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Letter

Search for bottom quark associated production of the standard model Higgs boson in final states with leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

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ABSTRACT

This Letter presents the first search for bottom quark associated production of the standard model Higgs boson, in final states with leptons. Higgs boson decays to pairs of tau leptons and pairs of leptonically decaying W bosons are considered. The search is performed using data collected from 2016 to 2018 by the CMS experiment in proton-proton collisions at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}. Upper limits at the 95% confidence level are placed on the signal strength for Higgs boson production in association with bottom quarks; the observed (expected) upper limit is 3.7 (6.1) times the standard model prediction.

1. Introduction

The discovery of the Higgs boson (H) [1–3] by the ATLAS [4] and CMS [5] Collaborations in 2012 was a milestone in the study of the standard model (SM) of particle physics. A broad programme of measurements, studying the properties of this newly found particle, has been carried out over the subsequent decade [6,7].

The production of the SM Higgs boson at the CERN LHC can occur via several mechanisms [8]; the dominant ones, listed in order of decreasing production rate, are: gluon-gluon fusion (ggH), vector boson fusion (VBF), Higgs-strahlung (VH), top quark associated production ($\mathrm{t\bar{t}H}$ and tH), and bottom quark associated production ($\mathrm{b\bar{b}H}$ and bH, jointly referred to as $\mathrm{b\bar{b}H}$ in this Letter). With the exception of the $\mathrm{b\bar{b}H}$ and tH processes, these production modes have all been observed [6,7]. With a predicted production cross section of $0.48^{+0.10}_{-0.11}$ pb, calculated assuming a Higgs boson mass of 125.38 GeV in the four-flavour-scheme (4FS) and 5FS with Santander matching [8–15], $\mathrm{b\bar{b}H}$ production occurs almost as frequently as $\mathrm{t\bar{t}H}$ production. However, distinguishing the Higgs boson signal from backgrounds is experimentally more challenging for $\mathrm{b\bar{b}H}$ production than for $\mathrm{t\bar{t}H}$ production, since the top quark decay products provide a clear experimental signature. As such, $\mathrm{t\bar{t}H}$ production was already observed by both ATLAS [16] and CMS [17] in 2018. In addition to challenges related to the suppression of backgrounds, the $\mathrm{b\bar{b}H}$ process interferes with other Higgs boson production mechanisms [18]. The destructive interference with Higgs boson production via ggH, in particular, hinders the possibility of directly constraining the Yukawa coupling between the Higgs boson and bottom quarks through studies of this process. Measurements of Higgs boson decays to bottom quarks provide more precise constraints on this Yukawa coupling, while $\mathrm{b\bar{b}H}$ production remains sensitive to the correlation between the Higgs boson couplings to bottom and top quarks.

This Letter presents constraints on the production cross section of the Higgs boson in association with b quarks, using the proton-proton (pp) collision data set recorded by the CMS detector at $\sqrt{s} = 13$ TeV in 2016–2018. The search primarily targets Higgs boson decays into pairs of tau leptons. Higgs boson decays to leptonically decaying W bosons are also considered in the electron-muon pair final state. These decay channels are chosen for their sizable branching fractions, in combination with moderate backgrounds, which result from the presence of leptons in the final state. Compared with previous searches performed by the CMS experiment [19,20], this search is optimized to target the production mechanism of the 125 GeV Higgs boson in the SM. Tabulated results are provided in the HEPData record for this analysis [21].

2. Higgs boson production mechanisms and analysis strategy

Fig. 1 shows the main Feynman diagrams for Higgs boson production in association with b quarks. The upper left diagram represents ggH pro-

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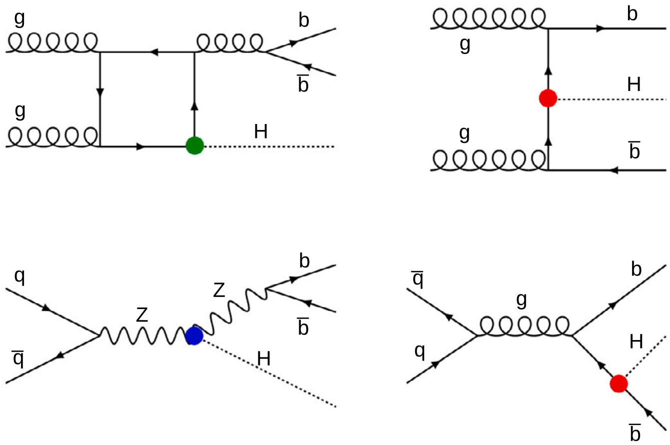

Fig. 1. Dominant Feynman diagrams contributing to Higgs boson production in association with b quarks in the four-flavor-scheme [18,22]. The diagrams initiated by gluons (quarks) are shown in the upper (lower) row. The red circle is used to mark the Higgs boson coupling to b quarks, the green circle marks the Higgs boson coupling to top quarks, and the blue circle marks the coupling between the Higgs boson and vector bosons. In the ggH diagram (upper left), the additional gluon is radiated from within the quark loop, although it can equivalently radiate from one of the initial-state gluons.

duction with an additional gluon splitting into a $b\overline{b}$ pair. In this diagram, the Higgs boson is produced via a quark (q) loop that mainly involves the top quark. The production cross section is therefore dominated by a contribution proportional to the square of the top quark Yukawa coupling (y_t). The theoretical production cross section for this process is evaluated as the fraction of the next-to-leading order (NLO) in quantum chromodynamics (QCD) ggH production cross section, calculated in the 4FS [8], in which the gluon converts into a $b\overline{b}$ pair. This diagram interferes destructively with the diagram in Fig. 1 (upper right), the production of a Higgs boson and a $b\overline{b}$ pair via bottom quark fusion. The production cross section of this process is proportional to the square of the bottom quark Yukawa coupling (y_b). Quark-initiated diagrams are shown in Fig. 1 (lower): the Higgs boson is produced via the trilinear coupling to vector bosons (HVV) on the left and via the coupling y_b on the right. In the Higgs-strahlung diagram on the lower left, the b quarks are produced through the decay of an on-shell Z boson, and the diagram includes only electroweak terms at leading order (LO). The resulting interference with the diagram on the lower right is therefore negligible with respect to the production cross section of the individual processes. In this Letter, the Higgs-strahlung process ($pp \to Z(\to b\overline{b})+H$) is treated as a background because of the different coupling structure. The same treatment is reserved for the VBF production process with one or two outgoing b quarks.

To distinguish the different contributions to Higgs boson production in association with b quarks, we use the following notation:

- $b\overline{b}H(y_b^2)$ refers to b quark associated Higgs boson production via Yukawa coupling to bottom quarks (e.g. the Feynman diagrams in Fig. 1 (right));
- $b\overline{b}H(y_t^2)$ marks Higgs boson production via a top quark loop; and
- $b\overline{b}H(y_t y_b)$ labels the interference term between the top-quark-mediated and the bottom-quark-mediated production processes.

The inclusive production across these terms is labelled as $b\overline{b}H$ or $b\overline{b}H(y_b, y_t)$.

The SM prediction for the $b\overline{b}H$ production cross section is therefore split into three contributions with the following production cross sections [8–15,18,22]: 1.040 pb for $b\overline{b}H(y_t^2)$ (NLO reweighted to next-to-next-to-NLO (N^{3}LO) in QCD and NLO in electroweak), 0.482 pb for $b\overline{b}H(y_b^2)$ (NLO in QCD), and −0.033 pb for $b\overline{b}H(y_t y_b)$ (NLO in QCD), amounting to a total predicted production cross section of $\sigma(y_b, y_t) = 1.489$ pb.

The $b\overline{b}H$ search presented in this Letter is performed in final states of two oppositely charged leptons with different flavour, or hadronically decaying tau lepton (τ_h) candidates:

- two hadronically decaying tau leptons ($\tau_h\tau_h$);
- an electron and a hadronically decaying tau lepton ($e\tau_h$);
- a muon and a hadronically decaying tau lepton ($\mu\tau_h$);
- an electron and a muon ($e\mu$).

