$ below 12 GeV.

IV. EVENT CLASSIFICATION

We perform searches using a multichannel counting experiment approach. A multilepton event consists of at least three isolated and prompt leptons (e, μ, τ_h), of which at least two must be electrons or muons ("light" leptons). A photon pair together with at least one lepton makes a lepton + diphoton event. The relatively low rates for multilepton and lepton + diphoton final states in SM allow this search to target rare signals.

A. The $H \to hh$, $A \to Zh$, and $t \to ch$ signals

In the $H \to hh$ search, seven combinations of the hh decays (WW^*WW^*, WW^*ZZ^*, $WW^*\tau\tau$, ZZ^*ZZ^*, $ZZ^*\tau\tau$, ZZ^*bb, and $\tau\tau\tau\tau$) can result in a final state containing multileptons and three combinations ($\gamma\gamma WW^*$, $\gamma\gamma ZZ^*$, and $\gamma\gamma\tau\tau$) can result in lepton + diphoton final states with appreciable rates.

In the $A \to Zh$ search, the multilepton and diphoton signal events can result from the WW, ZZ, $\tau\tau$, and $\gamma\gamma$ decays of the h, when accompanied by the appropriate decays of the W and Z bosons and the τ lepton. Five combinations of the Zh decays ($Z \to \ell\ell$, $h \to WW^*$; $Z \to \ell\ell$, $h \to ZZ^*$; $Z \to \ell\ell$, $h \to \tau\tau$; $Z \to \nu\nu$, $h \to ZZ^*$; $Z \to qq$, $h \to ZZ^*$) can result in a final state containing multileptons and one combination ($Z \to \ell\ell$, $h \to \gamma\gamma$) leads to lepton + diphoton states with substantial rates.

For the $t \to ch$ search, three combinations in the decay chain $t\bar{t} \to (bW)(ch) \to (b\ell\nu)(ch)$ can lead to multilepton final states, namely $h \to WW^*$, $h \to ZZ^*$, and $h \to \tau\tau$. The $bWch$ channel can also result in a lepton + diphoton final state when the Higgs boson decays to a photon pair. Finally, given the parent $t\bar{t}$ state, the amount of hadronic activity in the $t \to ch$ signal events is expected to be quite large.

B. Multilepton search channels

A three-lepton event must contain exactly three isolated and prompt leptons (e, μ, τ_h), of which two must be electrons or muons. Similarly, a four-lepton event must contain at least four leptons, of which three must be electrons or muons. With the goal of segregating SM backgrounds, these events are classified on the basis of the lepton flavor, their relative charges, as well as charge and flavor combinations and other kinematic quantities such as dilepton invariant mass and E_T^{miss}, as follows.

Events with τ_h are grouped separately because narrow jets are frequently misidentified as τ_h, leading to larger SM backgrounds for channels with τ_h. Similarly, the presence of a b-tagged jet in an event calls for a separate grouping in order to isolate the $t\bar{t}$ background.

The next classification criterion is the maximum number of opposite-sign and same-flavor (OSSF) dilepton pairs that can be constructed in an event using each light lepton only once. For example, both $\mu^+\mu^-\mu^-$ and $\mu^+\mu^-e^-$ are said to be OSSF1, and a $\mu^+e^-\tau_h$ would be OSSF0. Both $e^+e^+\mu^-$ and $\mu^+\mu^+\tau_h$ are OSSF0(SS), where SS additionally indicates the presence of same-signed electron or muon pairs. Similarly, $\mu^+\mu^-e^+e^-$ is OSSF2. An event with an OSSF pair is said to be "on Z" if the invariant mass of at least one of the OSSF pair is between 75 and 105 GeV, otherwise it is "off Z." An OSSF1 off-Z event is "below Z" or "above Z" depending on whether the mass of the pair is less than 75 or more than 105 GeV, respectively. An on-Z OSSF2 event may be a "one on-Z" or a "two on-Z" event.

Finally, the three-lepton events are classified in five E_T^{miss} bins: < 50, 50–100, 100–150, 150–200, and > 200 GeV and the four-lepton events are classified in four $E_{\mathrm{T}}^{\mathrm{miss}}$ bins: < 30, 30–50, 50–100, and > 100 GeV. This results in a total of 70 three-lepton channels and 72 four-lepton channels which are listed explicitly when we later present the tables of event yields and background predictions (Tables I and II).

C. Lepton+diphoton search channels

A diphoton pair together with at least one lepton makes a lepton + diphoton event. The diphoton invariant mass of the $h \to \gamma\gamma$ candidates must be between 120 and 130 GeV. The search channels are $\gamma\gamma\ell\ell$, $\gamma\gamma\ell\tau_{\mathrm{h}}$, $\gamma\gamma\ell$, and $\gamma\gamma\tau_{\mathrm{h}}$. Depending on the relative dilepton flavor and invariant mass, the $\gamma\gamma\ell\ell$ events can be OSSF0, OSSF1 on Z, or OSSF1 off Z. The SM background decreases with increasing $E_{\mathrm{T}}^{\mathrm{miss}}$, therefore the events are further classified, when appropriate, in three bins: $E_{\mathrm{T}}^{\mathrm{miss}} < 30$, 30–50, and > 50 GeV.

The $t \to ch$ signal populates the $\gamma\gamma\ell$ and $\gamma\gamma\tau_{\mathrm{h}}$ channels but not the dilepton + diphoton channels. Since the $t \to ch$ signal events always contain a b quark from the conventional bW decay of one of the top quarks, the $\gamma\gamma\ell$ and $\gamma\gamma\tau_{\mathrm{h}}$ search channels are further classified based on the presence of a b-tagged jet. For these channels, we also split the last $E_{\mathrm{T}}^{\mathrm{miss}}$ bin into two: 50–100 GeV and > 100 GeV.

The overall lepton + diphoton channel count in this search is seven for $\gamma\gamma\ell\ell$, three for $\gamma\gamma\ell\tau_{\mathrm{h}}$, and eight each for $\gamma\gamma\ell$ and $\gamma\gamma\tau_{\mathrm{h}}$. They are listed explicitly when we present the tables of event yields and background predictions later (Tables VI and VII).

V. BACKGROUND ESTIMATION

A. Multilepton background estimation

Significant sources of multilepton SM background are Z + jets, diboson production (VV + jets; $V = W, Z$), $t\bar{t}$ production, and rare processes such as $t\bar{t}V$ + jets. The techniques we use here to estimate these backgrounds are identical to those used in Ref. [9] and are described briefly below.

WZ and ZZ diboson production can yield events with three or four intrinsically prompt and isolated leptons that can be accompanied by significant $E_{\mathrm{T}}^{\mathrm{miss}}$ and H_{T}. To estimate these background contributions, we use a simulation validated after kinematic comparisons with appropriately enriched data samples.

