Search for Heavy Higgs Bosons $A/H$ Decaying to a Top Quark Pair in $pp$ Collisions at $\sqrt{s}$ = 8 TeV with the ATLAS Detector

M. Aaboud et al.*
(ATLAS Collaboration)
(Received 20 July 2017; published 9 November 2017)

A search for heavy pseudoscalar ($A$) and scalar ($H$) Higgs bosons decaying into a top quark pair ($t\bar{t}$) has been performed with 20.3 fb$^{-1}$ of proton-proton collision data collected by the ATLAS experiment at the Large Hadron Collider at a center-of-mass energy $\sqrt{s}$ = 8 TeV. Interference effects between the signal process and standard model $t\bar{t}$ production, which are expected to distort the signal shape from a single peak to a peak-dip structure, are taken into account. No significant deviation from the standard model prediction is observed in the $t\bar{t}$ invariant mass spectrum in final states with an electron or muon, large missing transverse momentum, and at least four jets. The results are interpreted within the context of a type-II two-Higgs-doublet model. Exclusion limits on the signal strength are derived as a function of the mass $m_{A/H}$ and the ratio of the vacuum expectation values of the two Higgs fields, $\tan\beta$, for $m_{A/H} > 500$ GeV.

DOI: 10.1103/PhysRevLett.119.191803

Introduction.—The production of new particles at the Large Hadron Collider (LHC) with masses close to the TeV scale is predicted by many models of physics beyond the standard model (SM). In this Letter, a search for massive pseudoscalar and scalar resonances decaying into a top-antitop quark pair ($t\bar{t}$) is presented. It is the first search in this final state to take into account the significant interference between the signal and the background from SM $t\bar{t}$ production. The search is conducted on a sample of $pp$ collision data with an integrated luminosity of 20.3 fb$^{-1}$ at a center-of-mass energy $\sqrt{s}$ = 8 TeV, collected with the ATLAS detector [1].

New pseudoscalar ($A$) and scalar ($H$) states coupling strongly to $t\bar{t}$ are predicted by a class of models in which the Higgs sector is extended to include a second Higgs doublet, the two-Higgs-doublet models (2HDMs) [2]. These models are motivated by many theories beyond the SM, such as supersymmetry [3–8] and axion models [9]. In 2HDMs of type II [2], such as the minimal supersymmetric standard model (MSSM) [10–14], these states decay predominantly into $t\bar{t}$ pairs if $m_{A/H} \geq 500$ GeV and the ratio of the vacuum expectation values of the two Higgs fields, $\tan\beta$, is small ($\tan\beta \lesssim 3$).

To date, this parameter region has not been probed directly by searches in other final states [15–20] or by previous searches for $t\bar{t}$ resonances [21–25]. The latter, which aim to identify resonant excesses in the $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) spectrum, have a reduced sensitivity to 2HDM signatures as they do not take into account interference effects between the signal and the dominant background from SM $t\bar{t}$ production. These are significant for (pseudo) scalar Higgs bosons with masses above the $t\bar{t}$ production threshold where the interference between the gluon-gluon ($gg$) initiated loop production and the irreducible background from SM $t\bar{t}$ production yields a non-negligible imaginary term in the amplitude, which at the LHC is dominated by $gg \rightarrow t\bar{t}$ production [26–31]. As a result of the interference, the signal shape is distorted from a Breit-Wigner peak to a peak-dip structure.

The results of the search are interpreted in a $CP$-conserving type-II 2HDM with a softly broken $Z_2$ symmetry [32]. The lighter of the two neutral $CP$-even states, $h$, is assumed to be the Higgs boson discovered at a mass of $m_h = 125$ GeV [33,34] with couplings as predicted by the SM. This corresponds to the condition $\sin(\alpha - \beta) = 1$, referred to as the alignment limit, where $\alpha$ denotes the mixing angle between the two $CP$-even states. The parameter $m_{12}$ of the $Z_2$ breaking term of the potential is taken to be $m^2_{12} = m_A^2 \tan\beta / (1 + \tan^2\beta)$. In this model, the production cross sections and widths of $A$ and $H$, as well as the signal shape, are determined by $\tan\beta$ and the masses $m_A$ and $m_H$. The search results are derived assuming mass degeneracy, $m_H = m_A$, such that both processes contribute to the $m_{t\bar{t}}$ spectrum, a scenario motivated, for example, by the MSSM [32]. We also consider two scenarios in which only the interference pattern of either $A$ or $H$ appears in the $m_{t\bar{t}}$ spectrum [35].