The first three final states originate from the decay of the Higgs boson to a pair of tau leptons, at least one of which decays hadronically. The eμ final state originates either from a Higgs boson decaying to a pair of tau leptons or from a Higgs boson decaying to a pair of W bosons. These two decay chains result in a similar event topology, and are therefore investigated as a single analysis channel. Final states with two electrons or muons have not been considered due to the overwhelming Drell-Yan background and low branching fractions.

3. The CMS detector

The CMS apparatus [5] is a multipurpose, nearly hermetic detector, designed to trigger on [23,24] and identify electrons, muons, photons, and hadrons [25–27] produced in proton-proton collisions. A “particle-flow” (PF) algorithm [28] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic (ECAL) and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build tau leptons, jets, and missing transverse momentum [29–31]. The missing transverse momentum vector $\vec{p}_T^{\,miss}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [31]. The $\vec{p}_T^{\,miss}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [23]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing and reduces the event rate to around 1 kHz before data storage [24].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [5].

4. Data and simulated samples

The pp collision data set used in this search was recorded by the CMS experiment between 2016 and 2018, at a centre-of-mass energy of 13 TeV. It corresponds to a total integrated luminosity of 138 fb^{-1}.

Several different Monte Carlo (MC) event generators are used to produce samples of simulated events of the signal and background processes. The simulation of the $b\overline{b}H$ signal was performed at NLO in QCD using the MadGraph5_aMC@NLO 2.6.1 generator [32]. Three samples of simulated events are used, corresponding to the three distinct Higgs boson couplings contributing to the $b\overline{b}H$ process (y_b^2, y_t^2, and $y_t y_b$). A sample of ggH events is simulated at NLO in QCD using the MadGraph5_aMC@NLO 2.6.5 generator. Other Higgs boson production mechanisms, including VBF, VH, and $t\overline{t}H$ are generated at NLO in QCD with the POWHEG 2.0 generator [33–35].

In all channels, the SM background is dominated by top quark-antiquark pair production ($t\bar{t}$) and by the production of a leptonically decaying weak boson in association with jets (V + jets). A sample of simulated $t\bar{t}$ events is generated with the POWHEG 2.0 generator at NLO in QCD. The production of V + jets events is simulated with the MADGRAPH5_aMC@NLO 2.6.5 generator at NLO in QCD. Samples of single top quark production events are generated at NLO in QCD with the POWHEG 2.0 generator, while diboson events are produced at NLO in QCD with the MADGRAPH5_aMC@NLO 2.6.5 generator, or with the POWHEG generator, depending on the specific combination of vector bosons studied. The background from SM events composed solely of jets produced through the strong interaction, referred to as QCD multijet events, is estimated from data as described in Section 6.

The NNPDF 3.1 [36] set of parton distribution functions (PDFs) at next-to-NLO (NNLO) in QCD is used in all simulated samples. Parton showering and hadronization are performed with PYTHIA 8.240 with the CP5 [37,38] underlying event tune. The CMS detector response simulation is performed with GEANT4 [39] for all processes. In the samples produced at NLO in QCD with MADGRAPH5_aMC@NLO, the FxFx jet merging scheme is employed [40].

Event reconstruction in simulated samples and recorded data is performed with the same software. The recorded data samples contain additional pp interaction vertices from the same or nearby bunch crossings (pileup). Such additional interaction vertices are generated with PYTHIA and added to all simulated events in accordance with the expected pileup distribution. Corrections are applied to the simulated samples to match the distribution of the pileup multiplicity measured in the recorded data for each year.

5. Trigger and event selection

The online selection [24] for the $\tau_h\tau_h$ channel requires two hadronically decaying tau leptons. In the $\mu\tau_h$ ($e\tau_h$) channel the presence of a muon (electron) is required, and in the $e\mu$ channel a muon-electron pair must be present. In all channels, the selected leptons (ℓ) or hadronically decaying tau leptons (τ_h) are required to match the objects used in the online event selection.

The following selection criteria are common across all channels:

- there must be a $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, or $e\mu$ pair with opposite electric charge. No additional electrons or muons, passing loose identification criteria, may be present in the event;
- the leptons and τ_h candidates must be separated by $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.5(0.3)$ in the $\tau_h\tau_h$, $e\tau_h$, and $\mu\tau_h$ ($e\mu$) channels. Here, ϕ and η refer to the azimuthal angle and the pseudorapidity of the object, respectively;
- there must be either one or two jets identified as originating from a b quark.

Across all channels, jets are selected if they have $p_T > 20$ GeV, $|\eta| < 2.4$, and if they pass quality criteria based on the jet shape. Jet constituents coming from pileup interactions are subtracted. Jets originating from b quarks are identified with the DEEPJET algorithm [41], which uses information on tracks and secondary vertices associated with the jet to identify its type (g, u/d/s, c, or b). In this Letter an efficiency of 75% for b tagging is chosen, corresponding to a mistagging probability for jets originating from gluons or light quarks of about 3%.

In the $\tau_h\tau_h$ channel, two isolated τ_h candidates with $p_T > 40$ GeV and $|\eta| < 2.1$ are required. To distinguish genuine τ_h decays from jets originating from the hadronization of quarks or gluons, and from electrons or muons, the DEEPTAU algorithm [42] is used. Information from all individually reconstructed particles near the τ_h candidate axis is combined with properties of the τ_h candidate and of the event. Genuine τ_h candidates are selected with an efficiency of 70% for a jet misidentification rate of approximately 0.43%, averaging across jet p_T and flavour. The misidentification rates of electrons and muons as τ_h candidates are approximately 3% and 0.2%.

In the $e\tau_h$, $\mu\tau_h$, and $e\mu$ channels, electrons and muons coming from W boson or tau lepton decays are treated according to the standard CMS reconstruction for electrons and muons [25,26].

In the $e\tau_h$ and $\mu\tau_h$ channels, the leptonically decaying tau lepton (τ_ℓ) must have p_T at least 1 GeV above the trigger threshold. The electron is required to have $|\eta| < 2.1$ and $p_T > 26\,(33)$ GeV in the analysis of 2016 (2017, 2018) data, while the muon is required to have $|\eta| < 2.1$ and $p_T > 23\,(25)$ GeV for the 2016 (2017, 2018) data-taking period. Quality criteria are used to select the leptons based on their relative isolation from surrounding hadronic activity and the reconstruction quality of their tracks and energy deposits in the CMS subdetectors. The τ_h candidates are required to have $p_T > 30$ GeV, $|\eta| < 2.3$, and to satisfy the same quality criteria as are applied in the $\tau_h\tau_h$ channel. To suppress the Drell–Yan background contribution, we use the DEEPTAU algorithm to reject electrons and muons that mimic τ_h signatures. The residual electron (muon) misidentification rate is 3% (< 0.1%) [42]. The invariant mass between the $\vec{p}_T^{\,\text{miss}}$ and the lepton $\vec{p}_T$, calculated as

$$m_T(\vec{p}_T, \vec{p}_T^{\,\text{miss}}) = \sqrt{2 p_T p_T^{\text{miss}} (1 - \cos[\Delta\phi(\vec{p}_T, \vec{p}_T^{\,\text{miss}})])}, d \quad (1)$$

is required to be smaller than 60 GeV to reduce the contribution from W + jets events. This also results in the rejection of $H \to WW$ events; the residual contribution of such events is around 50 times smaller than the $H \to \tau\tau$ signal yield in the $e\tau_h$ and $\mu\tau_h$ channels.

In the $e\mu$ channel, both the electron and the muon are required to have $p_T > 15$ GeV and $|\eta| < 2.4$, and to pass loose reconstruction criteria. As a result of the kinematical similarities for electron-muon pairs originating from $H \to WW$ and $H \to \tau\tau$ decays, as well as the overlap in acceptance, these decays were studied in a single analysis channel.