Processes such as Z + jets and $W^{+}W^{-}$ + jets can yield events with two prompt leptons. These can be accompanied by jets that may also contain leptons from the semileptonic decays of hadrons, or other objects that are misreconstructed as prompt leptons, leading to a three-lepton SM background. Since the simulation of the rare fluctuations that lead to such a misidentified prompt lepton can be unreliable, we use the data with two reconstructed leptons to estimate this SM background using the number of isolated prompt tracks in the dilepton data set.

The $t\bar{t}$ decay can result in two prompt leptons and is a source of background when the decay of one of the daughter b quarks reconstructs as the third prompt lepton candidate. This background is estimated from a $t\bar{t}$

TABLE I. Observed (Obs.) yields and SM expectations (Exp.) for three-lepton events. See text for the description of event classification by the number and invariant mass of opposite-sign, same-flavor lepton pairs that are on or below Z (see Sec. 4.2), presence of τ_{h}, tagged b jets, and the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event. The 70 channels are exclusive.

		$E_{\mathrm{T}}^{\mathrm{miss}}$	$N_{\tau_{\mathrm{h}}} = 0$, $N_b = 0$		$N_{\tau_{\mathrm{h}}} = 1$, $N_b = 0$		$N_{\tau_{\mathrm{h}}} = 0$, $N_b \geq 1$		$N_{\tau_{\mathrm{h}}} = 1$, $N_b \geq 1$	
3 leptons	$m_{\ell^+\ell^-}$	(GeV)	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
OSSF0(SS)	⋯	$(200, \infty)$	1	1.3 ± 0.6	2	1.4 ± 0.5	0	0.70 ± 0.36	0	0.7 ± 0.5
OSSF0(SS)	⋯	(150, 200)	2	2.1 ± 0.9	0	3.0 ± 1.1	1	2.1 ± 1.0	0	1.5 ± 0.6
OSSF0(SS)	⋯	(100, 150)	9	10.0 ± 4.9	4	9.9 ± 3.0	12	12.0 ± 5.9	4	6.3 ± 2.8
OSSF0(SS)	⋯	(50, 100)	34	37 ± 15	54	66 ± 14	32	32 ± 15	24	22 ± 10
OSSF0(SS)	⋯	(0, 50)	47	46 ± 11	196	221 ± 51	28	24 ± 11	21	31.0 ± 9.6
OSSF0	⋯	$(200, \infty)$	⋯	⋯	5	4.8 ± 2.4	⋯	⋯	6	5.9 ± 3.1
OSSF0	⋯	(150, 200)	⋯	⋯	12	18.0 ± 9.1	⋯	⋯	21	20 ± 10
OSSF0	⋯	(100, 150)	⋯	⋯	94	96 ± 47	⋯	⋯	91	121 ± 61
OSSF0	⋯	(50, 100)	⋯	⋯	351	329 ± 173	⋯	⋯	300	322 ± 163
OSSF0	⋯	(0, 50)	⋯	⋯	682	767 ± 207	⋯	⋯	230	232 ± 118
OSSF1	Below Z	$(200, \infty)$	2	2.5 ± 0.9	4	2.1 ± 1.0	1	1.9 ± 0.7	2	2.4 ± 1.2
OSSF1	On Z	$(200, \infty)$	17	19.0 ± 6.3	4	5.6 ± 1.9	1	2.4 ± 0.8	3	2.1 ± 0.9
OSSF1	Below Z	(150, 200)	7	4.4 ± 1.7	11	9.3 ± 4.6	3	4.7 ± 2.1	7	11.0 ± 5.9
OSSF1	On Z	(150, 200)	38	32.0 ± 8.5	10	11.0 ± 3.6	4	5.4 ± 1.7	2	5.7 ± 2.7
OSSF1	Below Z	(100, 150)	21	26.0 ± 9.9	45	56 ± 27	20	23 ± 11	56	66 ± 33
OSSF1	On Z	(100, 150)	134	129 ± 29	43	51 ± 16	20	18 ± 6	24	28 ± 14
OSSF1	Below Z	(50, 100)	157	129 ± 30	383	380 ± 104	58	60 ± 28	166	173 ± 87
OSSF1	On Z	(50, 100)	862	732 ± 141	1360	1230 ± 323	80	62 ± 17	117	101 ± 48
OSSF1	Below Z	(0, 50)	543	559 ± 93	10200	9170 ± 2710	40	52 ± 14	257	256 ± 79
OSSF1	On Z	(0, 50)	4040	4060 ± 691	51400	51400 ± 15300	181	181 ± 28	1000	1010 ± 286

TABLE II. Observed (Obs.) yields and SM expectation (Exp.) for four-lepton events. See text for the description of event classification by the number and invariant mass of opposite-sign, same-flavor lepton pairs that are on or off Z, presence of τ_h, tagged b jets, and the total $E_\mathrm{T}^\mathrm{miss}$ in the event. The 72 channels are exclusive.

		$E_\mathrm{T}^\mathrm{miss}$	$N_{\tau_\mathrm{h}} = 0,\ N_b = 0$		$N_{\tau_\mathrm{h}} = 1,\ N_b = 0$		$N_{\tau_\mathrm{h}} = 0,\ N_b \geq 1$		$N_{\tau_\mathrm{h}} = 1,\ N_b \geq 1$	
≥ 4 leptons	$m_{\ell^+\ell^-}$	(GeV)	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
OSSF0	⋯	$(100, \infty)$	0	0.07 ± 0.07	0	0.18 ± 0.09	0	0.05 ± 0.05	0	0.16 ± 0.10
OSSF0	⋯	(50, 100)	0	0.07 ± 0.06	2	0.80 ± 0.35	0	$0.00^{+0.03}_{-0.00}$	0	0.43 ± 0.22
OSSF0	⋯	(30, 50)	0	$0.001^{+0.020}_{-0.001}$	0	0.47 ± 0.24	0	$0.00^{+0.02}_{-0.00}$	0	0.11 ± 0.09
OSSF0	⋯	(0, 30)	0	$0.007^{+0.020}_{-0.007}$	1	0.40 ± 0.16	0	$0.001^{+0.020}_{-0.001}$	0	$0.02^{+0.04}_{-0.02}$
OSSF1	Off Z	$(100, \infty)$	0	0.07 ± 0.04	4	1.00 ± 0.33	0	0.14 ± 0.09	0	0.46 ± 0.20
OSSF1	On Z	$(100, \infty)$	2	0.6 ± 0.2	2	3.4 ± 0.8	1	0.80 ± 0.41	0	0.60 ± 0.26
OSSF1	Off Z	(50, 100)	0	0.21 ± 0.09	5	2.6 ± 0.6	0	0.21 ± 0.11	1	0.70 ± 0.32
OSSF1	On Z	(50, 100)	2	1.30 ± 0.39	10	12.0 ± 2.5	2	0.60 ± 0.33	1	0.8 ± 0.3
OSSF1	Off Z	(30, 50)	1	0.16 ± 0.07	4	2.4 ± 0.5	0	0.06 ± 0.06	0	0.47 ± 0.21
OSSF1	On Z	(30, 50)	3	1.20 ± 0.35	11	14.0 ± 3.1	0	0.22 ± 0.12	0	0.80 ± 0.31
OSSF1	Off Z	(0, 30)	1	0.38 ± 0.18	11	5.7 ± 1.7	0	0.05 ± 0.04	0	0.50 ± 0.26
OSSF1	On Z	(0, 30)	1	2.0 ± 0.5	32	30.0 ± 9.2	1	0.19 ± 0.11	3	1.30 ± 0.42
OSSF2	Two on Z	$(100, \infty)$	0	0.02 ± 0.15	⋯	⋯	0	0.21 ± 0.13	⋯	⋯
OSSF2	One on Z	$(100, \infty)$	1	0.43 ± 0.15	⋯	⋯	0	0.50 ± 0.29	⋯	⋯
OSSF2	Off Z	$(100, \infty)$	0	0.06 ± 0.03	⋯	⋯	0	0.09 ± 0.07	⋯	⋯
OSSF2	Two on Z	(50, 100)	3	2.8 ± 2.1	⋯	⋯	0	0.33 ± 0.11	⋯	⋯
OSSF2	One on Z	(50, 100)	1	2.0 ± 0.7	⋯	⋯	1	0.50 ± 0.28	⋯	⋯
OSSF2	Off Z	(50, 100)	2	0.20 ± 0.14	⋯	⋯	0	0.12 ± 0.10	⋯	⋯
OSSF2	Two on Z	(30, 50)	19	22 ± 9	⋯	⋯	2	0.70 ± 0.24	⋯	⋯
OSSF2	One on Z	(30, 50)	6	6.5 ± 2.4	⋯	⋯	0	0.32 ± 0.12	⋯	⋯
OSSF2	Off Z	(30, 50)	3	1.4 ± 0.6	⋯	⋯	1	0.15 ± 0.08	⋯	⋯
OSSF2	Two on Z	(0, 30)	118	109 ± 28	⋯	⋯	3	2.0 ± 0.5	⋯	⋯
OSSF2	One on Z	(0, 30)	24	29.0 ± 7.6	⋯	⋯	1	0.60 ± 0.17	⋯	⋯
OSSF2	Off Z	(0, 30)	5	7.8 ± 2.3	⋯	⋯	0	0.18 ± 0.06	⋯	⋯

