Search for heavy neutral Higgs bosons produced in association with $b$-quarks and decaying into $b$-quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

A search for heavy neutral Higgs bosons produced in association with one or two $b$-quarks and decaying to $b$-quark pairs is presented using 27.8 fb$^{-1}$ of $\sqrt{s} = 13$ TeV proton–proton collision data recorded by the ATLAS detector at the Large Hadron Collider during 2015 and 2016. No evidence of a signal is found. Upper limits on the heavy neutral Higgs boson production cross-section times its branching ratio to $b\bar{b}$ are set, ranging from 4.0 to 0.6 pb at 95% confidence level over a Higgs boson mass range of 450 to 1400 GeV. Results are interpreted within the two-Higgs-doublet model and the Minimal Supersymmetric Standard Model.
## Contents

1 Introduction ................................................. 3

2 The ATLAS detector ........................................ 4

3 Data and simulated samples ............................ 5
   3.1 Data ................................................ 5
   3.2 Signal model and background simulations .... 5

4 Object reconstruction and event selection ........ 7

5 Statistical analysis ........................................ 11

6 Systematic uncertainties ............................... 15
   6.1 Systematic uncertainties of the background model 15
   6.2 Experimental systematic uncertainties of the signal 15
   6.3 Theoretical systematic uncertainties of the signal 16

7 Results ...................................................... 16
   7.1 Cross-section limits ................................ 17
   7.2 Model interpretations ............................. 17

8 Conclusions .................................................. 24
1 Introduction

The measured properties of the Higgs boson discovered at the Large Hadron Collider (LHC) by the ATLAS and CMS collaborations [1, 2] with a mass of 125 GeV are consistent with those of the scalar particle that emerges from the mechanism of electroweak symmetry breaking in the Standard Model (SM) with its one doublet of complex scalar fields [3–6]. Alternative electroweak symmetry breaking models which contain a scalar particle with properties similar to the SM Higgs boson remain viable, however. A simple, well-studied and well-motivated extension of the mechanism of electroweak symmetry breaking in the SM is the two-Higgs-doublet model (2HDM), which contains two doublets of complex scalar fields [7, 8]. In the 2HDM there are, assuming negligible CP-violating effects, two CP-even scalar bosons, $h$ and $H$ which satisfy the mass relation $m_h < m_H$, one CP-odd pseudoscalar boson, $A$, and two electrically charged scalar bosons, $H^\pm$. The most general renormalizable, electroweak gauge invariant 2HDM contains tree-level Higgs-boson-mediated flavor-changing neutral currents [8] that are in conflict with experimental limits. When symmetries are imposed to naturally suppress flavor changing neutral currents, four model types well-studied and well-motivated extension of the mechanism of electroweak symmetry breaking in the SM parameter space since radiative corrections can significantly increase the ratio of the

\[
\text{mass ratio} \approx \tan^2 \beta \sin^2 \alpha
\]

They are not sensitive to flipped 2HDMs at large $\tan \beta$, however, and they do not cover the entire MSSM Type II 2HDM parameter space since radiative corrections can significantly increase the ratio of the $b \bar{b}$ and $\tau^+ \tau^-$ partial widths beyond the tree-level value of $3m_b^2/m_\tau^2$ [13].

Table 1: Tree-level fermion couplings of the 2HDM $h$, $H$, and $A$ bosons for model types I, II, X (or lepton-specific), and Y (or flipped). Here $U$, $D$, and $E$ refer to up-type quarks, down-type quarks, and charged leptons, respectively, $t_\beta \equiv \tan \beta$ is the ratio of the vacuum expectation values of the two scalar doublets, and $\epsilon \equiv \cos(\beta - \alpha)$ where $\alpha$ is the mixing angle of the two CP-even scalar bosons [9]. In the alignment limit, decays of the $H$ and $A$ bosons into gauge boson pairs $W^+ W^-$ and $ZZ$ are heavily suppressed, and the fermion coupling pattern simplifies to that of Table 1. The suppression of $H/A$ couplings to $W^+ W^-$ and $ZZ$, along with ATLAS and CMS limits on new particle production, implies that searches for the heavy neutral Higgs bosons of the 2HDM mainly rely on their couplings to third-generation fermions.

| $h$ | $h$ | $h$ | $h$ | $h$ | $h$ | $h$ | $h$ | $h$ |
|---|---|---|---|---|---|---|---|---|
| $U$ | $D$ | $E$ | $U$ | $D$ | $E$ | $U$ | $D$ | $E$ |
| $1 + \epsilon t_\beta$ | $1 + \epsilon t_\beta$ | $1 + \epsilon t_\beta$ | $-\epsilon t_\beta$ | $-\epsilon t_\beta$ | $-\epsilon t_\beta$ | $-\epsilon t_\beta$ | $-\epsilon t_\beta$ | $-\epsilon t_\beta$ |

The Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) is a Type II 2HDM, which has motivated searches for heavy neutral Higgs bosons at LEP [10] and the LHC [11, 12]. These searches use decays of heavy neutral Higgs bosons into $\tau^+ \tau^-$, and are sensitive to Type II and lepton-specific 2HDMs. They are not sensitive to flipped 2HDMs at large $t_\beta$, however, and they do not cover the entire MSSM Type II 2HDM parameter space since radiative corrections can significantly increase the ratio of the $b \bar{b}$ and $\tau^+ \tau^-$ partial widths beyond the tree-level value of $3m_b^2/m_\tau^2$ [13].
This paper presents a search for heavy neutral Higgs bosons produced in association with one or two $b$-quarks and decaying into $b$-quark pairs using 27.8 fb$^{-1}$ of $\sqrt{s} = 13$ TeV proton–proton collision data recorded by the ATLAS detector at the LHC during 2015 and 2016. The search is sensitive to the Type II and flipped scenarios of the 2HDM in the regime where $\tan \beta \gg 1$. In the 5-flavor scheme (5FS) [14], processes such as those shown in Figure 1 lead to the production of heavy neutral Higgs bosons in association with one $b$-quark (Figures 1(a) and 1(b)) or two $b$-quarks (Figures 1(c) and 1(d)). In practice, the optimal balance between signal efficiency and background rejection is achieved by requiring that signal events contain at least three $b$-quark-initiated jets. The search is performed for neutral Higgs bosons in the mass range 450–1400 GeV. A similar search was performed by the CMS Collaboration for the mass range 300–1300 GeV [15].

The kinematic distributions for the production and decay of $H$ and $A$ bosons are nearly identical, and therefore this search is insensitive to the CP properties of the two heavy neutral Higgs bosons of the 2HDM. The $\phi$ boson is be used in this paper to represent the CP-even $H$ boson, the CP-odd $A$ boson, or a Higgs boson mass eigenstate with an arbitrary mixture of CP-even and CP-odd eigenstates.

2 The ATLAS detector

The ATLAS experiment [16] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle.\footnote{ATLAS 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 coinciding with the axis of the beam pipe. The $x$-axis points from the IP towards the center of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r,\phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Angular distance is defined as $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.} It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. The innermost pixel layer [17, 18] was added before the start of collisions in 2015. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadronic steel/scintillator-tile calorimeter covers the central pseudorapidity range $|\eta| < 1.7$. The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and features three large air-core toroid superconducting magnets with eight coils each. The field integral of the toroids ranges from 2.0 to 6.0 T$\cdot$m across most of the detector. It includes a system of precision tracking chambers and fast
detectors for triggering. A two-level trigger system [19] consisting of the level-1 (L1) trigger, implemented in hardware, and the software-based high-level trigger (HLT), selects interesting events. The L1 trigger uses a subset of detector information to reduce the event rate to a design value of at most 100 kHz. The HLT, which can run offline reconstruction algorithms and is used in this analysis for the triggering of $b$-quark-initiated jets, reduces the event rate to about 1 kHz.