6. Background estimation

A multitude of background processes contribute to the presented search. Those backgrounds that include genuine hadronically decaying tau leptons, prompt leptons, or leptons misidentified as τ_h candidates are estimated from simulated events. Notable contributions to these backgrounds originate from DY + jets, diboson, and $t\bar{t}$ production in the absence of jets misidentified as τ_h candidates. Corrections are derived in sideband regions to better describe the data recorded by the CMS experiment. Processes involving jets misidentified as τ_h candidates and nonprompt leptons, appearing in multijet topologies, are estimated using control regions (CRs) in data, as discussed in the following section.

6.1. Methods based on control regions in data

In the $\tau_h\tau_h$, $e\tau_h$, and $\mu\tau_h$ final states, a large fraction of the background consists of jets misidentified as hadronic tau lepton decays. This contribution is estimated with the "fake factor" (F_F) method, as described in Ref. [43]. The shape of the misidentified τ_h background is estimated from a CR obtained by inverting the isolation criterion for the leading τ_h candidate. This CR is thus enriched in jets misidentified as τ_h candidates. The background shape is retrieved via event weights, denoted F_F, that are derived in determination regions (DRs) targeting a specific source of jet contamination. For the $\tau_h\tau_h$ channel only a QCD multijet DR is used, whereas the $e\tau_h$ and $\mu\tau_h$ channels require two additional DRs: one enriched in W + jets events and one enriched in $t\bar{t}$ events. The weights evaluated in these DRs are parameterized as a function of the transverse momenta of the τ_h candidates, and their angular separation, for the $\tau_h\tau_h$ channel. In the $e\tau_h$ and $\mu\tau_h$ channels, they are parameterized as a function of the τ_h candidate p_T. The parameterization in the $\tau_h\tau_h$ channel also depends on other event properties, such as the number of gluon and light-flavour quark jets or b jets, and the p_T^{miss}. The weighted sum of these F_F is then used to estimate the misidentified τ_h contribution to the signal region.

In the eμ channel, the QCD multijet background is estimated from events with a reconstructed electron-muon pair with the same electric charge. A transfer factor between this region, and the one where the leptons have opposite charge, is determined in events where the muon isolation requirement is inverted. The transfer factor is determined as a function of the lepton momenta, their angular separation, and the number of jets in the event. This background estimation method is commonly referred to as the "ABCD" method (discussed in Refs. [44,45]).

6.2. Other backgrounds

Other background processes are estimated from simulation. They are corrected to better describe the recorded data separately for each data-taking period.

Corrections are mostly determined in dedicated sideband regions, orthogonal to the event selection described in Section 5. For example, single-lepton trigger efficiencies are computed for the $e\tau_h$ and $\mu\tau_h$ channels using $Z \to \ell\ell$ enriched CRs, while those for the combined triggers requiring two τ_h candidates or an electron and muon pair are determined, respectively, in a $\mu\tau_h$- and a $t\bar{t}$-enriched CR.

Simulation-to-data correction factors are applied to the simulated samples to correct for the mismodelling of the electron and muon identification and isolation efficiencies, and for the τ_h candidate identification efficiency and energy scale. The light lepton efficiencies are measured as a function of the lepton p_T and $|\eta|$, using a "tag-and-probe" technique in $Z \to ee$ and $Z \to \mu\mu$ events [26]. Correction factors for genuine τ_h candidates are determined based on their decay mode and p_T, while those for misidentified electrons or muons depend on η [42].

Jet energy and resolution corrections are applied to mitigate the effect of pileup interactions and detector inefficiencies during data taking [46]. Measurements of the momentum balance in dijet, γ + jet, Z + jet, and multijet events are used to correct for any residual differences in the jet energy scale between data and simulation [30].

To each reconstructed jet with $p_T > 20$ GeV, b tagging scale factors are applied. The b tagging score is weighted based on a multivariate classifier using several jet properties to improve the data modelling [47].

The Z boson mass and momentum are corrected from $Z \to \mu\mu$ events as a function of the lepton p_T and η. The p_T spectrum in $t\bar{t}$ events is weighted to better describe the data, following the method described in Ref. [48].

7. Event classification

To improve the separation of signal from the background, boosted decision trees (BDTs) are used to classify events into distinct categories. Multiclass BDT models were trained for each channel and data-taking period. The output categories were chosen to reflect the different background compositions in each channel.

For an event, each trained BDT model returns a number of output scores equal to the number of output categories. The scores are then normalized so that their sum is equal to 1. Each output score is therefore interpreted as the probability for the event to originate from one of the physical processes targeting the associated category. Events are sorted into the category for which the output score is the highest.

All BDT models have a dedicated category targeting $H \to \tau\tau$ decays, trained on the $b\bar{b}H(y_b^2)$ and $b\bar{b}H(y_t^2)$ processes. The interference term was not used in the BDT training due to the low acceptance. Other common categories target the DY + jets (DY) and $t\bar{t}$ (TT) background processes, as their signatures in the detector resemble those of b quark associated Higgs boson production in final states involving tau leptons. The eμ channel has an additional signal category, targeting Higgs boson decays to W bosons. As the sensitivity of this channel is driven by the $H \to WW$ process, the BDT is trained to optimize the separation between this signal and the $t\bar{t}$ background. In the $\tau_h\tau_h$ channel the contribution of QCD multijet production with jets misidentified as τ_h candidates (j→ τ_h misid.) to the total background is larger than in the other channels and was therefore assigned to a dedicated category.

Table 1
Summary of the BDT categories defined for each channel.

Channel	eμ	$\ell\tau_h$	$\tau_h\tau_h$
BDT Categories	DY, TT, $b\bar{b}H$ (→ WW), $b\bar{b}H$ (→ ττ)	DY, TT, $b\bar{b}H$ (→ ττ)	DY+Higgs, TT, j→ τ_h misid., $b\bar{b}H$ (→ ττ)

Table 2
Input variables to the BDT classifiers used in each of the studied channels. Each variable is marked with the ✓ symbol if it is used for the training of the BDT models in a particular channel, or the × symbol if it is not used. Variables associated with the di-lepton system and serving as estimators for the Higgs boson properties are the most significant in the training.

Variable	eμ	$\ell\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}$	×	✓	✓
$p_{T,\tau\tau}$	×	✓	✓
$m_{T,tot}$	✓	×	×
$p_{T,tot}$	✓	×	×
m_{vis}	✓	✓	✓
m_{coll}	×	✓	×
m_T	×	✓	×
D_ζ	✓	✓	×
p_T^{miss}	×	×	✓
Electron p_T	✓	×	×
Muon p_T	✓	×	×
p_T of leading τ_h	×	×	✓
p_T of trailing τ_h	×	×	✓
$\Delta\eta$ between lepton and τ_h	×	✓	×
Number of b-tagged jets	✓	×	✓
p_T of leading b-tagged jet	✓	✓	✓
p_T of trailing b-tagged jet	×	✓	×
B tag score for leading b-tagged jet	×	✓	✓
$\Delta\eta$ between di-τ p_T and leading b-tagged jet	×	✓	×
B tag score for trailing b-tagged jet	×	✓	✓
Number of jets	✓	×	✓
p_T of leading jet	✓	×	✓
p_T of trailing jet	✓	×	✓
Dijet invariant mass	×	×	✓
Dijet $\Delta\eta$	✓	×	✓

Additional BDT models incorporating a further background category targeting other Higgs boson production mechanisms, such as the Higgs-strahlung process with a Z boson decaying into a pair of b quarks, were trained. These models identified the $b\bar{b}H$ process less efficiently, with a marginal improvement found only in the $\tau_h\tau_h$ channel. After applying the event selection introduced in Section 5, only a small number of events is left in this Higgs category, which is therefore merged with the DY + jets category for the statistical inference.