Monte Carlo sample and using the probability of occurrence of a misidentified third lepton derived from data.

For search channels that contain τ_h, we estimate the probability of a (sparse) jet misidentified as a τ_h candidate by extrapolating the isolation distribution of the τ_h candidates. Since the shape of this distribution is sensitive to the extent of jet activity, the extrapolation is carried out as a function of the hadronic activity in the sample as determined by the summed p_T of all tracks as well as the leading jet p_T in the event.

Finally, minor backgrounds from rare processes such as $t\bar{t}V +$ jets or SM Higgs production including its associated production with W, Z, or $t\bar{t}$ are estimated using simulation.

B. Lepton+diphoton background estimation

We use a 120–130 GeV diphoton invariant mass window to capture the $h \to \gamma\gamma$ signal. With the requirement of at least one lepton in these lepton + diphoton channels, the SM background tends to be small and is estimated by interpolating the diphoton mass sidebands of the signal window. We assume the background distribution shape to be a falling exponential as a function of the diphoton invariant mass over the 100–200 GeV mass range.

Figure 1 (top panel) shows the exponential fit to the 100–120 and 130–200 GeV sidebands in the mass distribution for $\gamma\gamma\tau_\mathrm{h}$ events with $E_\mathrm{T}^\mathrm{miss} < 30$ GeV. We choose this sample to determine the exponent because it is a high-statistics sample. This exponent is used for background determination in all diphoton channels, allowing only the normalization to float from channel to channel. Figure 1 (bottom panel) shows an example of such a fit for the $\gamma\gamma\ell$ sample with a 30–50 GeV $E_\mathrm{T}^\mathrm{miss}$ requirement along with an exponential fit where both the exponent and the normalization are allowed to float. We assign a 50% systematic uncertainty for background determination in the 120–130 GeV Higgs boson mass region. The figure also shows the expected signal multiplied by a factor of three for clarity for $m_H = 300$ GeV, assuming that the production cross section σ for $m_H = 300$ GeV is equal to the standard model Higgs gluon fusion value of 3.59 pb at this mass given by the LHC Higgs Cross Section Working Group in Ref. [29], and a branching fraction $\mathcal{B}(H \to hh) = 1$.

VI. OBSERVATIONS

Tables I and II list the observed number of events for the three-lepton and four-lepton search channels, respectively. The number of expected events from SM processes is also shown together with the combined statistical and systematic uncertainties. Table III lists the sources of systematic effects and the resultant uncertainties in estimating the

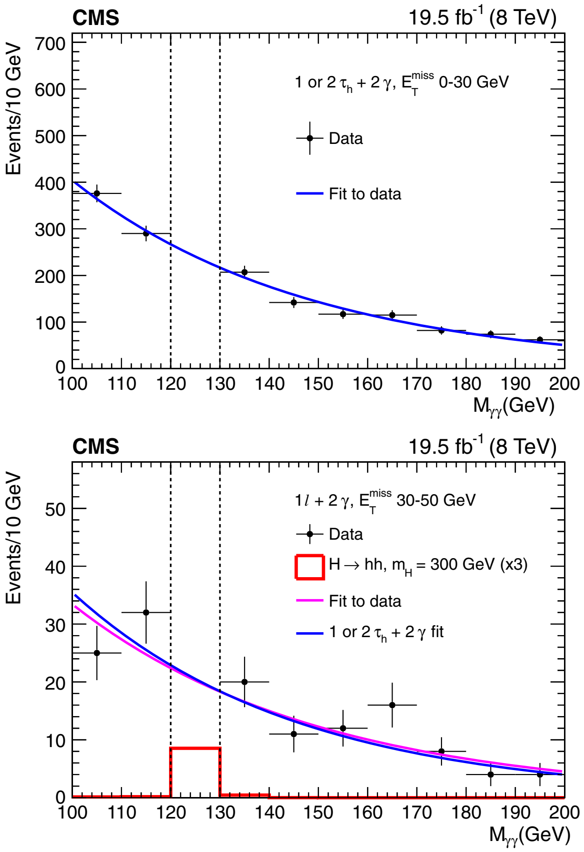

FIG. 1 (color online). (Top panel) Diphoton invariant mass distribution for $\gamma\gamma\tau_h$ events with $E_T^{miss} < 30$ GeV with an exponential fit derived from the 100–120 and 130–200 GeV sidebands regions. (Bottom panel) The same distribution for the $\gamma\gamma\ell$ events with E_T^{miss} in 30–50 GeV range with an exponential fit (blue curve) where the exponent is fixed to the value obtained from the fit shown in the top figure. Also shown for comparison purposes is an actual fit (magenta curve) to the shown data distribution. An example signal distribution (in red), assuming $\sigma\mathcal{B}(pp \to H \to hh)$ to be equal to three times 3.59 pb, as described in the text, shows that the signal is well contained in the 120–130 GeV window.