Data and Monte Carlo samples.—This analysis closely follows the resolved-topology analysis in Ref. [22]. Events with signatures compatible with $t\bar{t} \rightarrow W^+bW^−\bar{b}$, with one...
W boson decaying hadronically and the other leptonically, the lepton-plus-jets channel ($\ell^+ + jets$, $\ell = e, \mu$), were collected using single-electron and single-muon triggers. The trigger efficiency is constant in the transverse momentum ($p_T$) of leptons with $p_T > 25$ GeV [36,37]. The dominant background arises from SM $t\bar{t}$ production, followed by a contribution from $W +$ jets processes. Data-driven techniques were used to normalize the $W +$ jets background contribution and to estimate the background from multijet events. All other background processes were estimated using Monte Carlo (MC) simulation. The background estimates for all processes are identical to those in Ref. [22].

The signal process $gg \rightarrow AH \rightarrow t\bar{t}$, including the decays of the top quarks and resulting $W$ bosons, was simulated using MadGraph5_aMC@NLO [38] v2.3.3 with the model of Ref. [39], which implements the $A/H$ production through loop-induced gluon-gluon fusion with loop contributions from top and bottom quarks at leading order (LO) in QCD. The CT10 set [40] of parton distribution functions (PDFs) was used and the renormalization and factorization scales were set to $\sqrt{\sum_\text{decay products} (p_T^2 + m^2)}$.

For the statistical interpretation, the $t\bar{t}$ invariant mass distributions in the signal regions in data were compared to a combination of the expected distributions from all background processes $B$, the pure signal process $S$, and the signal-plus-interference component $S + I$ for a given signal hypothesis, as illustrated in Eq. (1) below. The most reliable description of the $t\bar{t}$ background [41] is obtained at next-to-leading order (NLO) with POWHEG-BOX [42–45] + PYTHIA6[46]. Therefore, the $S + I$ contribution was modeled separately from this background process by modifying the MadGraph5_aMC@NLO software to remove the pure SM $t\bar{t}$ process to yield only the $S + I$ contribution on an event-by-event basis. The nominal $t\bar{t}$ background prediction in $m_{t\bar{t}}$ is in good agreement with that obtained from MadGraph5_aMC@NLO in all signal regions. The $S + I$ events obtained with the modified software can have positive or negative weights. Figure 1 shows the $t\bar{t}$ invariant mass distributions for the $S$ and $S + I$ components in a model with $\tan \beta = 0.68$ and a pseudoscalar of mass $m_A = 500$ GeV. The $S + I$ component exhibits a peak-dip structure with the minimum around $m_{A/H} < 500$ GeV before the emission of final-state radiation and before the parton shower for the pure resonance $S$ (filled) and signal + interference contribution $S + I$ (unfilled). Events from all $t\bar{t}$ decay modes are included.

![Figure 1](https://example.com/figure1.png)

**FIG. 1.** Distributions of the invariant mass of the $t\bar{t}$ pair from the decay of a pseudoscalar $A$ of mass $m_A = 500$ GeV before the emission of final-state radiation and before the parton shower for the pure resonance $S$ (filled) and signal + interference contribution $S + I$ (unfilled). Events from all $t\bar{t}$ decay modes are included.

That obtained with the modified software within 0.4% across the whole spectrum. The difference is taken as a systematic uncertainty in $S + I$.