3 Data and simulated samples

3.1 Data

Proton–proton ($pp$) collision data recorded by the ATLAS detector at the LHC during 2015 and 2016 at a center-of-mass energy of $\sqrt{s} = 13$ TeV were used for the analysis described in this paper. For this data, it is required that the LHC operate with stable beam conditions and that all relevant detector systems be fully functional. The data, corresponding to integrated luminosities of $3.2 \pm 0.1$ fb$^{-1}$ and $24.5 \pm 0.5$ fb$^{-1}$ for 2015 and 2016, respectively, were collected using a combination of HLT triggers, which employ algorithms [19] to identify jets containing $b$-hadrons (resulting in ‘$b$-tagged jets’). Maximum-likelihood algorithms were utilized in 2015, while the offline multivariate classifier MV2c20 [20, 21] was used in 2016. Events were recorded if they passed the L1 single-jet trigger with a transverse energy ($E_T$) threshold of $E_T = 100$ GeV, and if the HLT identifies either one $b$-tagged jet with $E_T > 225$ GeV or two $b$-tagged jets with different thresholds of $E_T = 150$ GeV and $E_T = 50$ GeV. For the single (double) $b$-tagged jet trigger, the operating points correspond to a $b$-quark identification efficiency of 79% (72%) in 2015 and 60% (60%) in 2016, as measured with a reference $t\bar{t}$ sample. An inefficiency in the online vertex reconstruction affected a fraction of the data collected during 2016; events from these running periods were not included in the analysis. The efficiency of the combination of the two HLT $b$-jet triggers is shown in Figure 2 for events passing the final selection described in Section 4 and ranges from 80% for $m_\phi = 450$ GeV to 95% for $m_\phi > 700$ GeV.

3.2 Signal model and background simulations

Signal events for the subprocesses $bg \rightarrow b\phi + 0,1$ jet, $gg \rightarrow b\bar{b}\phi$, and $q\bar{q} \rightarrow b\bar{b}\phi$ with $\phi \rightarrow b\bar{b}$ were generated at leading order (LO) for fifteen $m_\phi$ values from 450 to 1400 GeV using the Sherpa 2.2.0 [22] Monte Carlo (MC) program in the 5FS with the NNPDF30NNLO [23] set of parton distribution functions (PDF). In order to determine the total width at each value of $m_\phi$, a specific MSSM scenario tailored for large values of the branching ratio ($B$) for $\phi \rightarrow b\bar{b}$ was used in which $\tan\beta = 20$, the higgsino mass parameter $\mu = -800$ GeV, the generic soft-SUSY-breaking mass parameter $M_{\text{SUSY}} = 1000$ GeV, the trilinear Higgs–top-squark coupling $A_t = 2000$ GeV, the $SU(2)$ gaugino mass parameter $M_2 = 800$ GeV, and the $SU(3)$ gaugino mass parameter $M_3 = 1600$ GeV. These parameters suppress $\phi$ boson decays into top quark pairs, top–squark pairs, and electroweak gauginos, while decays into pairs of $b$-quarks are enhanced through MSSM radiative corrections [13]. The FeynHiggs program [24] was used to calculate the branching ratios and the cross-sections shown in Table 2, where the branching ratio $B(\phi \rightarrow b\bar{b}) > 85\%$ for all $m_\phi$ values up to 1400 GeV. Given the large values for $B(\phi \rightarrow b\bar{b})$ in Table 2, the total widths derived from this set of MSSM parameters also represent the typical total widths in the flipped scenario of the 2HDM in the alignment limit for the same $m_\phi$ and $\tan\beta$. The values of the total width in Table 2 are much smaller than the 10–15% experimental $b\bar{b}$ mass resolution. Although several decay modes are present in this MSSM scenario, only the decay mode $\phi \rightarrow b\bar{b}$ was simulated in the generated signal samples.
The ATLAS detector response to the generated signal events was modeled using the ATLAS full simulation software [25] based on Geant4 [26]. The impact of multiple pp collisions in the same or nearby bunch crossings (pileup) was simulated by overlaying minimum-bias events on each generated event. The minimum-bias events were generated with Pythia 8.186 [27], using the A2 set of tuned parameters [28] and the MSTW2008LO PDF sets [29]. Finally, events were processed using the same reconstruction.
Table 2: Mass, total width, and branching ratios of the $\phi$ boson of the MSSM scenario used for signal event generation where $\tan \beta = 20$, $\mu = -800$ GeV, $M_{\text{SUSY}} = 1000$ GeV, $A_t = 2000$ GeV, $M_2 = 800$ GeV, and $M_3 = 1600$ GeV. The $p p \rightarrow b \bar{b} \phi$ cross-section at $\sqrt{s} = 13$ TeV is also shown. Full simulation samples of 300,000 events were produced for each of the mass points. The FeynHiggs program [24] was used to calculate the branching ratios and the cross-sections for $p p \rightarrow b \bar{b} \phi$ at $\sqrt{s} = 13$ TeV.

| $m_\phi$ (GeV) | $\Gamma_\phi$ (total) (GeV) | $\mathcal{B}(\phi \rightarrow b \bar{b})$ | $\mathcal{B}(\phi \rightarrow \tau^+ \tau^-)$ | $\mathcal{B}(\phi \rightarrow t \bar{t})$ | $\sigma(b \bar{b} \phi)$ (fb) |
|----------------|-----------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------|
| 450            | 4.7                         | 0.91                            | 0.07                            | 0.02                            | 2792                        |
| 500            | 5.1                         | 0.91                            | 0.07                            | 0.02                            | 1694                        |
| 550            | 5.5                         | 0.91                            | 0.07                            | 0.02                            | 1066                        |
| 600            | 5.9                         | 0.91                            | 0.07                            | 0.02                            | 693                         |
| 650            | 6.3                         | 0.91                            | 0.07                            | 0.02                            | 463                         |
| 700            | 6.7                         | 0.91                            | 0.07                            | 0.02                            | 317                         |
| 750            | 7.1                         | 0.90                            | 0.08                            | 0.02                            | 222                         |
| 800            | 7.5                         | 0.90                            | 0.08                            | 0.02                            | 158                         |
| 850            | 7.9                         | 0.90                            | 0.08                            | 0.02                            | 115                         |
| 900            | 8.3                         | 0.90                            | 0.08                            | 0.02                            | 85                          |
| 1000           | 9.1                         | 0.90                            | 0.08                            | 0.02                            | 48                          |
| 1100           | 9.8                         | 0.90                            | 0.08                            | 0.02                            | 29                          |
| 1200           | 10.7                        | 0.89                            | 0.08                            | 0.02                            | 18                          |
| 1300           | 11.6                        | 0.87                            | 0.08                            | 0.02                            | 12                          |
| 1400           | 12.5                        | 0.86                            | 0.08                            | 0.02                            | 8                           |

The background estimate is data-driven, as described in Section 5. Background MC samples (referred to later as ‘multi-jet MC samples’) served as a guide in developing the background model and consist of a SHERPA 2.1.1 simulation of multiple $b$-jets, a next-to-leading-order (NLO) POWHEG [30–32] simulation of $t \bar{t}$ production interfaced to PYTHIA 6.428 [33], and an LO MADGRAPH [34] simulation of the subprocess $j j \rightarrow Z j j$, $Z \rightarrow b \bar{b}$ interfaced to PYTHIA 8.205, where $j$ represents a gluon or a $u, d, s, c$ quark/anti-quark. The full ATLAS detector simulation software was used for $t \bar{t}$ production. A fast ATLAS detector simulation in which the calorimeter response is parameterized [25, 35] was used for the multiple $b$-jets and $j j \rightarrow Z j j$ samples.

The dominant background comes from the production of multiple $b$-jets. In the SHERPA 2.1.1 simulation of multiple $b$-jets all $2 \rightarrow 2, 3, 4$ hard subprocesses with at least one $b$-quark in the final state were generated at LO. Massive $c$- and $b$-quarks were used to properly simulate gluon splitting into heavy quarks.