TABLE III. A compilation of significant sources of systematic uncertainties in the event yield estimation. Note that a given uncertainty may pertain only to specific sources of background. The listed values are representative and the impact of an uncertainty varies from search channel to channel.

Source of uncertainty	Magnitude (%)
Luminosity	2.6
PDF	10
$E_T^{miss}(> 50$ GeV) resolution correction	4
Jet energy scale	0.5
b-tag scale factor ($t\bar{t}$)	6
$e(\mu)$ ID/isolation (at $p_T = 30$ GeV)	0.6 (0.2)
Trigger efficiency	5
$t\bar{t}$ misidentification	50
$t\bar{t}$, WZ, ZZ cross sections	10, 15, 15
τ_h misidentification	30
Diphoton background	50

expected events from the SM. All search channels share systematic uncertainties for luminosity, renormalization scale, PDF, and trigger efficiency.

The observations listed in the tables generally agree with the expectations within the uncertainties. Given the large number of channels being investigated simultaneously, certain deviations between observations and expected values are to be anticipated. We discuss one such deviation later in the context of the H search.

Figure 2 shows observations and background decomposition for some of the most sensitive channels for the $H \to hh$ search. The amount of signal for $m_H = 300$ GeV, as described above in the context of Fig. 1, is also shown. This information is also listed in Table IV. Figure 3 and Table V show the same for the $A \to Zh$ search for $m_A = 300$ GeV, assuming the same cross section and $\mathcal{B}(A \to Zh) = 1$.

The lepton + diphoton results are summarized in Tables VI and VII. The observations agree with the expectations within the uncertainties.

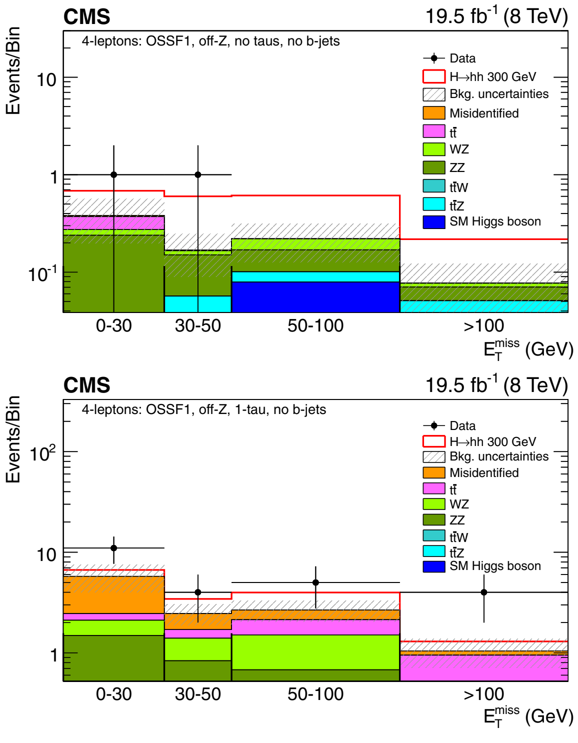

FIG. 2 (color online). The E_T^{miss} distributions for four-lepton events with an off-Z OSSF1 dilepton pair, no b-tagged jet, no τ_h (top panel), and one τ_h (bottom panel). These nonresonant (off-Z) channels are sensitive to the $H \to hh$ signal which is shown stacked on top of the background distributions, assuming $\sigma\mathcal{B}(pp \to H \to hh) = 3.59$ pb, as described in the text.

TABLE IV. Observed (Obs.) yields and SM expectation (Exp.) for selected four-lepton channels in the $H \to hh$ search. These are also shown in Fig. 2. See text for the description of event classification. The $H \to hh$ signal (Sig.) is also listed, assuming $\sigma\mathcal{B}(pp \to H \to hh) = 3.59$ pb.

Channel	E_T^{miss} (GeV)	Obs.	Exp.	Sig.
4ℓ (OSSF1, off Z)	(0, 30)	1	0.38 ± 0.18	0.30
(no τ_h, no b jets)	(30, 50)	1	0.16 ± 0.07	0.43
	(50, 100)	0	0.21 ± 0.09	0.39
	$(100, \infty)$	0	0.07 ± 0.04	0.14
4ℓ (OSSF1, off Z)	(0, 30)	11	5.7 ± 1.7	0.91
(1– τ_h, no b jets)	(30, 50)	4	2.4 ± 0.5	0.98
	(50, 100)	5	2.6 ± 0.6	1.31
	$(100, \infty)$	4	1.00 ± 0.33	0.25

TABLE V. Observed (Obs.) yields and SM expectation (Exp.) for selected four-lepton channels in the $A \to Zh$ search. These are also shown in Fig. 3. See text for the description of event classification. The $A \to Zh$ signal (Sig.) is also listed, assuming $\sigma\mathcal{B}(pp \to A \to Zh) = 3.59$ pb.

Channel	E_T^{miss} (GeV)	Obs.	Exp.	Sig.
4ℓ (OSSF1, on Z)	(0, 30)	32	30.0 ± 9.2	6.46
(1 τ_h, no b jets)	(30, 50)	11	14.0 ± 3.1	6.72
	(50, 100)	10	12.0 ± 2.5	7.05
	$(100, \infty)$	2	3.4 ± 0.8	1.12
4ℓ (OSSF2, one on Z)	(0, 30)	24	29.0 ± 7.6	3.15
(no τ_h, no b jets)	(30, 50)	6	6.5 ± 2.4	2.91
	(50, 100)	1	2.0 ± 0.7	4.92
	$(100, \infty)$	1	0.43 ± 0.15	0.82

VII. INTERPRETATION OF RESULTS

A. Statistical procedure

No significant disagreement is found between our observations and the corresponding SM expectations. We derive limits on the production cross section times branching fraction for the new physics scenarios under consideration, and use them to constrain parameters of the models. We set 95% C.L. upper limits on the cross sections using the modified frequentist construction C.L. [30,31]. We compute the single-channel C.L. limits for each channel and then obtain the combined upper limit.