Pythia6 with the Perugia 2011c set of tuned parameters [47] was used to model the parton shower and hadronization for all $S$ and $S + I$ samples and the stable particles obtained after hadronization were passed through the ATLAS fast detector simulation [48]. The effects of additional collisions within the same or nearby bunch crossings were simulated by overlaying additional $pp$ collisions, simulated with PYTHIA V8.1 [49], on each event. Correction factors were applied to adjust the trigger and selection efficiencies in simulated events to those measured in data. The $S$ and $S + I$ samples with this setup were generated separately for pseudoscalar and scalar Higgs bosons.

Event samples for both the $S$ and $S + I$ components for different values of $(m_{A/H}, \tan \beta)$ were obtained from signal samples $S$ after the detector simulation by applying an event-by-event reweighting. This reweighting substantially reduces the computing time required. The weight is the ratio of the MadGraph5_aMC@NLO matrix elements, calculated from the four-momenta of the incoming gluons and outgoing top quarks of the generated event with the new and the old values of $(m_{A/H}, \tan \beta)$, respectively. All $S + I$ and a small number of $S$ samples were obtained through reweighting. Signal hypotheses with $m_{A/H} < 500$ GeV were not considered as they require an accurate modeling of the Higgs boson decay into virtual top quarks and the implementation of higher-order corrections that are not available in the MadGraph5_aMC@NLO model. The requirement $\tan \beta \geq 0.4$ was imposed to ensure the perturbativity of the top-quark Yukawa coupling [2].

Correction factors $K_S$ were applied to normalize the generated signal ($S$) cross section to the value calculated at partial next-to-next-to-leading-order (NNLO) precision in
QCD [50–52]. The correction factor for the interference component \( I \) is \( K_I = \sqrt{K_S \times K_R} \), as suggested in Ref. [53], where \( K_R = 1.87 \) is the correction factor to normalize the total cross section of the SM \( t \bar{t} \) background generated at LO with MadGraph to the cross section calculated at NNLO accuracy in the strong coupling constant \( \alpha_s \), including resummation of next-to-next-to-leading-logarithmic soft gluon terms. The values of \( K_S \) range between two and three for the tested signal hypotheses.

**Event selection.**—The event selection criteria for the signal regions provide a high selection efficiency for \( t \bar{t} \) events. Only events with a resolved topology, in which the three jets from the hadronically decaying top quark are well separated in the detector, are selected. This is the most efficient selection strategy for signal hypotheses with \( m_{A/H} < 800 \) GeV. Events with a merged topology, in which the top quark is reconstructed as a single jet, are not considered. The event reconstruction and selection criteria are identical to those in Ref. [22] except that events that would satisfy the criteria for both topologies are classified as “resolved” instead of “merged.”

Events are required to contain exactly one isolated electron [54] or muon [55] with \( p_T > 25 \) GeV and pseudorapidity \(|\eta| < 2.5\) [56]. Events must have large missing transverse momentum, \( E_T^{\text{miss}} > 20 \) GeV, computed as the magnitude of the negative vector sum of lepton and jet transverse momenta [57]. In addition, \( E_T^{\text{miss}} + m_W > 60 \) GeV is required to further suppress the contribution from multijet events, where \( m_W \) is the lepton–\( E_T^{\text{miss}} \) transverse mass [22]. Events must contain at least four hadronic jets with \( p_T > 25 \) GeV and \(|\eta| < 2.5\), reconstructed using the anti-\( k_T \) algorithm [58,59] with radius parameter \( R = 0.4 \). Jets from additional collisions in the same bunch crossing are rejected using dedicated tracking and vertex requirements [60]. At least one of the jets must be identified as originating from the decay of a \( b \)-hadron (\( b \)-jet) using a multivariate tagging algorithm with a 70% efficiency for \( b \)-jets and light-quark and gluon mistag rates of 0.5%–2% [61].