A summary of the BDT categories used in each channel is shown in Table 1. Although the label "TT" is used in all categories, the $t\bar{t}$ events used in each trained model differ: in the $\tau_h\tau_h$ channel only events with genuine τ_h candidates are targeted by the "TT" category, in the other channels the "TT" categories target $t\bar{t}$ events with no further selection.

As shown in Table 2, the set of variables used in the BDT training differs slightly across channels. Each set was chosen based on the potential separation between the $b\bar{b}H$ signals from the various backgrounds in each channel. Variables that were not satisfactorily modelled in the MC samples used to train the BDT models were removed from a set to avoid introducing a bias in the relative channel towards a specific category. In cases where the mismodelling was specifically found for one year of data taking, the variable was nonetheless removed from the training set for all BDT models related to that channel. Several input features are based on approximations of the Higgs boson invariant mass and transverse momentum. These event properties bring the best separation power between the $\mathrm{b\bar{b}H}$ process and the backgrounds. In the $\mathrm{e}\tau_\mathrm{h}$, $\mu\tau_\mathrm{h}$, and $\tau_\mathrm{h}\tau_\mathrm{h}$ channels, a dedicated likelihood-based algorithm, SVFIT [49], is used to reconstruct the kinematical properties of the di-tau system based on the momentum of the individual tau leptons, their decay modes, and the $p_\mathrm{T}^\mathrm{miss}$. The resulting di-tau mass and momentum are labelled as $m_{\tau\tau}$ and $p_{\mathrm{T},\tau\tau}$. The kinematical properties of individual tau leptons are additionally used as separate input features in the $\tau_\mathrm{h}\tau_\mathrm{h}$ channel.

Other variables related to the di-tau system are the collinear di-tau mass (m_coll), the invariant mass of the visible tau decay product system (m_vis), and the pseudorapidity separation between the visible decay products of the tau leptons ($\Delta\eta_{\ell,\tau_\mathrm{h}}$). The collinear mass is reconstructed assuming that the neutrinos produced in tau lepton decays are collinear with the visible tau lepton decay products. It is defined as [50]:

$$m_\mathrm{coll} = \frac{m_\mathrm{vis}}{\sqrt{\frac{p_\mathrm{T}^{\ell}}{p_\mathrm{T}^{\ell}+p_\mathrm{T}^\mathrm{miss}} \frac{p_\mathrm{T}^{\tau_\mathrm{h}}}{p_\mathrm{T}^{\tau_\mathrm{h}}+p_\mathrm{T}^\mathrm{miss}}}}. \quad (2)$$

Both m_coll and $m_{\tau\tau}$ are insensitive to $\mathrm{H}\to\mathrm{WW}$ decays due to their different $p_\mathrm{T}^\mathrm{miss}$ distribution.

A similar assumption for the neutrino direction of flight underpins the introduction of the D_ζ variable. This is defined as the linear combination of the projection of the $p_\mathrm{T}^\mathrm{miss}$ along the bisector of the leptons or τ_h candidates ($\hat{\zeta}$) and the momentum of the dilepton (or lepton plus τ_h) system ($\vec{p}_\mathrm{T}^{\,\mathrm{tot}}$):

$$D_\zeta = p_\zeta^\mathrm{miss} - 0.85 p_\zeta^\mathrm{vis}, \quad (3)$$

with

$$p_\zeta^\mathrm{miss} = \vec{p}_\mathrm{T}^{\,\mathrm{miss}} \cdot \hat{\zeta} \text{ and } p_\zeta^\mathrm{vis} = \vec{p}_\mathrm{T}^{\,\mathrm{tot}} \cdot \hat{\zeta}. \quad (4)$$

The value of 0.85 was optimized to maximize the separation power between resonant $\tau_\mathrm{e}\tau_\mu$ decays from Higgs or Z bosons and the more isotropic neutrino emissions found in $\mathrm{t\bar{t}}$ or Higgs boson decays to W bosons [51].

The transverse mass (m_T), introduced in Eq. (1), is calculated using different objects, depending on the channel. In the $\mathrm{e}\tau_\mathrm{h}$ and $\mu\tau_\mathrm{h}$ channels, the transverse mass is computed from the charged lepton and the missing transverse momentum. The observable is used to reduce the background contribution from electroweak processes in these channels. In the $\mathrm{e}\mu$ channel, m_T is used to compute the total transverse mass of the electron, muon, and missing transverse momentum system:

$$m_\mathrm{T,tot} = \sqrt{m_\mathrm{T}(\mu,\mathrm{e})^2 + m_\mathrm{T}(\mathrm{e},p_\mathrm{T}^\mathrm{miss})^2 + m_\mathrm{T}(\mu,p_\mathrm{T}^\mathrm{miss})^2}, \quad (5)$$

with $p_\mathrm{T,tot}$ being the corresponding total transverse momentum. The two variables are used as estimators of the Higgs boson transverse mass and momentum for both the $\mathrm{H}\to\tau\tau$ and $\mathrm{H}\to\mathrm{WW}$ decays.

Other features that enter the BDT training relate to the reconstructed jets.

As discussed in the next sections, the limits on the $\mathrm{b\bar{b}H}$ production cross section are extracted from a combined fit of the distributions of the BDT scores across all categories. Fig. 2 shows these distributions for the $\mathrm{H}\to\tau\tau$ categories in the $\tau_\mathrm{h}\tau_\mathrm{h}$, $\mathrm{e}\tau_\mathrm{h}$, and $\mu\tau_\mathrm{h}$ channels, and for the $\mathrm{H}\to\mathrm{WW}$ category in the $\mathrm{e}\mu$ channel. The lower-BDT score regions are dominated by background processes, while the higher-score regions show an increasing contribution from the $\mathrm{b\bar{b}H}$ process.

8. Systematic uncertainties

The uncertainty model includes theoretical uncertainties, experimental uncertainties, and uncertainties due to the limited size of the simulated samples of events.

Theoretical uncertainties include those in the parameters used to compute the production cross section predictions. These are uncertainties in the chosen value of the strong coupling, the uncertainty coming from higher-order QCD and EW corrections, and effects due to the variation of the renormalization and factorization scales. Uncertainties from higher-order corrections to the $\mathrm{b\bar{b}H}$ production cross section lead to a normalization uncertainty ranging from −24% to 20% for the $\mathrm{b\bar{b}H}(y_\mathrm{b}^2)$ and $\mathrm{b\bar{b}H}(y_\mathrm{t}y_\mathrm{b})$ processes, and −6.7% to 4.6% for ggH production. An additional uncertainty ranging from −31% to 47% is introduced to cover theoretical uncertainties in the additional gluon splitting to $\mathrm{b\bar{b}}$ ($\mathrm{b\bar{b}H}(y_\mathrm{t}^2)$) [8,22].

The scale variation uncertainties not only affect the process normalization, but also the shapes of the distributions used for the statistical inference. These variations are computed by independently multiplying and dividing these scales by a factor of two with respect to their theoretical predictions, and re-evaluating the $\mathrm{b\bar{b}H}$ production cross section. Additional uncertainties are introduced to cover the scale variation effects on the parton shower.

Uncertainties that affect only the normalization of the distributions used for the statistical inference follow a log-normal probability density function, and are labelled 'lnN' in Table 3. Some of the most notable are:

- the uncertainty in the integrated luminosity measurement, partially correlated between the different data-taking periods. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have individual uncertainties ranging from 1.2 to 2.5% [52–54], while the overall uncertainty for the 2016–2018 period is 1.6%;
- the electron and muon identification efficiency uncertainties are estimated to be approximately 2%;
- the uncertainties in the misidentification rate of electrons and muons to τ_h depend on the $\tau_\mathrm{h}\,\eta$, and are estimated to be 7.5% and 6%, respectively;
- the production cross section uncertainties are estimated as 5% for the diboson and single top quark processes [55,56], 6% for $\mathrm{t\bar{t}}$ [57,58], 4% for the W + jets process [59], 2% for DY + jets [59,60], and 15% for $\mathrm{t\bar{t}V}$ + jets [61].