4 Object reconstruction and event selection

Primary vertex candidates [36] are reconstructed from tracks in the inner detector, and the vertex with the highest sum of the squared transverse momenta of all associated tracks is selected as the hard-scatter primary vertex. Jets are reconstructed using the anti-$k_t$ algorithm [37] with radius parameter $R = 0.4$ from topological clusters of energy in the calorimeter calibrated at the electromagnetic scale [38]. Jets are then
calibrated using correction factors derived from simulation and data [39]. In order to suppress jets arising from pileup, jets with transverse momentum $p_T < 60$ GeV and $|\eta| < 2.4$ are removed if they fail to satisfy a requirement imposed by the multivariate jet vertex tagger (JVT) algorithm [40], where the JVT working point provides a 92% selection efficiency for hard-scatter jets. In addition, events with jets consistent with noise in the calorimeter or non-collision backgrounds are vetoed [41].

Jets containing a $b$-hadron are identified offline using the MV2c20 multivariate classifier [20, 21], which combines information from several algorithms. These algorithms are based on impact parameters of tracks, reconstructed secondary vertices, and a multi-vertex fitter which reconstructs the $b \to c$ hadron decay chain. A working point with an average $b$-tagging efficiency of 70%, as determined using simulated $t\bar{t}$ events, is chosen. The corresponding misidentification rates for $c$-jets and jets originating from light $(u,d,s)$ quarks or gluons is 8.2% and 0.3%, respectively. Jets tagged as $b$-jets receive an additional energy correction to account for the presence of muons in the jet [42].

Event preselection begins by requiring that the event pass the trigger selection and that there be at least three jets with $p_T > 20$ GeV and $|\eta| < 2.4$. The leading and second-leading jets (ordered in $p_T$) are then required to have $p_{T1} > 160$ GeV and $p_{T2} > 60$ GeV, respectively. The two leading jets must also be $b$-tagged. Events are considered to be in the signal region, and classified as ‘$bbb$’, if there exists at least one additional $b$-tagged jet. Events with only two $b$-tagged jets are considered to be in the control region, and are classified as ‘$bb\bar{c}$’. For $bb$ events the ‘third jet’ is defined to be the third-leading $b$-tagged jet in $p_T$, while for $bb\bar{c}$ events the third jet is the third-leading jet in $p_T$. The final preselection requirement is that the minimum $\Delta R$ between the third jet and the two leading jets must be greater than 0.8. This requirement reduces the background from gluon splitting into $bb$ in parton showers and subprocesses such as $bg \to bg^* \to bbb$.

Events are further classified according to the number of jets. The 3-jet, 4-jet and 5-jet regions are defined, where the last one contains events with five or more jets. A larger number of jets often means that significant final-state radiation (FSR) is present in the $\phi$ boson decay, making it more difficult to accurately reconstruct $m_\phi$ from the two highest-$p_T$ jets. Consequently, a categorization based on the number of jets improves experimental sensitivity.

Signal sensitivity is enhanced with a transformation of the kinematic variables $p_{T1}$, $p_{T2}$, and the invariant mass of the two leading $b$-tagged jets, $m_{bb}$. Two-dimensional distributions of $p_{T1}$ versus $m_{bb}$ and of $p_{T2}$ versus $m_{bb}$ for events with the $bb$ classification are displayed in Figure 3. As $m_\phi$ increases the two high-$p_T$ jets from the $\phi$ boson decay produce additional FSR, but the jet radius parameter remains fixed at $R = 0.4$. As a consequence, the reconstructed mass distribution based on the two highest-$p_T$ jets smears out and it becomes more difficult to distinguish signal from background. However, since FSR occurs stochastically, the $\phi$ boson decays with little or no FSR in a subset of the signal events, and these have reconstructed masses close to the true $m_\phi$ (bottom row of Figure 3). If these events can be isolated from the others, they offer a chance to improve the sensitivity via improved mass resolution and signal-to-background ratio.

To isolate events with small FSR and good $m_\phi$ resolution, a principal component analysis (PCA) [43] is performed on the three-dimensional distribution of the variables $m_{bb}$, $p_{T1}$, and $p_{T2}$ using events drawn from the signal MC sample with the $bb$ classification following preselection. Separate PCAs are performed for each of the fifteen simulated values of $m_\phi$ and for each of the three $n$-jet regions. Upon diagonalization of the covariance matrix for $m_{bb}$, $p_{T1}$, and $p_{T2}$, the first, second, and third principal components define the variables $m'_{bb}$, $p'_{T1}$, and $p'_{T2}$, respectively. The point $(m'_{bb}, p'_{T1}, p'_{T2}) = (0, 0, 0)$ corresponds to the vector of mean values for $m_{bb}$, $p_{T1}$, and $p_{T2}$. Two-dimensional distributions of $p'_{T1}$ versus $m'_{bb}$ and of $p'_{T2}$ versus $m'_{bb}$ are shown in Figure 4.
Figure 3: Two-dimensional distributions of $p_{T1}$ versus $m_{bb}$ (left column) and of $p_{T2}$ versus $m_{bb}$ (right column) for events with the $bbb$ classification following preselection, summed over all three $n$-jet regions. Plots are shown for data (top row), the multi-jet MC sample (middle row), and the $m_{\phi} = 1200$ GeV signal MC sample (bottom row). The multi-jet plots are normalized to an integrated luminosity of 27.8 fb$^{-1}$ based on the cross-sections provided by the event generators. The signal plots are normalized to $\sigma(pp \rightarrow b\bar{b}\phi) \times B(\phi \rightarrow b\bar{b}) = 1$ pb.
Figure 4: Two-dimensional distributions of $p_T^{T1}$ versus $m_{bb}'$ (left column) and of $p_T^{T2}$ versus $m_{bb}'$ (right column) for events with the $bbb$ classification following preselection, summed over all three $n$-jet regions, using the PCA for $m_{bb} = 1200$ GeV. Plots are shown for data (top row), the multi-jet MC sample (middle row), and the $m_{bb} = 1200$ GeV signal MC sample (bottom row). The multi-jet plots are normalized to an integrated luminosity of 27.8 fb$^{-1}$ based on the cross-sections provided by the event generators. The signal plots are normalized to $\sigma(pp\rightarrow bb\phi) \times B(\phi\rightarrow bb) = 1$ pb. The minimum values of $p_T^{T1}$ and $p_T^{T2}$ in the final event selection are indicated by horizontal lines.
The presence of a signal is tested with a binned maximum-likelihood fit to the data using the final event selection requirements are given in Table 3 for the 3-jet region. The largest component of the MC sample along with their ratio. The polynomial correction factor accounts for this and any other differences between the signal distributions are obtained from signal MC samples, with the exception of a global normalization factor representing the primary variable of interest, the heavy Higgs bosons production cross-section times branching ratio \( \sigma(pp \rightarrow bb\phi) \times \mathcal{B}(\phi \rightarrow b\bar{b}) \). The shapes and normalizations of the background distributions are determined by data. The background shapes are free to take any form satisfying the constraint that the \( bb \) and \( bbanti \) shapes for a specific jet-multiplicity region be identical modulo a second-order polynomial correction factor. The six background normalization factors float freely in the fit.

Based on the multi-jet MC sample, the backgrounds for both the \( bb \) and \( bbanti \) regions are dominated by the subprocesses \( gg \rightarrow gbb \) and \( gg \rightarrow ggb \), such events enter the \( bb \) region via gluon splitting into \( bb \) in the parton showering of one of the final-state gluons. However, the subprocesses \( gb \rightarrow b\bar{b} \) and \( gg \rightarrow bbb \) uniquely provide a small but non-negligible contribution to the \( bb \) background, and the polynomial correction factor accounts for this and any other differences between the \( bb \) and \( bbanti \) regions. The \( m_{bb}' \) distributions for both the \( bb \) and \( bbanti \) classifications are plotted in Figure 5 for the multi-jet MC sample along with their ratio. The \( bb \) and \( bbanti \) shapes for the 3-jet and 4-jet regions in Figure 5 are

| \( m_\phi \) [GeV] | 3-jet | 4-jet | 5-jet |
|-------------------|------|------|------|
| 600               | 0.74 | 0.12 | 0.14 |
| 900               | 0.55 | 0.20 | 0.26 |
| 1200              | 0.45 | 0.25 | 0.30 |

Examples of the relative contributions of \( m_{bb}, pT1 \), and \( pT2 \) to the rotated variable \( m'_{bb} \) are shown in Table 3 for the 3-jet region. The largest component of \( m'_{bb} \) comes from \( m_{bb} \), regardless of the mass point. However, at larger values of \( m_\phi \) -- where there is greater FSR -- the \( pT1 \) and \( pT2 \) components become more important.