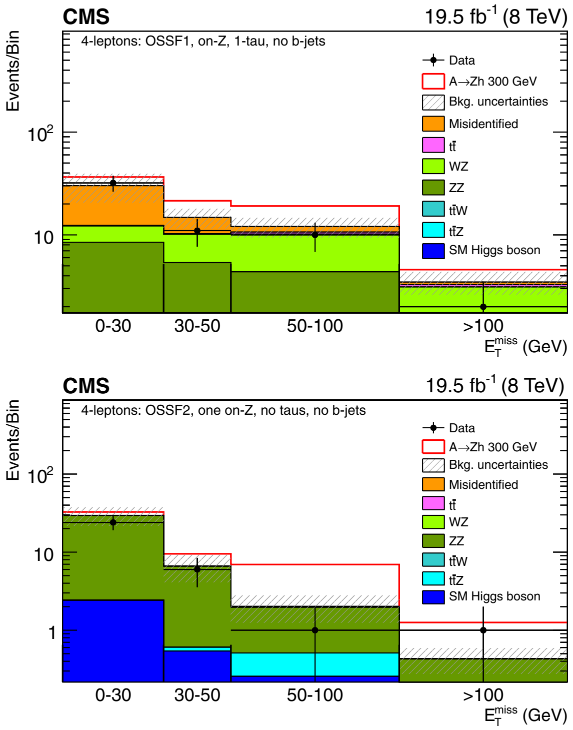

FIG. 3 (color online). The E_T^{miss} distributions for four-lepton events without b-tagged jets which contain an on-Z OSSF1 dilepton pair and one τ_h (top panel), and an OSSF2 dilepton pair with one Z candidate and no τ_h (bottom panel). These resonant (containing a Z) channels are sensitive to the $A \to Zh$ signal which is shown stacked on top of the background distributions, assuming $\sigma\mathcal{B}(pp \to A \to Zh) = 3.59$ pb, as described in the text.

TABLE VI. Observed yields and SM expectations for dilepton + diphoton events. The diphoton invariant mass is required to be in the 120–130 GeV window. The ten channels are exclusive.

Channel	E_T^{miss} (GeV)	Obs.	Exp.
$\gamma\gamma\ell\ell$ (OSSF1, off Z)	$(50, \infty)$	0	$0.19^{+0.25}_{-0.19}$
	(30, 50)	1	$0.17^{+0.25}_{-0.17}$
	(0, 30)	1	1.20 ± 0.74
$\gamma\gamma\ell\ell$ (OSSF1, on Z)	$(50, \infty)$	0	$0.10^{+0.17}_{-0.10}$
	(30, 50)	1	0.33 ± 0.28
	(0, 30)	0	1.01 ± 0.55
$\gamma\gamma\ell\ell$ (OSSF0)	All	0	$0.00^{+0.17}_{-0.00}$
$\gamma\gamma\ell\tau_h$	$(50, \infty)$	0	$0.16^{+0.66}_{-0.16}$
	(30, 50)	0	$0.50^{+0.57}_{-0.50}$
	(0, 30)	0	0.76 ± 0.60

TABLE VII. Observed yields and SM expectations for single lepton + diphoton events. The diphoton invariant mass is required to be in the 120–130 GeV window. The eight channels are exclusive.

		$N_b = 0$		$N_b \geq 1$	
Channel	E_T^{miss} (GeV)	Obs.	Exp.	Obs.	Exp.
$\gamma\gamma\ell$	$(100, \infty)$	1	2.2 ± 1.0	0	0.5 ± 0.4
	(50, 100)	7	9.5 ± 4.4	1	2.3 ± 1.2
	(30, 50)	29	21 ± 10	2	1.1 ± 0.6
	(0, 30)	72	77 ± 38	2	2.1 ± 1.1
$\gamma\gamma\tau_h$	$(100, \infty)$	1	$0.24^{+0.25}_{-0.24}$	0	0.35 ± 0.28
	(50, 100)	14	9.3 ± 4.7	1	1.5 ± 0.8
	(30, 50)	71	67 ± 34	2	2.1 ± 1.2
	(0, 30)	229	235 ± 117	6	6.4 ± 3.3

B. $H \to hh$ and $A \to Zh$ model-independent interpretations

Figure 4 (top panel) shows 95% C.L. observed and expected $\sigma\mathcal{B}$ upper limits for the gluon fusion production of heavy scalar H, with the decay $H \to hh$ along with one and two standard deviation bands around the expected limits using only the multilepton channels. Figure 4 (bottom panel) shows the same using both multilepton and diphoton channels. In placing these model-independent limits, we explicitly assume that h is the recently discovered SM-like Higgs boson [1–3] particularly in regards to the branching fraction of its various decay modes as predicted in the SM.

For low masses, there is an almost two standard deviation discrepancy between the expected and observed 95% C.L. limits in Fig. 4. Its origin traces back to three four-lepton channels listed in Table II, which can also be located in Fig. 2 (bottom panel). They consist of events with a τ_h and three light leptons containing an off-Z OSSF dilepton pair, but not a b-tagged jet. The $H \to hh$ signal resides almost entirely in the 0–100 GeV range in E_T^{miss} which is spanned by these three channels collectively. The observed (expected) number of events is 11 (5.7 ± 1.7), 4 (2.4 ± 0.5), and 5 (2.6 ± 0.6) for E_T^{miss} in ranges 0–30, 30–50, and 50–100 GeV, respectively. Summing over the three channels, the observed count is 20 with an expectation of 10.7 ± 1.9, giving the probability of observing 20 events over the 0–100 GeV E_T^{miss} range to be approximately 2.2%. Systematic uncertainties and their correlations are taken into account when evaluating this probability. The observed discrepancy in the limits shown in Fig. 4 is thus consistent with a broad fluctuation in the observed E_T^{miss} distribution. Given the large number of channels under scrutiny in this search, fluctuations at this level are to be expected. No such deviation is observed in the E_T^{miss} distribution for other search channels.

Next we probe the sensitivity to gluon fusion production of the heavy pseudoscalar A with the decay $A \to Zh$. Figure 5 (top panel) shows 95% C.L. upper limits on $\sigma\mathcal{B}$ for $A \to Zh$ search along with one and two standard

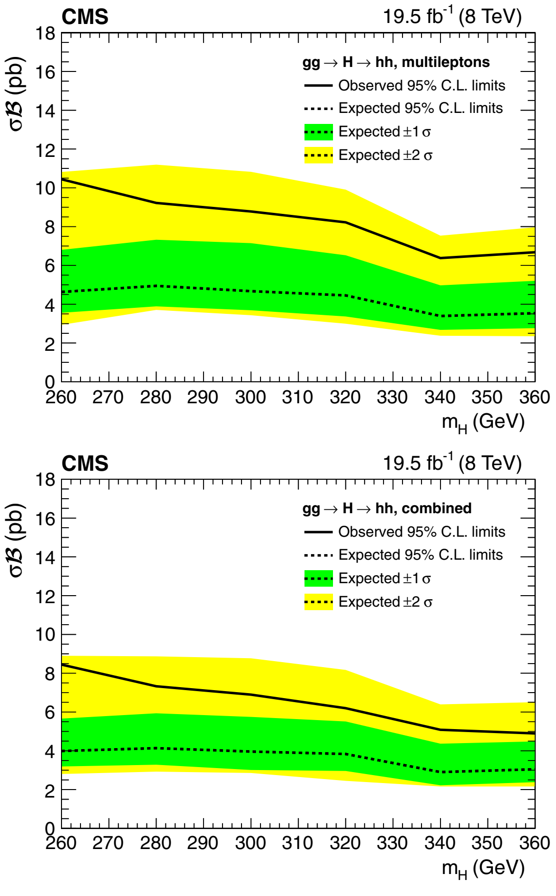

FIG. 4 (color online). (Top panel) Observed and expected 95% C.L. $\sigma\mathcal{B}$ limits for gluon fusion production of H and the decay $H \to hh$ with one and two standard deviation bands shown. These limits are based only on multilepton channels. The h branching fractions are assumed to have SM values. (Bottom panel) The same, but also including lepton + diphoton channels.