Uncertainties in the energy scale of objects such as jets, τ_h, and $p_\mathrm{T}^\mathrm{miss}$ alter the distributions of the input features to the BDT models, and as such modify the shape of the BDT score distribution. The jet energy is corrected based on sources such as the detector efficiency during data taking, pileup interactions, and the clustering efficiency. The corresponding uncertainties are divided into groups depending on whether they are correlated across data-taking years and channels, or uncorrelated. They are shown in Table 3 as *Jet ES* and *Jet energy resolution*, and their values depend primarily on the jet p_T. These corrections are propagated to the $p_\mathrm{T}^\mathrm{miss}$, in addition to those accounting for PF candidates that are not clustered within jets. The τ_h identification and energy scale depend on the τ_h candidate decay mode (DM) and p_T. Additional uncertainties cover the energy scales of prompt and misidentified electrons and muons, and the $p_\mathrm{T}^\mathrm{miss}$.

The estimation of background contributions originating from nonprompt or misidentified leptons and jets leads to additional uncertainties. The "ABCD" method for the $\mathrm{e}\mu$ channel and the F_F method for the $\tau_\mathrm{h}\tau_\mathrm{h}$, $\mathrm{e}\tau_\mathrm{h}$, and $\mu\tau_\mathrm{h}$ channels introduce shape-altering uncertainties pertaining to the statistical uncertainties in the samples used for the measurement of the extrapolation scale factors, the misidentification rate for jets as leptons or τ_h, and closure tests on observables used in the analysis. Nonclosure uncertainties, generally below 5–7% across the studied parameter space, cover the residual disagreement in the background modelling.

The shape correction for the b tagging classifier introduces shape-altering effects on the BDT score. Further uncertainties originate from

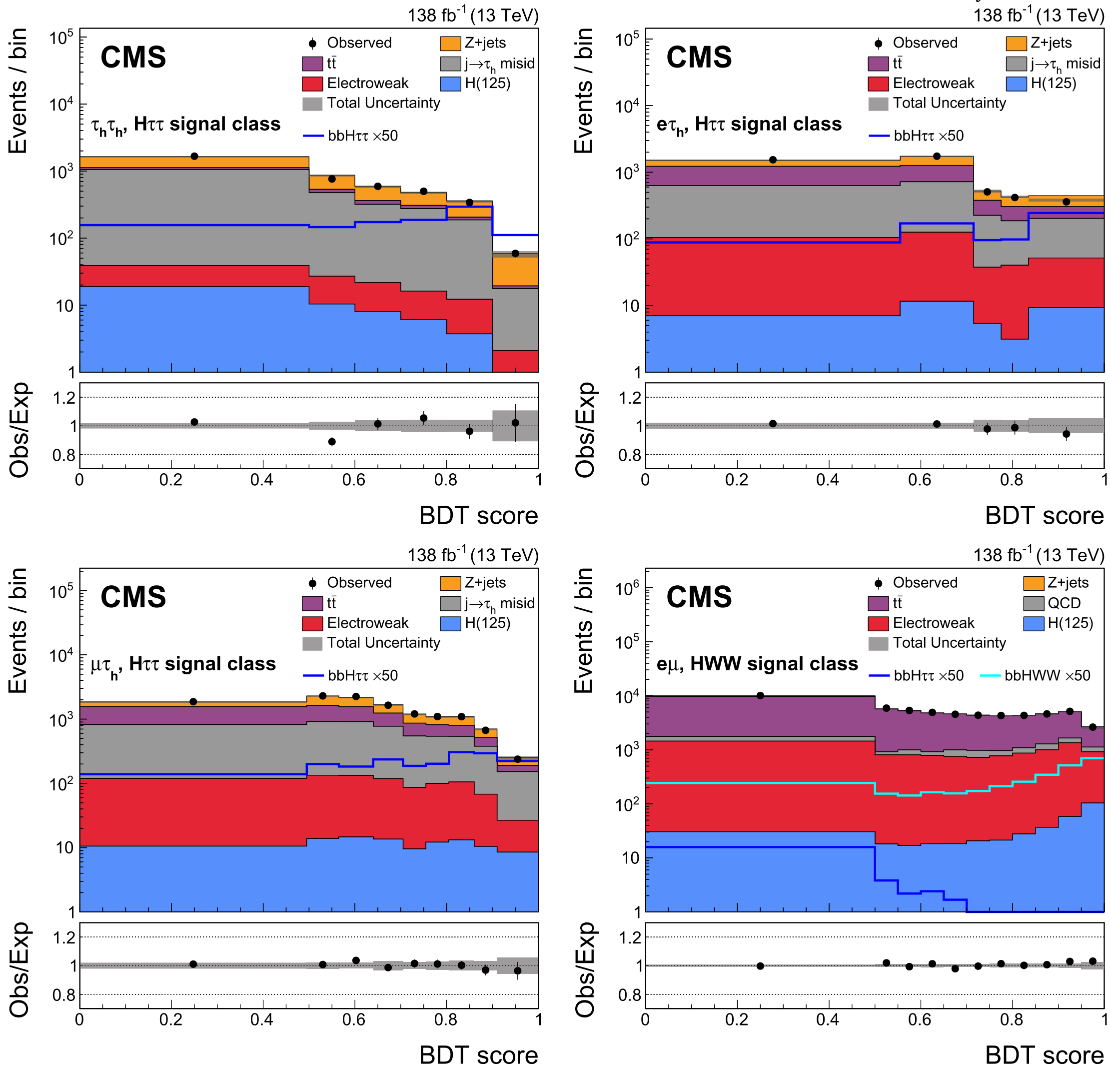

Fig. 2. The BDT H → ττ class output score distributions for the $\tau_h\tau_h$ (upper left), $e\tau_h$ (upper right), and $\mu\tau_h$ (lower left) channels; and the H → WW output score for the eμ channel (lower right). The bin widths in the different channels were optimized independently, considering the analysis sensitivity as well as the size of statistical uncertainties in the simulated templates. The $b\bar{b}$H signal is multiplied by a factor of 50, while all other processes are scaled according to a combined fit of all BDT categories for all channels and years used in this analysis. The total uncertainty includes the statistical and systematic uncertainties. Electroweak processes in the figure include diboson, W + jets, and single top quark production. For channels involving τ_h candidates, the j → τ_h misid contribution is estimated from data with the F_F method and grouped together. Simulated events with jets misidentified as τ_h candidates are removed from the electroweak, DY + jets, and $t\bar{t}$ groups. For the eμ channel, the QCD multijet process is estimated using the "ABCD" method. The H(125) group includes processes where a Higgs boson is produced not in association with b quarks, including the top quark associated production and Higgs-strahlung processes, since the b jets in these events originate from the top quark and vector boson decays.

the correction of the top quark and Z boson p_T spectra in the $t\bar{t}$ [62] and DY + jets processes, respectively. For both, the uncertainty is estimated as the size of the correction itself.

During the 2016 and 2017 data-taking periods, an increase in the offset of the ECAL timing pulse led the Level-1 trigger relying on ECAL to fire on the previous bunch crossing (prefiring). An uncertainty, negligible in some cases and ranging up to 4%, is introduced to account for this phenomenon.

Uncertainties accounting for the finite sizes of the simulated event samples, and the sideband regions used for the data-driven background estimates, are incorporated via the Barlow–Beeston "light" procedure [63,64].

9. Results

The statistical analysis is performed via a simultaneous binned maximum likelihood fit to the data in all BDT categories described in Section 7. The results were obtained using the CMS statistical analysis tool Combine [65].