The final event selection requirements are \( pT1' > -10 \) GeV and \( pT2' > -50 \) GeV, independent of \( n \)-jet and \( m_\phi \). These requirements reduce the background while retaining a large fraction of the signal events in regions of high signal density in \( (m_{bb}', pT1', pT2') \) space, as shown in Figure 4. Using \( m'_{bb} \) instead of \( m_{bb} \) as the final discriminant leads to increased sensitivity, which becomes more pronounced with increasing values of \( m_\phi \).

### 5 Statistical analysis

The presence of a signal is tested with a binned maximum-likelihood fit to the data using \( m'_{bb} \) as the final discriminating variable. For each of the considered mass points, a fit is performed simultaneously over six categories corresponding to all combinations of the three jet-multiplicity regions (3-jet, 4-jet, and 5-jet) and of the two \( b \)-tag classifications, \( bb \) and \( bbanti \). The shapes and normalizations for the different categories consist of a sum of signal and background contributions. The shapes and normalizations of the signal distributions are obtained from signal MC samples, with the exception of a global normalization factor representing the primary variable of interest, the heavy Higgs bosons production cross-section times branching ratio \( \sigma(pp \rightarrow bb\phi) \times \mathcal{B}(\phi \rightarrow b\bar{b}) \). The shapes and normalizations of the background distributions are determined by data. The background shapes are free to take any form satisfying the constraint that the \( bb \) and \( bbanti \) shapes for a specific jet-multiplicity region be identical modulo a second-order polynomial correction factor. The six background normalization factors float freely in the fit.
nearly identical, while the $bbb/bbanti$ ratio for the 5-jet region appears to have an approximately linear dependence on $m_{bb}'$. Application of the $\chi^2$ probability test and the $F$-test \cite{44} to the simulated multi-jet $m_{bb}'$ distributions over all values of $m_\phi$ demonstrates that a first-order polynomial is sufficient to describe the ratio of the simulated multi-jet $bbb$ and $bbanti$ background shapes for signal masses $m_\phi < 1200$ GeV, while a second-order polynomial is needed for $m_\phi \geq 1200$ GeV.

The data $bbb$ and $bbanti$ shapes, as well as their ratio, after applying the selection on $p_T^{bb}$ and $p_T^{bb'}$ are qualitatively similar to the multi-jet MC distributions, as shown in Figure 6. Applying $\chi^2$ probability and $F$-test criteria to the data $m_{bb}'$ distributions over all values of $m_\phi$, it is found that a first-order polynomial is sufficient for the 3-jet region with masses $m_\phi < 1200$ GeV and for the 4-jet and 5-jet regions with masses $m_\phi < 800$ GeV. For all other jet-category/mass combinations, a second-order polynomial is needed. Potential signal contamination does not affect the results of the tests.

The binned maximum-likelihood fit is performed using the RooFit \cite{45} framework and the HistFactory \cite{46} software tool. A product of Poisson probability terms over the bins of the $m_{bb}'$ distributions involving the numbers of data events $n_{i,j}$ and the sum of expected signal and background yields $\nu_{i,j}$ in each category $i$ and mass bin $j$ forms the binned likelihood function. It accounts for the effects of floating background normalization and systematic uncertainties and is

$$P(n, a|\mu, N, \gamma, \alpha) = \prod_{i \in \text{categories}} \prod_{j \in \text{bins}} \text{Pois}(n_{i,j}|\nu_{i,j}) \prod_{p \in \text{sys. nuis. param.}} f_p(\alpha_p|\alpha_p, \sigma_p),$$

$$\nu_{i,j} = N_i \cdot \gamma_{i,j} + \mu \cdot S_{i,j} \cdot \beta_{i,j}(\alpha_p)$$

$$\gamma_{i,j} = \begin{cases} B_{k,j} \cdot (Q_k \cdot P_j + A_k \cdot L_j + 1), & t = bbb \\
B_{k,j}, & t = bbanti. \end{cases}$$

The index $t$ runs over the two flavor categories $bbb$ and $bbanti$, $k$ runs over the three jet-multiplicity regions, $i = (t, k)$ runs over the six categories, and $p$ runs over the systematic error nuisance parameters. The boldfaced symbols represent vectors of parameters whereas the symbols of the same type in lightface represent individual parameters (usually containing indices). The template histograms, $S_{i,j}$, are taken directly from signal simulation for the given mass point and are normalized to the event yields expected for a one picobarn signal. Thus, the signal strength parameter $\mu$, which is common to all categories, is $\sigma(pp \to bbb\phi) \times B(\phi \to b\bar{b})$ in picobarns.

The $P$ and $L$ parameters describe the histogram representations of the $m_{bb}'$ and $m_{bb}'$ functions, respectively. The normalization parameters for these histograms, $Q_k$ and $A_k$, correspond to the parabolic and linear parameters, respectively, for the jet-multiplicity region $k$. The signal strength parameter $\mu$, the six background normalization parameters $N_i$, the background shape parameters $B_{k,j}$, the linear parameters $A_k$, and the parabolic parameters $Q_k$, are freely floating parameters in the fit, with the exception that, for a fixed jet-multiplicity region $k$, the sum over bins $j$ of $B_{k,j}$ is constrained to unity.

The fit model contains nuisance parameters accounting for the statistical uncertainty of the MC signal samples and for systematic variations of the shapes and normalizations of the histogram templates used in the fit, as described in Section 6. The variable $\beta_{i,j}$ represents the systematic variation in the bin content as a function of the nuisance parameters $\alpha_p$. The nuisance parameters $\alpha_p$ are constrained within the allowed systematic variations by the $f_p(\alpha_p|\alpha_p, \sigma_p)$ terms, where $\alpha_p$ are auxiliary measurements and $\sigma_p$ denotes the uncertainty in $\alpha_p$. Individual sources of uncertainties are considered uncorrelated.
Figure 5: Distributions of $m'_{bb}$ in simulated multi-jet events with the $bbb$ and $bbanti$ classifications following all selection requirements for the 3-jet (top row), 4-jet (middle row), and 5-jet (bottom row) regions. Distributions for the $m_\phi = 600$ GeV (left column) and $m_\phi = 1200$ GeV (right column) mass hypotheses are shown. For each case, the $bbanti$ distribution is normalized to an integrated luminosity of 27.8 fb$^{-1}$ based on the cross-section provided by the event generator, and the $bbb$ distribution is normalized to the same area as the $bbanti$ distribution. The ratios of $bbb$ to $bbanti$ are also shown.
Figure 6: Distributions of $m'_{bb}$ in data with the $bbb$ and $bbanti$ classifications following all selection requirements for the 3-jet (top row), 4-jet (middle row), and 5-jet (bottom row) regions. Distributions for the $m_\phi = 600$ GeV (left column) and $m_\phi = 1200$ GeV (right column) mass hypotheses are shown. For each case, the $bbb$ distribution is normalized to the $bbanti$ distribution. The ratios of $bbb$ to $bbanti$ are also shown.
The statistical uncertainty related to the size of MC signal samples is estimated with a variation of the Barlow–Beeston method [47]. In this analysis, each bin in each category is given a single Poisson-constrained nuisance parameter associated with the signal MC prediction for the number of events entering the bin and the total statistical uncertainty in that bin.