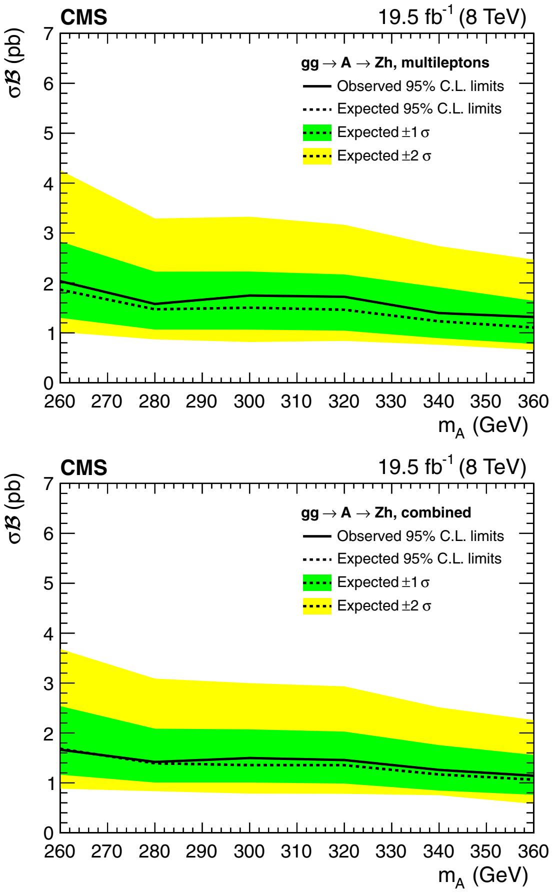

FIG. 5 (color online). (Top panel) Observed and expected 95% C.L. $\sigma\mathcal{B}$ limits for gluon fusion production of A and the decay $A \to Zh$ with one and two standard deviation bands shown. These limits are based only on multilepton channels. The h branching fraction are assumed to have SM values. (Bottom panel) The same, but also including lepton + diphoton channels.

deviation bands around the expected contour using only the multilepton channels. Figure 5 (bottom panel) shows the same signal probed with both multilepton and diphoton channels. The observed and expected exclusions are consistent.

C. Interpretations in the context of two-Higgs-doublet models

General models with two Higgs doublets may exhibit new tree-level contributions to flavor-changing neutral currents that are strongly constrained by low-energy experiments. Prohibitive flavor violation is avoided in a 2HDM if all fermions of a given representation receive their masses through renormalizable Yukawa couplings to a single Higgs doublet, as in the case of supersymmetry. There are four such possible distinct assignments of fermion couplings in models with two Higgs doublets, the most commonly considered of which are called type I and type II models. In type I models all fermions receive their masses through Yukawa couplings to a single Higgs doublet, while in type II models the up-type quarks receive their masses through couplings to one doublet and down-type quarks and leptons couple to the second doublet. In either type, after electroweak symmetry breaking the physical Higgs scalars are linear combinations of these two electroweak Higgs doublets, so that fermion couplings to the physical states depend on the type of 2HDM, the mixing angle α, and the ratio of vacuum expectation values $\tan\beta$. We next present search interpretations in the context of type I and type II 2HDMs [5]. In these models, the production cross sections for H and A as well as the branching fractions for them to decay to two SM-like Higgs bosons depend on parameters α and $\tan\beta$. The mixing angle between H and h is given by α, whereas $\tan\beta$ gives the relative contribution of each Higgs doublet to electroweak symmetry breaking. In obtaining these model-dependent limits, the daughter h is assumed to be the recently discovered SM-like Higgs boson, but the branching fractions to its various decay modes are assumed to be dictated by the parameters α and $\tan\beta$ of the 2HDM, as described below.

We use the SusHi [32] program to obtain the 2HDM cross sections. The branching fraction for SM-like Higgs

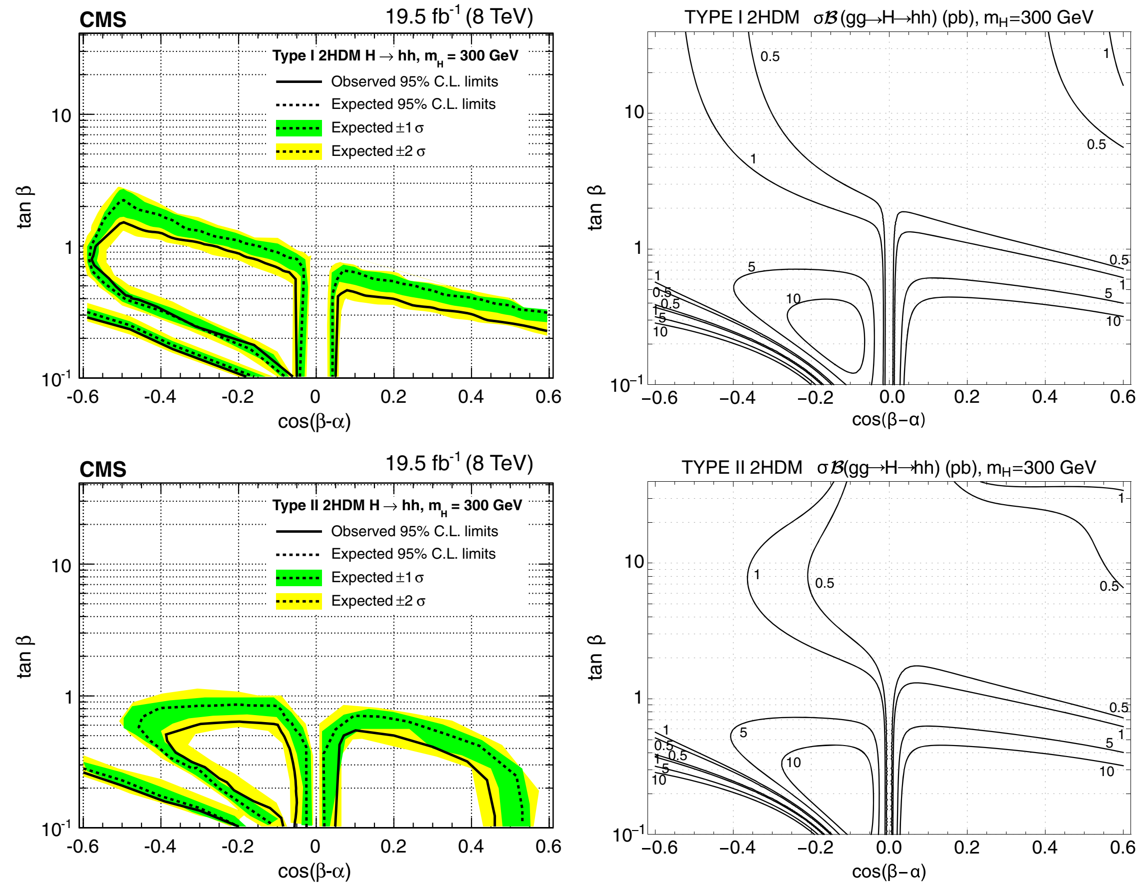

FIG. 6 (color online). (Left panels) Observed and expected 95% C.L. upper limits for gluon fusion production of a heavy Higgs boson H of mass 300 GeV as a function of parameters $\tan\beta$ and $\cos(\beta-\alpha)$ of the types I (upper panel) and II (lower panel) 2HDM. The parameters determine the H production cross section as well as the branching fractions $\mathcal{B}(H\to hh)$ and $\mathcal{B}(h\to WW^*, ZZ^*, \tau\tau, \gamma\gamma)$, which are relevant to this search. (Right panel) The $\sigma\mathcal{B}(H\to hh)$ contours for types I (upper panel) and II (lower panel) 2HDM adopted from Ref. [35]. The excluded regions are either below the open limit contours or within the closed ones.