Upper limits at the 95% confidence level (CL) are set, considering as signal the sum of the $b\bar{b}H(y_b^2)$ and $b\bar{b}H(y_t^2)$ contributions together with their interference term. These sum up to a total cross section of $\sigma_{\text{theory}} = 1.489$ pb. Limits are placed on the ratio between the measured cross section and its theoretical prediction:

$$\mu = \frac{\sigma(pp \to b\bar{b}H(y_b, y_t))}{\sigma_{\text{theory}}}, \tag{6}$$

which is referred to as the signal strength.

The upper limits are set using the modified frequentist CL_s criterion [66,67], with the profile likelihood ratio modified for upper limits [68] as the test statistic. The asymptotic approximation [69] is used in the limit setting procedure. To extract the two-dimensional constraints presented later in this section, we use the profile likelihood ratio from

Table 3
Summary table of the systematic uncertainties affecting the background processes. For uncertainties that vary significantly depending on the kinematic properties of the event, a range indicates the typical size of the uncertainty. The labels 'lnN' and 'shape' are used, respectively, for uncertainties affecting only the process normalization or having shape-altering effects.

Description	Value	Templates affected	Type
Luminosity	2016: 1.2%	MC	lnN
	2017: 2.3%		
	2018: 2.5%		
Production cross section	2%	DY	lnN
	6%	$t\bar{t}$	lnN
	4%	W + jets	lnN
	5%	VV	lnN
	5%	single top	lnN
	15%	$t\bar{t}$V + jets	lnN
	0.5–8%	H (except $b\bar{b}$H)	lnN
$H \to \tau\tau$ branching fraction	2.1%	$H \to \tau\tau$	lnN
$H \to WW$ branching fraction	1.5%	$H \to WW$	lnN
α_S variation	3.2%	$b\bar{b}$H	lnN
μ/e identification	2%.	MC	lnN
eμ trigger	1.5%	MC	lnN
Single μ/e trigger	p_T and η dep. (<1%)	MC	shape
τ_h trigger	p_T and DM dep. (<5%)	MC	shape
b tagging	1–9%	MC	shape
$\mu(e) \to \tau_h$ fake rate	η_{τ_h} dep. (1–7%)	MC with $\ell \to \tau_h$	shape
τ_h identification	p_T and DM dep. (2–3%)	MC	shape
τ_h energy scale	DM dep. (1%)	MC	shape
Jet energy scale	5–10%	MC	shape
Jet energy resolution	2–5%	MC	shape
p_T^{miss} unclustered energy scale	5–10%	MC	shape
Top quark p_T reweighting	<10%	$t\bar{t}$, single top	shape
Z boson p_T reweighting	<5%	DY	shape
QCD multijet unc.	10–15%	nonprompt ℓ	shape
F_F uncertainties	1–5%	$j \to \tau_h$ fakes	shape
Prefiring	0.5–1%	MC	lnN
Bin-by-bin stat. unc.	$\sqrt{N_{events}}$	All	shape

Ref. [68] as the test statistic. The 68% (95%) confidence intervals are constructed as the union of points for which the difference in twice the negative log-likelihood with respect to the minimum is below 2.28 (5.99). In all cases, the experimental and theoretical uncertainties are incorporated in the likelihood as nuisance parameters.

The 95% CL upper limits on the signal strength are shown in Fig. 3. These limits are obtained by coherently varying all contributions to the production cross section considered, namely those depending on Yukawa couplings to the bottom or top quark and their interference term. The combination of all channels yields an observed (expected) upper limit of 3.7 (6.1) at 95% CL.

Varying each contribution separately makes it possible to constrain the coupling structure of the Higgs boson. This is done by introducing the coupling scaling parameters κ_t and κ_b, which represent deviations from the SM expectation in the Higgs boson coupling strengths, and performing a likelihood ratio scan over the κ_t-κ_b parameter space. To account for the bottom quark contribution to the quark loop in the $b\bar{b}H(y_t^2)$ process, this contribution is scaled by $1.04\kappa_t^2 - 0.04\kappa_b\kappa_t + 0.002\kappa_b^2$ [8], while the $b\bar{b}H(y_b^2)$ contribution and the interference term are scaled by κ_b^2 and $\kappa_b\kappa_t$, respectively. To constrain the κ_t parameter, the results obtained in this analysis have been combined with the Higgs boson production cross section measurement in final states with two tau leptons [70] previously published by the CMS Collaboration. The published measurement required the absence of b-tagged jets, meaning that its limits on κ_b are entirely derived from the constraints on the Higgs boson decay width that are present in the coupling modifier model. The combination was performed at the level of the inputs for the statistical inference, because the presence of a b jet veto in Ref. [70] makes that measurement orthogonal to the search presented here.

The expected constraints in the κ_t-κ_b parameter space are shown in Fig. 4 for the previous CMS results in red, and in combination with the study presented in this Letter in green. A noticeable improvement in the constraint on the κ_b parameter, shown by the tightening of the 68% confidence interval contour, is observed in the combined limits. The constraints observed when fitting to the data are shown in blue, with the best fit point found at the coordinates $(\kappa_t, \kappa_b) = (-0.73, 1.58)$. The limits are compatible with the SM expectation at 95% CL. In this fit the κ_b and κ_t parameters are left freely floating, together with the coupling modifier for the tau leptons Yukawa coupling (κ_τ); the other coupling parameters are fixed to their SM values. This means some of the constraints on κ_b are indirect, from assumptions on the total Higgs boson decay width. The effects of these constraints can be observed in the red contours in Fig. 4, as the measurement of the $H \to \tau\tau$ production cross section from Ref. [70] did not include Higgs boson production processes involving the κ_b coupling, beyond its contribution to the quark loop in the ggH process.

Most of the considered processes are not sensitive to the sign of the Yukawa couplings, leading to a partial degeneracy with respect to the coupling sign. This is more noticeable for κ_b, since the degeneracy is only broken by the $b\bar{b}H(y_t y_b)$ interference term and the different flavour contributions to the quark loop in the ggH process. The observed limits on κ_t show a slight preference for negative values and are compatible with the SM prediction at 95% CL. The observed limits on κ_b exclude $\kappa_b = 0$ at 95% CL and are also compatible within 68% CL with

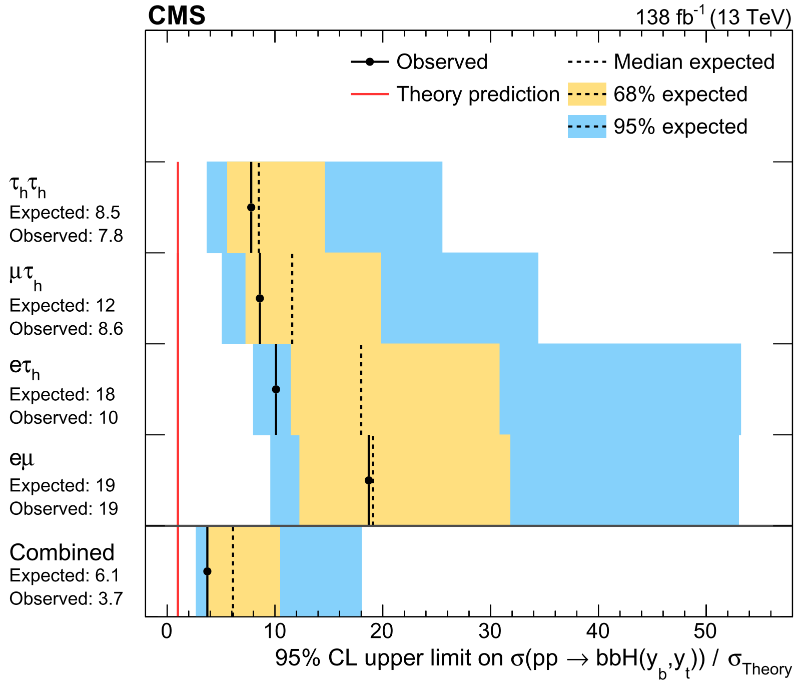

Fig. 3. Upper limits at the 95% CL on the signal strength for the pp → $b\bar{b}H(y_b, y_t)$ process. The terms in which the Higgs boson is produced via Yukawa couplings with top or bottom quarks contribute to the estimated relative production cross sections. The interference term between these contributions is also accounted for. The pp → $Z(\rightarrow b\bar{b})H$ process is treated as a background in this search. The theoretical prediction, shown as a red line placed at 1, corresponds to the estimated production cross section of 1.489 pb. The black markers show the observed limits, and the dashed lines with the yellow and blue uncertainty bands represent the expected upper limits with their 68% and 95% central intervals.