6 Systematic uncertainties

This analysis relies on the prediction of the shapes and normalizations of the discriminating variable $m_{bb}'$ for the searched signal. The signal uncertainties are divided into two categories: experimental and those related to the theoretical modeling of the signal. The background model is validated through statistical analysis of the data and tests utilizing the multi-jet MC sample.

6.1 Systematic uncertainties of the background model

A cross-check of the background model is performed by applying the full fit procedure to a small multi-jet MC sample with an equivalent integrated luminosity of 6.8 fb$^{-1}$ for eight $m_{bb}$ hypotheses. The results are summarized in Table 4. The eight separate fits should be uncorrelated given the 10–15% mass resolution for a heavy Higgs boson. With the assumption of no correlation, the $\chi^2$ per degree of freedom is 1.09 for the eight measurements, indicating that no statistically significant spurious signal is found by the analysis.

Table 4: Best-fit values for $\sigma(pp \rightarrow b\bar{b}\phi) \times B(\phi \rightarrow b\bar{b})$ in the multi-jet MC sample with a total uncertainty $\Delta(\sigma \times B)$ for each mass point. The multi-jet MC sample has an equivalent integrated luminosity of 6.8 fb$^{-1}$.

| Mass [GeV] | $\sigma \times B$ [pb] | $\Delta(\sigma \times B)$ [pb] |
|------------|-----------------|-----------------|
| 450        | -0.99           | 2.42            |
| 550        | 0.77            | 1.44            |
| 650        | -0.75           | 0.80            |
| 750        | 0.42            | 0.62            |
| 850        | -0.31           | 0.50            |
| 1000       | -0.24           | 0.49            |
| 1200       | 0.71            | 0.35            |
| 1400       | -0.29           | 0.20            |

Given this result, as well as the $\chi^2$ probability and the $F$-test results of Section 5, the systematic uncertainty arising from the choice of function for the ratio of the $bbb$ and $b\bar{b}anti$ shape distributions is deemed to be much smaller than the statistical uncertainty and is therefore neglected.

6.2 Experimental systematic uncertainties of the signal

The dominant experimental systematic uncertainties are related to the calibration of the $b$-tagging efficiencies in simulation relative to those measured in data for $p_T < 300$ GeV. They are extrapolated to $p_T > 300$ GeV using MC simulation taking into account uncertainties in the jet modeling and detector response affecting $b$-tagging performance. This calibration is performed separately for $b$-jets, $c$-jets, and light-flavor jets and
as a function of jet $p_T$ and $|\eta|$ [20]. Uncertainties in the cross-sections for processes used in the $b$-tagging calibration, modeling of the jet kinematics and flavor composition in the simulated signal samples, detector simulation, and event reconstruction are included [48–50]. These uncertainties are decomposed into uncorrelated components resulting in three components for $b$-jets and $c$-jets, and five components for light-flavor jets.

Simulation-to-data efficiency differences are also corrected for the trigger, specifically for $b$-tagged jets. Since the background estimation is data-driven, this scaling only affects signal. Scale factors obtained by comparing data and simulated dilepton $t\bar{t}$ events, which are enriched in $b$-jets, are used to correct simulation-to-data efficiency differences in the $b$-jet trigger for $p_T < 240$ GeV. For $p_T > 240$ GeV, due to the limited size of the $t\bar{t}$ data sample, extrapolation based on simulation is used. The systematic uncertainties in these scale factors include mismodeling of the fraction of $b$-jets in simulation, mismodeling of the $b$-jet trigger efficiency for non-$b$-jets, simulation statistical uncertainty, data statistical uncertainty for $p_T < 240$ GeV, uncertainty in the simulation-based extrapolation to $p_T > 240$ GeV, and uncertainties in the dependence of the $b$-jet trigger efficiency on jet $p_T$ and $\eta$. The $b$-jet trigger was calibrated relative to a set of offline $b$-tagging operating points to correctly take into account correlations between the $b$-jet trigger and offline $b$-tagging.

Systematic uncertainties in the jet energy scale and jet energy resolution are based on measurements with data [39, 51]. All sources of the jet energy scale uncertainty are decomposed into 21 uncorrelated components that are treated as independent.

The uncertainty in the combined 2015+2016 integrated luminosity is 2.1%. It is derived from the calibration of the luminosity scale using $x$-$y$ beam-separation scans, following a methodology similar to that detailed in Ref. [52], and using the LUCID-2 detector for the baseline luminosity measurements [53].

### 6.3 Theoretical systematic uncertainties of the signal

The uncertainty related to the choice of generator for the signal hard process and showering model is estimated by comparing the nominal sample with the one obtained by reweighting the nominal sample to the NLO generator MadGraph5_aMC@NLO [54, 55] with a 4 flavor scheme (4FS) PDF interfaced to the Pythia 8.205 parton showering model. The particle-level Higgs boson mass, Higgs boson $p_T$, and the $p_T$ values of the two leading $b$-tagged jets are used for sequential reweighting. The uncertainty from the PDF set used in the nominal sample is computed using the standard-deviation method described in Ref. [23].

### 7 Results

The search for a single heavy neutral Higgs boson $\phi$ produced in association with $b$-quarks and decaying into a $b\bar{b}$ pair shows no significant excess above the SM background for any of the analyzed mass points. The post-fit $b\bar{b}$ category distributions of the rotated $bb$ invariant mass $m'_{bb}$ are shown in Figure 7 together with the $m'_{bb}$ distribution extracted from the $bb$anti region (pre-fit background).
7.1 Cross-section limits

Since no significant excess over the background expectation is observed, upper limits on the production of a single heavy neutral Higgs boson $\phi$ decaying into a $b\bar{b}$ pair are set. Figure 8 presents the observed and expected limits for $\sigma(pp \rightarrow b\bar{b}\phi) \times B(\phi \rightarrow b\bar{b})$ at the 95% confidence level (CL). The limits are calculated with the CL$_s$ method [56].

The leading sources of uncertainty affecting the best-fit value of $\sigma \times B$ for two of the mass points, 600 and 1200 GeV, are given in Table 5, together with their relative importance. The impact of the given source of uncertainty is obtained by first fixing all the nuisance parameters related to other systematic uncertainties to their best-fit values and then allowing only the nuisance parameters ascribed to the considered source of uncertainty to float in the fit. The uncertainty is dominated by the statistical error, which improves significantly between $m_\phi = 600$ and 1200 GeV due to the sharp drop in the background level. The systematic uncertainties with the largest impact on the sensitivity are related to the flavor-tagging calibration of the offline $b$-tagging algorithm and $b$-jet trigger and to jet reconstruction.

Table 5: Grouped contributions to the systematic uncertainty of the best-fit value of $\sigma \times B$. The best-fit values for $m_\phi = 600$ and 1200 GeV are 0.76 and $-0.1$ pb, respectively.

| Source of uncertainty | $m_\phi = 600$ GeV $\Delta(\sigma \times B)$ [pb] | $m_\phi = 1200$ GeV $\Delta(\sigma \times B)$ [pb] |
|-----------------------|-------------------------------------------------|-------------------------------------------------|
| Total                 | 0.80                                            | 0.29                                            |
| Statistical           | 0.77                                            | 0.26                                            |
| Systematic            | 0.20                                            | 0.11                                            |
| Experimental uncertainties |                                              |                                                  |
| Jet-related           | 0.05                                            | 0.05                                            |
| Flavor-tagging        | 0.12                                            | 0.05                                            |
| Trigger               | 0.04                                            | 0.05                                            |
| Luminosity            | 0.02                                            | 0.01                                            |
| Theoretical and modeling uncertainties |                                              |                                                  |
| Generator             | 0.03                                            | 0.03                                            |
| PDF                   | 0.08                                            | 0.04                                            |
| MC statistical        | 0.09                                            | 0.04                                            |

7.2 Model interpretations

The two 2HDM scenarios with enhanced $pp \rightarrow b\bar{b}\phi$ production and $\phi \rightarrow b\bar{b}$ decay at large $\tan \beta$ are Type II and Type Y (flipped). The most commonly analyzed scenario is Type II since the Higgs sector of the MSSM is a Type II 2HDM. The results of this search are interpreted in the context of the MSSM for the hMSSM scenario [57] and for the $m_h^{mod^+}$ and $m_h^{mod^-}$ scenarios [58]. The Higgs boson production cross-sections and branching ratios are calculated using the procedures outlined in the LHC Higgs Cross-section Working Group report [59]. The cross-sections for Higgs boson production through $b\bar{b}$ fusion [14] are determined by matching the 5FS [60, 61] and 4FS [62, 63] cross-section calculations. For the hMSSM scenario, the Higgs boson masses and branching ratios are calculated using HDecay [64, 65]. For the $m_h^{mod^+}$ and $m_h^{mod^-}$.
scenarios, the Higgs boson masses and couplings are calculated with FeynHiggs [24, 66–69], and the branching ratios are calculated by combining the most precise results from FeynHiggs, HDECAY, and PROPHECY4f [70, 71].