**Event reconstruction.**—Jets are assigned to the top quarks using a \( \chi^2 \) algorithm that relies on kinematic constraints and the expected values of the top quark and \( W \) boson masses [22]. The invariant mass \( m_{\tilde{t}\tilde{t}}^{\text{reco}} \) of the candidate \( t \bar{t} \) pair is reconstructed from the four selected jets, the lepton, and the \( E_T^{\text{miss}} \) vector. The experimental resolution for the \( \tilde{t}\tilde{t} \) invariant mass is 8% for \( m_{A/H} = 500 \) GeV. Events in the \( e + \text{jets} \) and \( \mu + \text{jets} \) channels are classified into three categories, based on whether a \( b \)-tagged jet was assigned to either the hadronically or the semileptonically decaying top quark, or to both of them. Each category defines a signal region; hence six orthogonal signal regions are used in the statistical analysis.

**Systematic uncertainties.**—The impact of the systematic uncertainties on both the normalization and the shape of the \( m_{\tilde{t}\tilde{t}}^{\text{reco}} \) distributions is taken into account. The average impact of the dominant uncertainties on the event yields is summarized in Table I.

The experimental uncertainties with the largest impact on the event yields and the shape of the \( m_{\tilde{t}\tilde{t}}^{\text{reco}} \) distributions are those related to the jet energy scale (JES) and the jet energy resolution (JER) [63,64], followed by uncertainties on the \( b \)-tagging efficiency and misidentification rates [61]. The uncertainties related to leptons include those in the reconstruction and isolation efficiency, the single-lepton triggers, and the energy scale and resolution [54,55].

The uncertainty of 6.5% in the NNLO + NNLL cross section for SM \( t \bar{t} \) production is the dominant uncertainty in the total background normalization [22]. Modeling uncertainties affecting the shape of the \( m_{\tilde{t}\tilde{t}}^{\text{reco}} \) distribution for the SM \( t \bar{t} \) background are also taken into account. These uncertainties affect the data in the same way as in the signal analysis. The uncertainties on the total background normalization and the shape of the \( m_{\tilde{t}\tilde{t}}^{\text{reco}} \) distributions are summarized in Table II.

**Table I.** Average impact of the dominant uncertainties on the estimated yields for the total background and for a pseudoscalar \( A \) with \( m_A = 500 \) GeV and \( \tan \beta = 0.68 \) in percent of the nominal value for all signal regions combined. Only uncertainties with a yield impact > 0.5% are shown. Dots (⋯) indicate that an uncertainty is not applicable to a sample.

<table>
<thead>
<tr>
<th>Systematic uncertainties [%]</th>
<th>Total background</th>
<th>( S )</th>
<th>( S + I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [62]</td>
<td>1.7</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>PDF</td>
<td>2.5</td>
<td>2.1</td>
<td>12</td>
</tr>
<tr>
<td>( t\bar{t} ) initial-final-state radiation</td>
<td>3.2</td>
<td>⋯⋯</td>
<td>⋯⋯</td>
</tr>
<tr>
<td>( t\bar{t} ) parton shower + fragmentation</td>
<td>4.9</td>
<td>⋯⋯</td>
<td>⋯⋯</td>
</tr>
<tr>
<td>( t\bar{t} ) normalization</td>
<td>5.7</td>
<td>⋯⋯</td>
<td>⋯⋯</td>
</tr>
<tr>
<td>( t\bar{t} ) event generator</td>
<td>0.5</td>
<td>⋯⋯</td>
<td>⋯⋯</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>0.5</td>
<td>2.2</td>
<td>13</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>6.4</td>
<td>4.9</td>
<td>9.3</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>1.3</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>( b )-tagging: ( b )-jet efficiency</td>
<td>1.5</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>( b )-tagging: c-jet efficiency</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>0.3</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Signal MC scales</td>
<td>⋯⋯</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Reweighting</td>
<td>⋯⋯</td>
<td>5.0</td>
<td>⋯⋯</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>0.5</td>
<td>2.4</td>
<td>11</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>11</td>
<td>10</td>
<td>25</td>
</tr>
</tbody>
</table>

**Table II.** Number of events observed in data and expected number of background events after the event selection, before the profile-likelihood fit to the full data set. The uncertainty in the background yields is derived by summing all uncertainties in quadrature. The "other bkg." component comprises single top quark, \( t\bar{t} + W/Z, Z + \text{jets}, \) diboson, and multijet production.