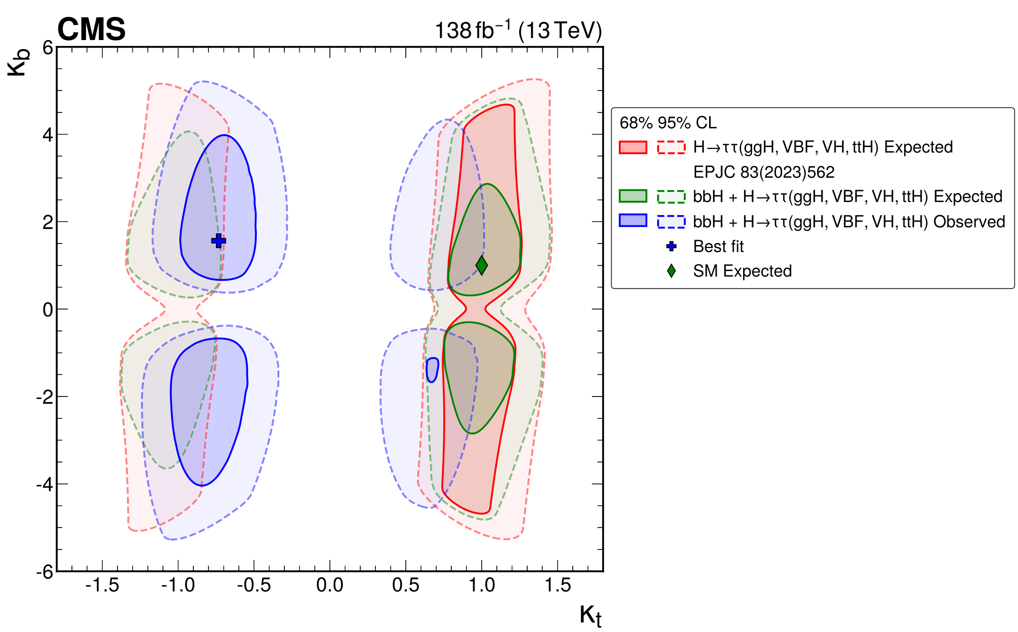

Fig. 4. Two-dimensional confidence intervals on the κ_b and κ_t parameters for the channels studied in this search. Expected limits are shown in red for the H → ττ cross section measurement [70] performed for other Higgs boson production mechanisms and in green for the combination with the analysis presented in this Letter. The observed constraints are shown in blue, with a cross marking the best fit point. A green diamond is placed to mark the SM expectation. Solid lines with shaded areas mark the 68% confidence interval contours, and dashed lines mark the 95% confidence interval.

those measured in a combined fit of Higgs boson production and decay channels, including H → $b\bar{b}$, performed by the CMS Collaboration with data collected in Run 2 [7]. At present, the uncertainty in the κ_b measurement is around 7 times larger than the established constraints provided by the analysis of Higgs boson decays.

10. Summary

A search for the 125 GeV Higgs boson produced in association with bottom quarks and decaying into a pair of tau leptons or W bosons has been presented. The search was performed on data collected by the

CMS experiment in the period 2016–2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1}. This search was performed in four final states: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, and $e\mu$. Higgs boson decays to tau leptons were targeted in all four final states, while $H \to WW$ decays contributed only in the $e\mu$ channel as a result of the kinematical similarities between the two decay processes. At the current level of precision, the background processes provide an adequate description of the observed data, and no significant excess above the background-only expectation was found. The observed (expected) upper limit at the 95% confidence level (CL) on the joint bH and $b\bar{b}H$ production cross section is 3.7 (6.1) times the standard model prediction. The search also constrained the Higgs Yukawa couplings to bottom and top quarks in the κ-model interpretation. The best fit value for the coupling modifiers was found to be $(\kappa_t, \kappa_b) = (-0.73, 1.58)$. The observed constraints are compatible with the standard model expectation at the 95% CL.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

References

[1] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, https://doi.org/10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, https://doi.org/10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[3] CMS Collaboration, Observation of a new boson with mass near 125 GeV in *pp* collisions at $\sqrt{s}$ = 7 and 8 TeV, J. High Energy Phys. 06 (2013) 081, https://doi.org/10.1007/JHEP06(2013)081, arXiv:1303.4571.

[4] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider, J. Instrum. 3 (2008) S08003, https://doi.org/10.1088/1748-0221/3/08/S08003.

[5] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[6] ATLAS Collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, Nature 607 (2022) 52, https://doi.org/10.1038/s41586-022-04893-w, arXiv:2207.00092.

[7] CMS Collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery, Nature 607 (2022) 60, https://doi.org/10.1038/s41586-022-04892-x, arXiv:2207.00043.

[8] LHC Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, vol. 2/2017, CERN, 2016, arXiv:1610.07922.

[9] S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, Exclusive Higgs boson production with bottom quarks at hadron colliders, Phys. Rev. D 69 (2004), https://doi.org/10.1103/physrevd.69.074027.

[10] S. Dittmaier, M. Krämer, M. Spira, Higgs radiation off bottom quarks at the Fermilab Tevatron and the CERN LHC, Phys. Rev. D 70 (2004), https://doi.org/10.1103/physrevd.70.074010.

[11] R.V. Harlander, W.B. Kilgore, Higgs boson production in bottom quark fusion at next-to-next-to-leading order, Phys. Rev. D 68 (2003), https://doi.org/10.1103/physrevd.68.013001.

[12] S. Forte, D. Napoletano, M. Ubiali, Higgs production in bottom-quark fusion in a matched scheme, Phys. Lett. B 751 (2015) 331, https://doi.org/10.1016/j.physletb.2015.10.051.

[13] S. Forte, D. Napoletano, M. Ubiali, Higgs production in bottom-quark fusion: matching beyond leading order, Phys. Lett. B 763 (2016) 190, https://doi.org/10.1016/j.physletb.2016.10.040.

[14] M. Bonvini, A.S. Papanastasiou, F.J. Tackmann, Resummation and matching of b-quark mass effects in $b\bar{b}H$ production, J. High Energy Phys. 11 (2015) 196, https://doi.org/10.1007/JHEP11(2015)196, arXiv:1508.03288.

[15] M. Bonvini, A.S. Papanastasiou, F.J. Tackmann, Matched predictions for the $b\bar{b}H$ cross section at the 13 TeV LHC, J. High Energy Phys. 10 (2016) 053, https://doi.org/10.1007/JHEP10(2016)053, arXiv:1605.01733.

[16] ATLAS Collaboration, Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector, Phys. Lett. B 784 (2018) 173, https://doi.org/10.1016/j.physletb.2018.07.035, arXiv:1806.00425.

[17] CMS Collaboration, Observation of $\mathrm{t\bar{t}H}$ production, Phys. Rev. Lett. 120 (2018) 231801, https://doi.org/10.1103/PhysRevLett.120.231801, arXiv:1804.02610.

[18] D. Pagani, H.-S. Shao, M. Zaro, RIP $Hb\bar{b}$: how other Higgs production modes conspire to kill a rare signal at the LHC, J. High Energy Phys. 11 (2020) 036, https://doi.org/10.1007/JHEP11(2020)036, arXiv:2005.10277.

[19] CMS Collaboration, Search for additional neutral MSSM Higgs bosons in the $\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 09 (2018) 007, https://doi.org/10.1007/JHEP09(2018)007, arXiv:1803.06553.