The 95% CL exclusion limits on tan β as a function of \( m_A \) are shown in Figure 9 for the hMSSM benchmark. The hMSSM scenario is well defined and broadly representative of the remaining parameter space with SUSY partners too heavy for direct detection at the LHC. As an indication of the sensitivity variation for different MSSM scenarios, Figure 9 also displays the expected sensitivities for the \( \Phi^{\text{mod}+} \) and \( \Phi^{\text{mod}−} \) scenarios, in which top squark mixing parameters are chosen to allow a wide range of tan β values while maintaining compatibility with \( m_h = 125 \) GeV. The hMSSM limits obtained by this search are comparable to the limits obtained in the charged Higgs boson search in the \( H^+ \to \tau ν \) decay channel by ATLAS and CMS Collaborations [72, 73] but not as stringent as the hMSSM limits obtained in the ATLAS and CMS searches for heavy neutral Higgs bosons decaying via \( \Phi \to \tau^+ \tau^- \) [11, 12].

The 95% CL tan β exclusion limits for this search assuming the Type Y (flipped) 2HDM scenario are presented, first in Figure 10 for the specific \( \Phi \) mass of 450 GeV as a function of \( \cos(\beta − \alpha) \) and then in Figure 11 as a function of \( m_\Phi \) in the alignment limit \( \cos(\beta − \alpha) = 0 \). For these limits, it is assumed that the flipped 2HDM is CP-conserving with \( m_h = 125 \) GeV and \( m_H = m_{H±} = m_A \). The model grid points are generated using SusHi [61] and 2HDMC [74]. These limits complement the flipped 2HDM limits obtained from the searches for \( A \to Zh \) in ATLAS [75], which exclude regions with \( | \cos(\beta − \alpha) | \gtrsim 0.2 \) or \( \tan β \lesssim 4 \), and from the search for \( A \to ZH \) in ATLAS [76], which excludes regions with \( m_A − m_H \gtrsim 100 \) GeV.
Figure 7: Post-fit $bbb$ category distributions of $m_{bb\ell}$ for the 600 GeV (left) and 1200 GeV (right) mass points in the 3-jet (top), 4-jet (middle), and 5-jet (bottom) categories. The pre-fit background shape is also shown in the top panels, and its ratio to the post-fit shape is shown in the bottom panels (green dashed line). The signal shape (red dashed line) is overlaid for illustration.
Figure 8: Observed and expected upper limits on \( \sigma(pp \rightarrow b\bar{b}\phi) \times B(\phi \rightarrow b\bar{b}) \) at 95% CL as a function of the Higgs boson mass in 27.8 fb\(^{-1}\) of \( pp \) collision data at \( \sqrt{s} = 13 \) TeV.
Figure 9: Observed and expected 95% CL exclusion limits for the hMSSM scenario as a function of $m_A$. The expected sensitivities for the $m_{h}^{\text{mod}+}$ and $m_{h}^{\text{mod}−}$ scenarios are also shown. The observed 95% CL limits for the $m_{h}^{\text{mod}+}$ and $m_{h}^{\text{mod}−}$ scenarios follow the same pattern with respect to their expected limits as the hMSSM observed limits. Limits are not shown for $\tan \beta > 60$ since the Higgs boson coupling becomes non-perturbative for very large values of $\tan \beta$ in the considered models.
Figure 10: Observed and expected 95% CL exclusion limits for the flipped 2HDM scenario at $m_\phi = 450$ GeV as a function of $\cos(\beta - \alpha)$. Limits are not shown for $\tan \beta > 50$ since the Higgs boson coupling becomes non-perturbative for very large values of $\tan \beta$ in this model.
Figure 11: Observed and expected 95% CL exclusion limits for the flipped 2HDM scenario in the alignment limit as a function of $m_\phi$. Limits are not shown for $\tan \beta > 50$ since the Higgs boson coupling becomes non-perturbative for very large values of $\tan \beta$ in this model.
8 Conclusions

A search for heavy neutral Higgs bosons produced in association with at least one $b$-quark and decaying into a pair of $b$-quarks was performed using 27.8 fb$^{-1}$ of 13 TeV $pp$ collision data recorded by the ATLAS detector at the LHC in 2015 and 2016. The data are compatible with SM expectations, yielding no significant excess of events in the mass range 450–1400 GeV. Upper limits on the cross-section times branching ratio were derived as a function of the mass of the heavy Higgs boson. The 95% CL upper limits are in the range 0.6–4.0 pb. Compared to heavy neutral Higgs boson searches utilizing $\phi \rightarrow \tau^+ \tau^-$ or $A \rightarrow Zh$ decays, these limits expand the excluded Type Y (flipped) 2HDM parameter space into regions with $|\cos(\beta - \alpha)| \approx 0$ and $\tan \beta \gtrsim 20$.

Acknowledgments

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; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; 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, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, 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. [77].
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, arXiv: 1207.7214 [hep-ex].

[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, arXiv: 1207.7235 [hep-ex].

[3] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys. Rev. Lett. 13 (1964) 321.

[4] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, Phys. Lett. 12 (1964) 132.

[5] P. W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, Phys. Rev. Lett. 13 (1964) 508.

[6] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Global Conservation Laws and Massless Particles*, Phys. Rev. Lett. 13 (1964) 585.

[7] G. C. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, Phys. Rept. 516 (2012) 1, arXiv: 1106.0034 [hep-ph].

[8] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, *The Higgs Hunter’s Guide*, Front. Phys. 80 (2000), url: https://cds.cern.ch/record/425736.

[9] D. M. Asner et al., *ILC Higgs White Paper*, 2013, arXiv: 1310.0763 [hep-ph].

[10] ALEPH, DELPHI, L3 and OPAL Collaborations, *Search for neutral MSSM Higgs bosons at LEP*, Eur. Phys. J. C 47 (2006) 547, arXiv: hep-ex/0602042 [hep-ex].

[11] ATLAS Collaboration, *Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36 fb^{-1} of pp collisions at √s = 13 TeV with the ATLAS detector*, JHEP 01 (2018) 055, arXiv: 1709.07242 [hep-ex].

[12] CMS Collaboration, *Search for additional neutral MSSM Higgs bosons in the ττ final state in proton-proton collisions at √s = 13 TeV*, JHEP 09 (2018) 007, arXiv: 1803.06553 [hep-ex].

[13] M. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, *MSSM Higgs boson searches at the Tevatron and the LHC: Impact of different benchmark scenarios*, Eur. Phys. J. C 45 (2006) 797, arXiv: hep-ph/0511023.

[14] R. Harlander, M. Krämer, and M. Schumacher, *Bottom-quark associated Higgs-boson production: reconciling the four- and five-flavour scheme approach*, (2011), arXiv: 1112.3478 [hep-ph].

[15] CMS Collaboration, *Search for beyond the standard model Higgs bosons decaying into a b b̅ pair in pp collisions at √s = 13 TeV*, JHEP 08 (2018) 113, arXiv: 1805.12191 [hep-ex].

[16] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003.