<table>
<thead>
<tr>
<th>Type</th>
<th>( e + \text{jets} )</th>
<th>( \mu + \text{jets} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>95 000 ± 11 000</td>
<td>93 000 ± 11 000</td>
</tr>
<tr>
<td>( W + \text{jets} )</td>
<td>6600 ± 2100</td>
<td>7200 ± 2300</td>
</tr>
<tr>
<td>Other bkg.</td>
<td>11 200 ± 1400</td>
<td>6100 ± 600</td>
</tr>
<tr>
<td>Total</td>
<td>112 800 ± 13 000</td>
<td>106 300 ± 12 000</td>
</tr>
<tr>
<td>Data</td>
<td>115 785</td>
<td>110 218</td>
</tr>
</tbody>
</table>
include uncertainties related to the choice of NLO event generator, the modeling of the parton shower and fragmentation, the modeling of gluon initial- and final-state radiation, and the value of the top quark mass \( m_t \). Other sources of uncertainty related to the various background components are described in Ref. [22].

The largest uncertainty in the modeling of the \( S+I \) and \( S \) components is related to the ±1.0 GeV uncertainty of the value \( m_t = 172.5 \) GeV [65]. Uncertainties related to the choice of PDF set and renormalization and factorization scales are also considered. The latter is estimated by varying the scales by factors of 0.5 and 2.0, which yields a constant \( \pm 7.3\% \) variation across the \( m_{t\text{reco}} \) spectrum. An asymmetric variation, for which the bins at the low and high ends of the \( m_{t\text{reco}} \) spectrum are taken as anticorrelated [66] is also considered to estimate the impact of the scale variations on the shape of the \( m_{t\text{reco}} \) spectrum. For the

\[ S+I \] samples, an additional constant \( \pm 5\% \) uncertainty is included to cover the difference between reweighted and generated distributions.

**Results.**—A breakdown of the observed and expected event yields in the \( e+jets \) and \( \mu+jets \) channels and their total uncertainties is shown in Table II. Good agreement is found between the observed number of events in data and the expected total number of background events.

The exclusion limits are derived separately for each signal hypothesis from a profile-likelihood fit [67] of the expected \( m_{t\text{reco}} \) distributions to the observed ones simultaneously in all signal regions, taking the statistical and systematic uncertainties into account as nuisance parameters [22]. Only bins with \( m_{t\text{reco}} > 320 \) GeV are considered to avoid threshold effects not well described by the simulation. The shape of the binned \( m_{t\text{reco}} \) distributions is parametrized in terms of the signal strength \( \mu \) [26,27]:

\[
\mu S + \sqrt{\mu}I + B = (\mu - \sqrt{\mu})S + \sqrt{\mu}(S + I) + B. \tag{1}
\]

The fitted variable is \( \sqrt{\mu} \) and the case \( \mu = 1 \ (\mu = 0) \) corresponds to the type-II 2HDM in the alignment limit (the background-only hypothesis). This approach relies on the assumption that, for a given signal hypothesis, the shape of the \( t\bar{t} \) invariant mass distributions for \( S \) and \( S+I \) in Eq. (1) does not change with \( \mu \). The terms \( S \) and \( S+I \) on the right-hand side of Eq. (1) correspond to the \( m_{t\text{reco}} \) distributions obtained from the \( S \) and \( S+I \) samples, respectively, while \( B \) stands for the expected \( m_{t\text{reco}} \) distribution of the total background.

The level of agreement between the observed and expected mass spectra is quantified in a fit under the background-only hypothesis in which only the nuisance parameters are allowed to vary. The observed \( m_{t\text{reco}} \) spectra are compatible with the postfit expected spectra within the (constrained) uncertainty bands (Fig. 2).