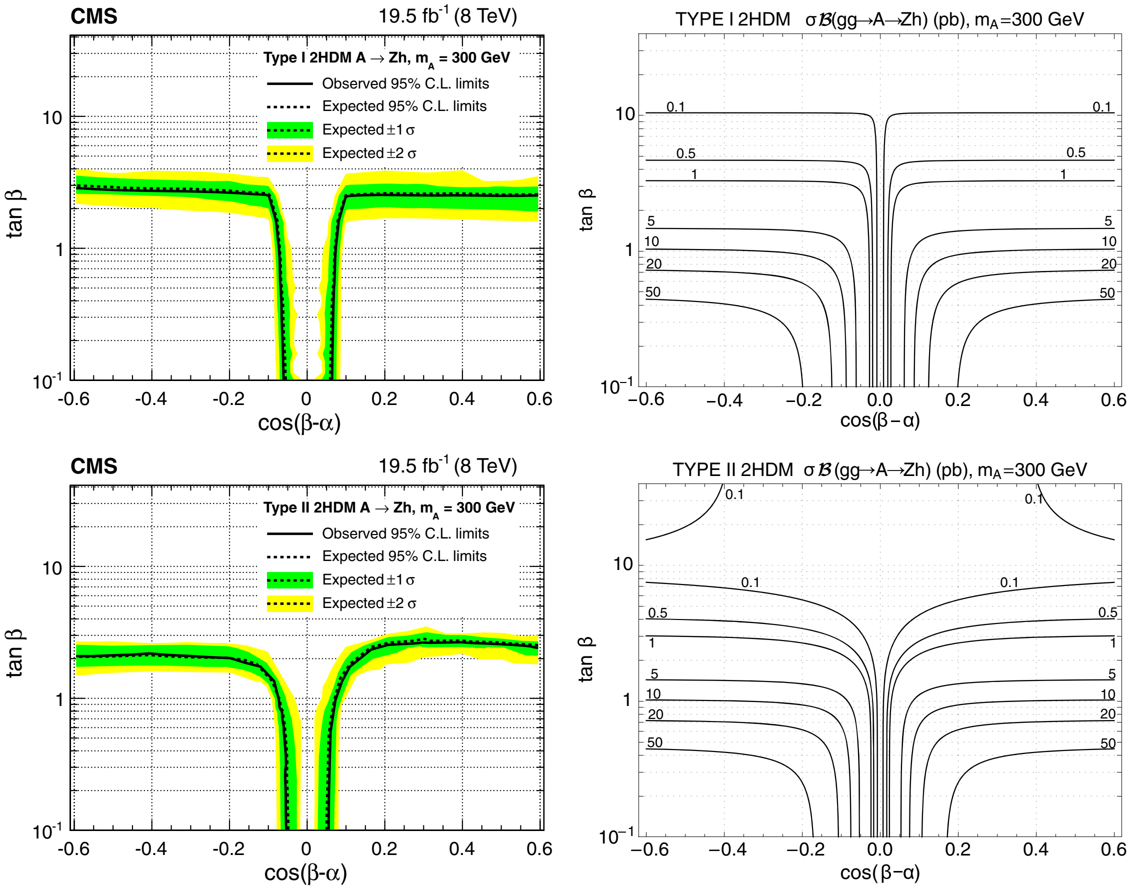

FIG. 7 (color online). (Left panels) Observed and expected 95% C.L. upper limits for gluon fusion production of an A boson of mass 300 GeV as a function of parameters $\tan\beta$ and $\cos(\beta-\alpha)$ of the types I (upper panel) and II (lower panel) 2HDM. The parameters determine the A production cross section as well as the branching fractions $\mathcal{B}(A\to Zh)$ and $\mathcal{B}(h\to WW^*, ZZ^*, \tau\tau, \gamma\gamma)$ which are relevant to this search. (Right panels) The $\sigma\mathcal{B}(A\to Zh)$ contours for types I (upper panel) and II (lower panel) 2HDM adopted from Ref. [35]. The excluded regions are below the open limit contours.

boson are calculated using the 2HDMC [33] program. The 2HDMC results are consistent with those provided by the LHC Higgs Cross Section Working Group [34]. A detailed list of couplings of H and A to SM fermions and massive gauge bosons in types I and II 2HDMs has been tabulated in Ref. [6]. Figure 6 (top left and bottom left panels) shows observed and expected 95% C.L. upper limits for gluon fusion production of a heavy Higgs boson H of mass 300 GeV for type I and type II 2HDMs, respectively, along with the $\sigma\mathcal{B}$ theoretical predictions (right panels) adopted from Ref. [35] for the two models. Figure 7 (top left and bottom left panels) shows similar results for the pseudoscalar A Higgs boson of mass 300 GeV. The branching fractions for the SM-like Higgs boson daughters of the H and A vary across the $\tan\beta$ versus $\cos(\beta-\alpha)$ plane and are incorporated in the upper limit calculations.

Finally, we further improve constraints on the 2HDM parameters using the simultaneous null findings for the H and A. Figure 8 shows exclusion in $\tan\beta$ versus $\cos(\beta-\alpha)$ plane for the combined gluon fusion signal for type I (top panel) and type II (bottom panel) 2HDMs, assuming H and A to be mass degenerate with a mass of 300 GeV. Once again, the branching fractions of the SM-like h daughters are allowed to vary across the plane.

D. $t\to ch$ search results

The $t\to ch$ signal predominantly populates lepton + diphoton channels with a b tag and $\ell\ell\ell$ (no τ_h) multilepton channels that lack an OSSF dilepton pair or have an off-Z OSSF pair. Beyond the fact that the presence of charm quark increases the likelihood of an event being classified as being b tagged, no special effort is made to identify the charm quark present in the signal. The observations and SM expectations for the ten most sensitive channels are listed in Table VIII along with the signal yield for a nominal value of $\mathcal{B}(t\to ch)=1\%$. No significant excess is observed.