[17] ATLAS Collaboration, *ATLAS Insertable B-Layer Technical Design Report*, ATLAS-TDR-19, 2010, url: https://cds.cern.ch/record/1291633, ATLAS Insertable B-Layer Technical Design Report Addendum, ATLAS-TDR-19-ADD-1, 2012, url: https://cds.cern.ch/record/1451888.

[18] B. Abbott et al., *Production and integration of the ATLAS Insertable B-Layer*, JINST 13 (2018) T05008, arXiv: 1803.00844 [physics.ins-det].

[19] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, Eur. Phys. J. C 77 (2017) 317, arXiv: 1611.09661 [hep-ex].
[20] ATLAS Collaboration, *Performance of b-jet identification in the ATLAS experiment*, JINST **11** (2016) P04008, arXiv: 1512.01094 [hep-ex].

[21] ATLAS Collaboration, *Optimisation of the ATLAS b-tagging performance for the 2016 LHC Run*, ATLAS-PHYS-PUB-2016-012, 2016, url: https://cds.cern.ch/record/2160731.

[22] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **02** (2009) 007, arXiv: 0811.4622 [hep-ph].

[23] R. D. Ball et al., *Parton distributions for the LHC run II*, JHEP **04** (2015) 040, arXiv: 1410.8849 [hep-ph].

[24] S. Heinemeyer, W. Hollik, and G. Weiglein, *FeynHiggs: A program for the calculation of the masses of the neutral CP-even Higgs bosons in the MSSM*, Comput. Phys. Commun. **124** (2000) 76, arXiv: hep-ph/9812320.

[25] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, Eur. Phys. J. C **70** (2010) 823, arXiv: 1005.4568 [physics.ins-det].

[26] S. Agostinelli et al., *GEANT4–A simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[27] T. Sjöstrand, S. Mrenna, and P. Z. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, arXiv: 0710.3820 [hep-ph].

[28] ATLAS Collaboration, *Summary of ATLAS Pythia 8 tunes*, ATL-PHYS-PUB-2012-003, 2012, url: https://cds.cern.ch/record/1474107.

[29] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, *Parton distributions for the LHC*, Eur. Phys. J. C **63** (2009) 189, arXiv: 0901.0002 [hep-ph].

[30] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **11** (2004) 040, arXiv: hep-ph/0409146.

[31] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, JHEP **11** (2007) 070, arXiv: 0709.2092 [hep-ph].

[32] S. Frixione, P. Nason, and G. Ridolfi, *A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, JHEP **09** (2007) 126, arXiv: 0707.3088 [hep-ph].

[33] T. Sjöstrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026, arXiv: hep-ph/0603175.

[34] F. Maltoni and T. Stelzer, *MadEvent: automatic event generation with MadGraph*, JHEP **02** (2003) 027, arXiv: hep-ph/0208156.

[35] ATLAS Collaboration, *The simulation principle and performance of the ATLAS fast calorimeter simulation FastCaloSim*, ATL-PHYS-PUB-2010-013, 2010, url: https://cds.cern.ch/record/1300517.

[36] ATLAS Collaboration, *Reconstruction of primary vertices at the ATLAS experiment in Run 1 proton–proton collisions at the LHC*, Eur. Phys. J. C **77** (2017) 332, arXiv: 1611.10235 [hep-ex].

[37] M. Cacciari, G. P. Salam, and G. Soyez, *The anti-k_{t} jet clustering algorithm*, JHEP **04** (2008) 063, arXiv: 0802.1189 [hep-ph].

[38] ATLAS Collaboration, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, Eur. Phys. J. C **77** (2017) 490, arXiv: 1603.02934 [hep-ex].
[39] ATLAS Collaboration, *Jet energy scale measurements and their systematic uncertainties in proton–proton collisions at \( \sqrt{s} = 13 \) TeV with the ATLAS detector*, Phys. Rev. D 96 (2017) 072002, arXiv: 1703.09665 [hep-ex].

[40] ATLAS Collaboration, *Performance of pile-up mitigation techniques for jets in \( pp \) collisions at \( \sqrt{s} = 8 \) TeV using the ATLAS detector*, Eur. Phys. J. C 76 (2016) 581, arXiv: 1510.03823 [hep-ex].

[41] ATLAS Collaboration, *Selection of jets produced in 13 TeV proton–proton collisions with the ATLAS detector*, ATLAS-CONF-2015-029, 2015, url: https://cds.cern.ch/record/2037702.

[42] ATLAS Collaboration, *Evidence for the \( H \rightarrow b\bar{b} \) decay with the ATLAS detector*, JHEP 12 (2017) 024, arXiv: 1708.03299 [hep-ex].

[43] I. Jolliffe, *Principal Component Analysis*, in M. Lovric (Ed.), International Encyclopedia of Statistical Science. Springer, Berlin, Heidelberg, (2011).

[44] B. Roe, *Probability and Statistics in Experimental Physics*, Springer-Verlag (2001) 264pp.

[45] W. Verkerke and D. P. Kirkby, *The RooFit toolkit for data modeling*, 2003, arXiv: physics/0306116.

[46] K. Cranmer, G. Lewis, L. Moneta, A. Shibata, and W. Verkerke, *HistFactory: A tool for creating statistical models for use with RooFit and RooStats*, CERN-OPEN-2012-016, 2012, url: https://cds.cern.ch/record/1456844/.

[47] R. Barlow and C. Beeston, *Fitting using finite Monte Carlo samples*, Comput. Phys. Commun. 77 (1993) 219.

[48] ATLAS Collaboration, *Measurements of \( b \)-jet tagging efficiency with the ATLAS detector using \( t\bar{t} \) events at \( \sqrt{s} = 13 \) TeV*, JHEP 08 (2018) 089, arXiv: 1805.01845 [hep-ex].

[49] ATLAS Collaboration, *Measurement of \( b \)-tagging efficiency of \( c \)-jets in \( t\bar{t} \) events using a likelihood approach with the ATLAS detector*, ATLAS-CONF-2018-001, 2018, url: https://cds.cern.ch/record/2306649.

[50] ATLAS Collaboration, *Calibration of light-flavour \( b \)-jet mistagging rates using ATLAS proton–proton collision data at \( \sqrt{s} = 13 \) TeV*, ATLAS-CONF-2018-006, 2018, url: https://cds.cern.ch/record/2314418.

[51] ATLAS Collaboration, *Jet energy resolution in proton–proton collisions at \( \sqrt{s} = 7 \) TeV recorded in 2010 with the ATLAS detector*, Eur. Phys. J. C 73 (2013) 2306, arXiv: 1210.6210 [hep-ex].

[52] ATLAS Collaboration, *Luminosity determination in \( pp \) collisions at \( \sqrt{s} = 8 \) TeV using the ATLAS detector at the LHC*, Eur. Phys. J. C 76 (2016) 653, arXiv: 1608.03953 [hep-ex].

[53] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, JINST 13 (2018) P07017.

[54] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP 07 (2014) 079, arXiv: 1405.0301 [hep-ph].

[55] M. Wiesemann et al., *Higgs production in association with bottom quarks*, JHEP 02 (2015) 132, arXiv: 1409.5301 [hep-ph].

[56] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, Eur. Phys. J. C 71 (2011) 1554, arXiv: 1007.1727 [hep-ex], Erratum: *Erratum to: Asymptotic formulae for likelihood-based tests of new physics*, Eur. Phys. J. C 73 (2013) 2501.
A. Djouadi et al., *The post-Higgs MSSM scenario: habemus MSSM?* Eur. Phys. J. C 73 (2013) 2650, arXiv: 1307.5205 [hep-ph].

M. Carena, S. Heinemeyer, O. Stål, C. E. M. Wagner, and G. Weiglein, *MSSM Higgs boson searches at the LHC: benchmark scenarios after the discovery of a Higgs-like particle*, Eur. Phys. J. C 73 (2013) 2552, arXiv: 1302.7033 [hep-ph].

D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the nature of the Higgs sector*, CERN-2017-002-M (2017), arXiv: 1610.07922 [hep-ph].