[20] CMS Collaboration, Searches for additional Higgs bosons and for vector leptoquarks in $\tau\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2023) 073, https://doi.org/10.1007/JHEP07(2023)073, arXiv:2208.02717.

[21] HEPData record for this analysis, https://doi.org/10.17182/hepdata.153508, 2024.

[22] N. Deutschmann, F. Maltoni, M. Wiesemann, M. Zaro, Top-Yukawa contributions to bbH production at the LHC, J. High Energy Phys. 07 (2019) 054, https://doi.org/10.1007/JHEP07(2019)054, arXiv:1808.01660.

[23] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P10017, https://doi.org/10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[24] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[25] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. 16 (2021) P05014, https://doi.org/10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.

[26] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P06015, https://doi.org/10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[27] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, https://doi.org/10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[28] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[29] CMS Collaboration, Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P10005, https://doi.org/10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.

[30] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[31] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, J. Instrum. 14 (2019) P07004, https://doi.org/10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.

[32] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.

[33] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, https://doi.org/10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[34] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, https://doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.

[35] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, https://doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[36] R.D. Ball, V. Bertone, S. Carrazza, L.D. Debbio, S. Forte, P. Groth-Merrild, A. Guffanti, N.P. Hartland, Z. Kassabov, J.I. Latorre, E.R. Nocera, J. Rojo, L. Rottoli, E. Slade, M. Ubiali, NNPDF, Parton distributions from high-precision collider data, Eur. Phys. J. C 77 (2017) 663, https://doi.org/10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.

[37] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[38] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, Eur. Phys. J. C 80 (2020) 4, https://doi.org/10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[39] S. Agostinelli, et al., GEANT4, Geant4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.

[40] R. Frederix, S. Frixione, Merging meets matching in MC@NLO, J. High Energy Phys. 12 (2012) 061, https://doi.org/10.1007/JHEP12(2012)061, arXiv:1209.6215.

[41] E. Bols, J. Kieseler, M. Verzetti, M. Stoye, A. Stakia, Jet flavour classification using DeepJet, J. Instrum. 15 (2020) P12012, https://doi.org/10.1088/1748-0221/15/12/p12012.

[42] CMS Collaboration, Identification of hadronic tau lepton decays using a deep neural network, J. Instrum. 17 (2022) P07023, https://doi.org/10.1088/1748-0221/17/07/P07023, arXiv:2201.08458.

[43] CMS Collaboration, Measurement of the $Z/\gamma^* \to \tau\tau$ cross section in pp collisions at $\sqrt{s} = 13$ TeV and validation of τ lepton analysis techniques, Eur. Phys. J. C 78 (2018) 708, https://doi.org/10.1140/epjc/s10052-018-6146-9, arXiv:1801.03535.

[44] F. Abe, et al., CDF, A measurement of the ratio $\sigma \times B(p\bar{p} \to W \to e\nu)/\sigma \times B(p\bar{p} \to Z^0 \to ee)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV, Phys. Rev. D 52 (1995) 2624, https://doi.org/10.1103/PhysRevD.52.2624.

[45] CMS Collaboration, Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector, Phys. Lett. B 779 (2018) 283, https://doi.org/10.1016/j.physletb.2018.02.004, arXiv:1708.00373.

[46] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, J. Instrum. 15 (2020) P09018, https://doi.org/10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.

[47] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, J. Instrum. 13 (2018) P05011, https://doi.org/10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

[48] CMS Collaboration, Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 81 (2021) 378, https://doi.org/10.1140/epjc/s10052-021-09014-x, arXiv:2011.03652.

[49] L. Bianchini, J. Conway, E.K. Friis, C. Veelken, Reconstruction of the Higgs mass in $H \to \tau\tau$ events by dynamical likelihood techniques, J. Phys. Conf. Ser. 513 (2014) 022035, https://doi.org/10.1088/1742-6596/513/2/022035.

[50] A. Elagin, P. Murat, A. Pranko, A. Safonov, A new mass reconstruction technique for resonances decaying to di-tau, Nucl. Instrum. Methods Phys. Res., Sect. A 654 (2011) 481, https://doi.org/10.1016/j.nima.2011.07.009, arXiv:1012.4686.

[51] A. Abulencia, et al., CDF, Search for neutral MSSM Higgs bosons decaying to tau pairs in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 96 (2006) 011802, https://doi.org/10.1103/PhysRevLett.96.011802, arXiv:hep-ex/0508051.

[52] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, Eur. Phys. J. C 81 (2021) 800, https://doi.org/10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[53] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-17-004 2018, https://cds.cern.ch/record/2621960/.

[54] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019, https://cds.cern.ch/record/2676164/.

[55] J.M. Campbell, R.K. Ellis, C. Williams, Vector boson pair production at the LHC, J. High Energy Phys. 07 (2011) 018, https://doi.org/10.1007/JHEP07(2011)018, arXiv:1105.0020.

[56] T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, W^+W^- production at hadron colliders in next to next to leading order QCD, Phys. Rev. Lett. 113 (2014) 212001, https://doi.org/10.1103/PhysRevLett.113.212001, arXiv:1408.5243.

[57] M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders, Comput. Phys. Commun. 185 (2014) 2930, https://doi.org/10.1016/j.cpc.2014.06.021, arXiv:1112.5675.

[58] N. Kidonakis, Top quark production, in: Helmholtz International Summer School on Physics of Heavy Quarks and Hadrons, 2014, p. 139, arXiv:1311.0283.

[59] K. Melnikov, F. Petriello, Electroweak gauge boson production at hadron colliders through $O(\alpha_s^2)$, Phys. Rev. D 74 (2006) 114017, https://doi.org/10.1103/PhysRevD.74.114017, arXiv:hep-ph/0609070.

[60] R. Gavin, Y. Li, F. Petriello, S. Quackenbush, FEWZ 2.0: a code for hadronic z production at next-to-next-to-leading order, Comput. Phys. Commun. 182 (2011) 2388, https://doi.org/10.1016/j.cpc.2011.06.008.

[61] CMS Collaboration, Measurement of the cross section for top quark pair production in association with a W or Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 08 (2018) 011, https://doi.org/10.1007/JHEP08(2018)011, arXiv:1711.02547.

[62] CMS Collaboration, Differential cross section measurements for the production of top quark pairs and of additional jets using dilepton events from pp collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. (2024), http://cds.cern.ch/record/2889176, arXiv:2402.08486, submitted for publication.

[63] R.J. Barlow, C. Beeston, Fitting using finite Monte Carlo samples, Comput. Phys. Commun. 77 (1993) 219, https://doi.org/10.1016/0010-4655(93)90005-W.

[64] J.S. Conway, Incorporating nuisance parameters in likelihoods for multisource spectra, in: PHYSTAT 2011, 2011, p. 115, arXiv:1103.0354.

[65] CMS Collaboration, The CMS statistical analysis and combination tool: COMBINE, Comput. Softw. Big Sci. 8 (2024) 19, https://doi.org/10.1007/s41781-024-00121-4, arXiv:2404.06614.

[66] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods Phys. Res., Sect. A 434 (1999) 435, https://doi.org/10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
[67] A.L. Read, Presentation of search results: the CL_s technique, J. Phys. G 28 (2002) 2693, https://doi.org/10.1088/0954-3899/28/10/313.
[68] The ATLAS Collaboration, The CMS Collaboration, The LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in Summer 2011, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011, https://cds.cern.ch/record/1379837.
[69] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71 (2011) 1554, https://doi.org/10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727, Erratum: https://doi.org/10.1140/epjc/s10052-013-2501-z.
[70] CMS Collaboration, Measurements of Higgs boson production in the decay channel with a pair of τ leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 83 (2023) 562, https://doi.org/10.1140/epjc/s10052-023-11452-8, arXiv:2204.12957.

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