The upper limits on \( \mu \) at 95% confidence level (C.L.) are obtained with the C.L.s method [68] for a number of \( \langle m_A / m_t, \tan \beta \rangle \) values. The upper limits at intermediate points are obtained from a linear interpolation among

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}, \text{all limits at 95\% C.L.} \]

FIG. 2. Distribution of \( m_{t\text{reco}} \) for the data and the expected background after the profile-likelihood fit under the background-only hypothesis for all signal regions combined. The lines in the bottom panel show the individual \( S + I \) distributions (scaled by a factor of 4) for a pseudoscalar \( A \) (solid line) and scalar \( H \) (bold dashed line) with \( m_A/H = 500 \) GeV and \( \tan \beta = 0.68 \) relative to the total background.

\[ \tan \beta = m_A = m_H \text{ [GeV]} \]

FIG. 3. The 95% C.L. observed and expected exclusion regions for the type-II 2HDM (\( \mu = 1 \)) considering only a pseudoscalar \( A \) (left), only a scalar \( H \) (middle), and the mass-degenerate scenario \( m_A = m_H \) (right). Blue points indicate parameter values at which signal samples are produced.
TABLE III. The 95% C.L. observed (obs.) and expected (exp.) exclusion limits on $\tan \beta$ for a type-II 2HDM in the alignment limit considering only a pseudoscalar $A$ (left), only a scalar $H$ (middle), and the mass-degenerate scenario $m_A = m_H$ (right). Dots (⋯) indicate that no value of $\tan \beta \geq 0.4$ is excluded.

<table>
<thead>
<tr>
<th>Mass [GeV] $\tan \beta$:</th>
<th>$m_A$</th>
<th>$m_H$</th>
<th>$m_A = m_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$500$</td>
<td>$&lt;1.00$</td>
<td>$&lt;1.55$</td>
<td>$&lt;1.50$</td>
</tr>
<tr>
<td>$550$</td>
<td>$&lt;0.69$</td>
<td>$&lt;0.72$</td>
<td>$&lt;0.52$</td>
</tr>
<tr>
<td>$600$</td>
<td>$&lt;0.59$</td>
<td>$&lt;0.73$</td>
<td>$&lt;1.09$</td>
</tr>
<tr>
<td>$650$</td>
<td>$&lt;0.58$</td>
<td>$&lt;0.62$</td>
<td></td>
</tr>
</tbody>
</table>

the three closest points. In Fig. 3, the observed and expected exclusion regions for the type-II 2HDM ($\mu = 1$) are shown for the three scenarios discussed in the Introduction. The excluded values of $\tan \beta$ for the different mass hypotheses are listed in Table III.

Conclusion.—In conclusion, the search for massive pseudoscalar and scalar resonances decaying to $t\bar{t}$ in 20.3 fb$^{-1}$ of $pp$ collisions at 8 TeV recorded by the ATLAS experiment yields no statistically significant deviations from the SM prediction. The results are interpreted in a type-II 2HDM in the alignment limit, and upper limits are set on the signal strength $\mu$ at 95% C.L. in the $m_{A/H}$ versus $\tan \beta$ plane. Unlike previous searches for $t\bar{t}$ resonances, this analysis takes into account interference effects between the signal process and the background from SM $t\bar{t}$ production. It tightens significantly the previously published constraints on the 2HDM parameter space in the low $\tan \beta$ and high mass ($m_{A/H} > 500$ GeV) region.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DFR and DLR, Germany; INFN, Italy; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russian and NRC KI, Russian Federation; JINR; MESRD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleiteos, Thales and Ariete programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [69].

[17] CMS Collaboration, Searches for heavy Higgs bosons in two-Higgs-doublet models and for $t \bar{t} h$ decay using multilepton and diphoton final states in $pp$ collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. D 90, 112013 (2014).
[19] CMS Collaboration, Searches for a heavy scalar boson $H$ decaying to a pair of 125 GeV Higgs bosons $hh$ or for a heavy pseudoscalar boson $A$ decaying to $Zh$, in the final states with $h \rightarrow \tau \tau$, Phys. Lett. B 755, 217 (2016).
[25] V. M. Abazov et al. (D0 Collaboration), Search for a narrow $t\bar{t}$ resonance in $pp$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 85, 051101 (2012).
[35] Scenarios with $m_H \neq m_A$ may not yield a stable Higgs potential for the chosen value of $m_{12}$ without extending the 2HDM.