The statistical procedure yields an observed limit of $\mathcal{B}(t\to ch)=0.56\%$ and an expected limit of $\mathcal{B}(t\to ch)=(0.65^{+0.29}_{-0.19})\%$ from SM $t\bar{t}$ production followed by either $t\to ch$ or its charge-conjugate decay. The $t\to ch$ branching

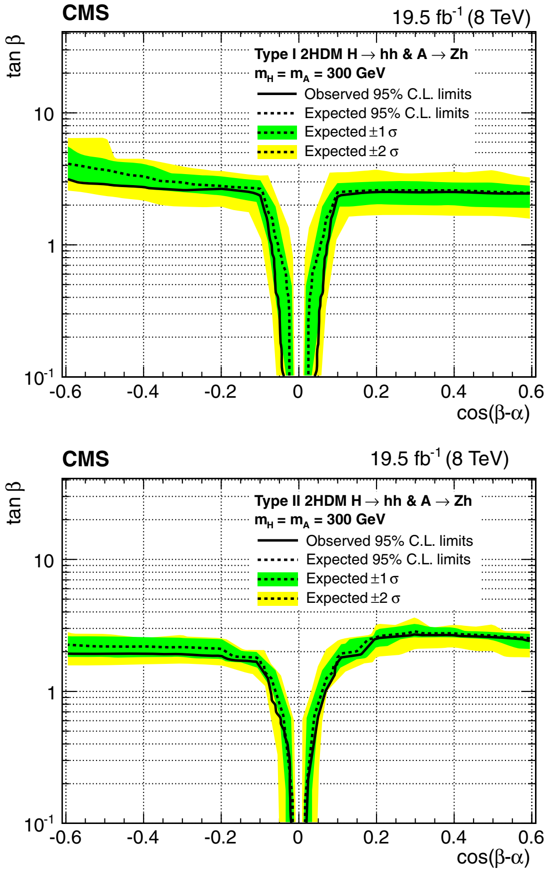

FIG. 8 (color online). Combined observed and expected 95% upper limits for gluon fusion production of a heavy Higgs boson H and A of mass 300 GeV for type I (top panel) and type II (bottom panel) 2HDM as a function of parameters $\tan\beta$ and $\cos(\beta-\alpha)$. The parameters determine the H and A production cross sections as well as the branching fractions $\mathcal{B}(H \to hh)$, $\mathcal{B}(A \to Zh)$, and $\mathcal{B}(h \to WW^*, ZZ^*, \tau\tau, \gamma\gamma)$, which are relevant to this search.

TABLE VIII. The ten most sensitive search channels for $t \to ch$, along with the number of observed (Obs.), expected SM background (Exp.), and expected signal (Sig.) events [assuming $\mathcal{B}(t \to ch) = 1\%$]. The three-lepton channels are taken from Ref. [9], have $H_T < 200$ GeV, and do not contain a τ_h. The stated uncertainties contain both systematic and statistical components.

Channel	E_T^{miss} (GeV)	N_b	Obs.	Exp.	Sig.
$\gamma\gamma\ell$	(50, 100)	≥ 1	1	2.3 ± 1.2	2.88 ± 0.39
	(30, 50)	≥ 1	2	1.1 ± 0.6	2.16 ± 0.30
	(0, 30)	≥ 1	2	2.1 ± 1.1	1.76 ± 0.24
	(50, 100)	0	7	9.5 ± 4.4	2.22 ± 0.31
	$(100, \infty)$	≥ 1	0	0.5 ± 0.4	0.92 ± 0.14
	$(100, \infty)$	0	1	2.2 ± 1.0	0.94 ± 0.17
$\ell\ell\ell$(OSSF1,	(50, 100)	≥ 1	48	48 ± 23	9.5 ± 2.3
below Z)	(0, 50)	≥ 1	34	42 ± 11	5.9 ± 1.2
$\ell\ell\ell$(OSSF0)	(50, 100)	≥ 1	29	26 ± 13	5.9 ± 1.3
	(0, 50)	≥ 1	29	23 ± 10	4.3 ± 1.1

fraction is related to the left- and right-handed top-flavor-changing Yukawa couplings λ_{tc}^h and λ_{ct}^h, respectively, by $\mathcal{B}(t \to ch) \simeq 0.29(|\lambda_{tc}^h|^2 + |\lambda_{ct}^h|^2)$ [7], so that the observed limit corresponds to a limit on the couplings of $\sqrt{|\lambda_{tc}^h|^2 + |\lambda_{ct}^h|^2} < 0.14$.

To facilitate interpretations in broader contexts [36], we also provide limits on $\mathcal{B}(t \to ch)$ from individual Higgs boson decay modes. For this purpose, we assume the SM branching fraction for the Higgs boson decay mode [37] under consideration, and ignore other decay modes. Table IX shows the results, illustrating the analysis sensitivity for the $t \to ch$ decay in each of the Higgs boson decay modes.

VIII. SUMMARY

We have performed a search for the $H \to hh$ and $A \to Zh$ decays of heavy scalar (H) and pseudoscalar (A) Higgs bosons, respectively, which occur in the extended Higgs sector described by the 2HDM. This is the first search for these decays carried out at the LHC. We used multilepton and diphoton final states from a data set corresponding to an integrated luminosity of 19.5 fb^{-1} of data recorded in 2012 from pp collisions at a center-of-mass energy of 8 TeV. We find no significant deviation from the SM expectations and place 95% C.L. cross section upper limits of approximately 7 pb on $\sigma\mathcal{B}$ for $H \to hh$ and 2 pb for $A \to Zh$. We further interpret these limits in the context of type I and type II 2HDMs, presenting exclusion contours in the $\tan\beta$ versus $\cos(\beta-\alpha)$ plane.

TABLE IX. Comparison of the observed and expected 95% C.L. limits on $\mathcal{B}(t \to ch)$ from individual Higgs boson decay modes along with the 68% C.L. uncertainty ranges.

		Upper limits on $\mathcal{B}(t \to ch)$		
Higgs boson decay mode		Obs.	Exp.	68% C.L. range
$\mathcal{B}(h \to WW^*)$	$= 23.1\%$	1.58%	1.57%	(1.02–2.22)%
$\mathcal{B}(h \to \tau\tau)$	$= 6.15\%$	7.01%	4.99%	(3.53–7.74)%
$\mathcal{B}(h \to ZZ^*)$	$= 2.89\%$	5.31%	4.11%	(2.85–6.45)%
Combined multileptons (WW^*, $\tau\tau$, ZZ^*)		1.28%	1.17%	(0.85–1.73)%
$\mathcal{B}(h \to \gamma\gamma)$	$= 0.23\%$	0.69%	0.81%	(0.60–1.17)%
Combined multileptons + diphotons		0.56%	0.65%	(0.46–0.94)%

Using diphoton and multilepton search channels that are sensitive to the decay $t \to ch$, we place an upper limit of 0.56% on $\mathcal{B}(t \to ch)$, where the expected limit is 0.65%. This is a significant improvement over the earlier limit of 1.3% from the multilepton search alone [9].

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