[56] The ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as η = − ln[ tan(θ/2) ]. Transverse momenta are computed from the three-momenta, p, as p T = | p | sin θ.


Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
Department of Physics, The University of Hong Kong, Hong Kong, China
Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Department of Physics, National Tsing Hua University, Taiwan, Taiwan
Department of Physics, Indiana University, Bloomington Indiana, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, London, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston Louisiana, USA
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst Massachusetts, USA
Department of Physics, McGill University, Montreal Québec, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, USA
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
Group of Particle Physics, University of Montreal, Montreal QuébecCanada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
112 Department of Physics, New York University, New York New York, USA
113 Ohio State University, Columbus Ohio, USA
114 Faculty of Science, Okayama University, Okayama, Japan
115 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA
116 Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA
117 Palacky University, RCPTM, Olomouc, Czech Republic
118 Center for High Energy Physics, University of Oregon, Eugene Oregon, USA
119 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
119 Graduate School of Science, Osaka University, Osaka, Japan
120 Department of Physics, University of Oslo, Oslo, Norway
121 Department of Physics, Oxford University, Oxford, United Kingdom
122 INFN Sezione di Pavia, Italy
123 INFN Sezione di Pavia, Pavia, Italy
124 Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA
125 National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
126 INFN Sezione di Pisa, Pisa, Italy
127 Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada, Portugal
128 Instituto de Física and CEFITEC de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
129 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
130 Czech Technical University in Prague, Praha, Czech Republic
131 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
132 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
133 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
134 INFN Sezione di Roma, Italy
135 INFN Sezione di Roma Tor Vergata, Italy
136 Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
137 INFN Sezione di Roma Tre, Italy
138 Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
139 Faculty des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
140 Department of Physics, University of Washington, Seattle Washington, USA
141 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
142 Department of Physics, Shinshu University, Nagano, Japan
143 Department of Physics, Simon Fraser University, Burnaby British Columbia, Canada
144 SLAC National Accelerator Laboratory, Stanford California, USA
145 Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic
146 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
147 Department of Physics, University of Cape Town, Cape Town, South Africa
148 Department of Physics, University of Johannesburg, Johannesburg, South Africa
149 School of Physics, University of the Witwatersrand, Johannesburg, South Africa
150 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook New York, USA
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Tomsk State University, Tomsk, Russia
Department of Physics, University of Toronto, Toronto Ontario, Canada
INFN-TIFPA, Italy
University of Trento, Trento, Italy
TRIUMF, Vancouver British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto Ontario, Canada
Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine California, USA
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
ICTP, Trieste, Italy
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana Illinois, USA
Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain
Department of Physics, University of British Columbia, Vancouver British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison Wisconsin, USA
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at TRIUMF, Vancouver BC, Canada.
Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
Also at Physics Department, An-Najah National University, Nablus, Palestine.
Also at Department of Physics, California State University, Fresno CA, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.
Also at Departamento de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain.
Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
Also at Universita di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Borough of Manhattan Community College, City University of New York, New York City, USA.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
Also at Louisiana Tech University, Ruston LA, USA.
Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Georgian Technical University (GTU), Tbilisi, Georgia.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York NY, USA.

Also at Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile.

Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.

Also at The City College of New York, New York NY, USA.

Also at School of Physics, Shandong University, Shandong, China.

Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal.

Also at Department of Physics, California State University, Sacramento CA, USA.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Department de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.

Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

Also at School of Physics, Sun Yat-sen University, Guangzhou, China.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Department of Physics, Stanford University, Stanford CA, USA.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Giresun University, Faculty of Engineering, Turkey.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

Also at Department of Physics, Nanjing University, Jiangsu, China.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.