R. V. Harlander and W. B. Kilgore, *Higgs boson production in bottom quark fusion at next-to-next-to leading order*, Phys. Rev. D 68 (2003) 013001, arXiv: hep-ph/0304035.

R. V. Harlander, S. Liebler, and H. Mantler, *SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM*, Comput. Phys. Commun. 184 (2013) 1605, arXiv: 1212.3249 [hep-ph].

S. Dittmaier, M. Krämer, and M. Spira, *Higgs radiation off bottom quarks at the Fermilab Tevatron and the CERN LHC*, Phys. Rev. D 70 (2004) 074010, arXiv: hep-ph/0309204.

S. Dawson, C. B. Jackson, L. Reina, and D. Wackeroth, *Exclusive Higgs boson production with bottom quarks at hadron colliders*, Phys. Rev. D 69 (2004) 074027, arXiv: hep-ph/0311067.

A. Djouadi, J. Kalinowski, and M. Spira, *HDECAY: A Program for Higgs boson decays in the standard model and its supersymmetric extension*, Comput. Phys. Commun. 108 (1998) 56, arXiv: hep-ph/9704448.

A. Djouadi, J. Kalinowski, M. Mühlleitner, and M. Spira, *HDECAY: Twenty++ years after*, Comput. Phys. Commun. 238 (2019) 214, arXiv: 1801.09506 [hep-ph].

S. Heinemeyer, W. Hollik, and G. Weiglein, *The masses of the neutral CP-even Higgs bosons in the MSSM: Accurate analysis at the two loop level*, Eur. Phys. J. C 9 (1999) 343, arXiv: hep-ph/9812472.

G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, and G. Weiglein, *Towards high precision predictions for the MSSM Higgs sector*, Eur. Phys. J. C 28 (2003) 133, arXiv: hep-ph/0212020.

M. Frank et al., *The Higgs boson masses and mixings of the complex MSSM in the Feynman-diagrammatic approach*, JHEP 02 (2007) 047, arXiv: hep-ph/0611326.

T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, and G. Weiglein, *High-Precision Predictions for the Light CP-Even Higgs Boson Mass of the Minimal Supersymmetric Standard Model*, Phys. Rev. Lett. 112 (2014) 141801, arXiv: 1312.4937 [hep-ph].

A. Bredenstein, A. Denner, S. Dittmaier, and M. M. Weber, *Precise predictions for the Higgs-boson decay H → WW/ZZ → 4 leptons*, Phys. Rev. D 74 (2006) 013004, arXiv: hep-ph/0604011.

A. Bredenstein, A. Denner, S. Dittmaier, and M. M. Weber, *Radiative corrections to the semileptonic and hadronic Higgs-boson decays H → WW/ZZ → 4 fermions*, JHEP 02 (2007) 080, arXiv: hep-ph/0611234 [hep-ph].

ATLAS Collaboration, *Search for charged Higgs bosons decaying via H* → τ⁺τ⁻ in the τ+jets and τ+lepton final states with 36 fb⁻¹ of pp collision data recorded at √s = 13 TeV with the ATLAS experiment*, JHEP 09 (2018) 139, arXiv: 1807.07915 [hep-ex].

CMS Collaboration, *Search for charged Higgs bosons in the H* → τ⁺τ⁻ decay channel in proton-proton collisions at √s = 13 TeV*, (2019), arXiv: 1903.04560 [hep-ex].
[74] D. Eriksson, J. Rathsman, and O. Stål, **2HDMC – two-Higgs-doublet model calculator**, Comput. Phys. Commun. **181** (2010) 189, arXiv: 0902.0851 [hep-ph].

[75] ATLAS Collaboration, *Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b-jets in 36 fb$^{-1}$ of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, JHEP **03** (2018) 174, arXiv: 1712.06518 [hep-ex].

[76] ATLAS Collaboration, *Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Lett. B **783** (2018) 392, arXiv: 1804.01126 [hep-ex].

[77] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-GEN-PUB-2016-002, url: https://cds.cern.ch/record/2202407.
The ATLAS Collaboration

G. Aad$^{101}$, B. Abbott$^{128}$, D.C. Abbott$^{102}$, O. Abdinov$^{13^a}$, A. Abdes Abud$^{70a,70b}$, K. Abeling$^{53}$, D.K. Abhayasinghe$^{93}$, S.H. Abidi$^{167}$, O.S. AbouZeid$^{40}$, N.L. Abraham$^{156}$, H. Abramowicz$^{161}$, H. Abreu$^{160}$, Y. Abulaiti$^{6}$, B.S. Acharya$^{66a,66b,66o}$, B. Achkar$^{53}$, S. Adachi$^{163}$, L. Adam$^{99}$, C. Adam Bourdarios$^{132}$, L. Adamczyk$^{83a}$, L. Adamek$^{167}$, J. Adelman$^{121}$, M. Adersberger$^{114}$, A. Adiguez$^{12,aj}$, S. Adorni$^{54}$, T. Adye$^{144}$, A.A. Affolder$^{146}$, Y. Afkami$^{160}$, C. Agapopoulou$^{13,22b}$, M.N. Agaras$^{38}$, A. Aggarwal$^{119}$, C. Agheorghiesi$^{27c}$, J.A. Aguilar-Saavedra$^{140f,140a,ai}$, F. Ahmadov$^{79}$, W.S. Ahmed$^{103}$, X. Ai$^{15a}$, G. Aielli$^{72a,73s}$, S. Akatsuka$^{85}$, T.P.A. Åkesson$^{96}$, E. Akhill$^{154}$, A.V. Akimov$^{110}$, K. Al Khoury$^{132}$, G.L. Alberghi$^{23b,23a}$, J. Albert$^{176}$, M.J. Alconada Verzini$^{88}$, S. Alderweireldt$^{36}$, M. Aleks$^{36}$, I.N. Aleksandrov$^{79}$, C. Alexa$^{72b}$, D. Alexandre$^{7}$, T. Alexopoulos$^{10}$, A. Alfonsi$^{120}$, M. Alhroor$^{128}$, B. Ali$^{142}$, G. Alimonti$^{68b}$, J. Alison$^{37}$, S.P. Alkire$^{148}$, C. Allaire$^{132}$, B.M.M. Allbrooke$^{156}$, W.B. Allen$^{131}$, P.P. Allport$^{21}$, A. Aloisio$^{69a,69b}$, A. Alonso$^{10}$, F. Alonso$^{88}$, C. Alpigiani$^{148}$, A.A. Alshehri$^{57}$, M. Alvarez Estevez$^{98}$, D. Álvarez Piqueras$^{174}$, L. Aperio Bella$^{36}$, E.M. Baldin$^{84}$, L. Aperio Bella$^{53}$, P. Bartos$^{21}$, M. Bahmani$^{23b,23a}$, H. Bahrasemani$^{83}$, J. Barreiro Guimarães da Costa$^{36}$, E. Bergeaas Kuutmann$^{99}$, B. Bedognetti$^{6}$, M. Biedermann$^{120}$, R. Bartoldus$^{54}$, D.P. Benjamin$^{6}$, M. Benoit$^{54}$, J.K. Bensinger$^{6}$, S. Bentvelsen$^{112}$, S. Bents$^{57}$, J.R. Batley$^{84}$, M. Bauce$^{60a}$, R. Batool$^{24}$, S. Barsov$^{35a}$, B. Batool$^{28a}$, M. Bavaj$^{83}$, C. Bella$^{30}$, G. Bella$^{148}$, P. Bello$^{34}$, K. Belot$^{99}$, K. Belotskiy$^{71a,71b}$, M. Biglietti$^{74a}$, T.R.V. Billoud$^{76}$, A. Betti$^{74}$, M. Biedermann$^{142}$, R. Bielski$^{36}$, K. Bierwagen$^{99}$, N.V. Biesuz$^{71a,71b}$, M. Birman$^{180}$, T. Bish$^{53}$, J.K. Beh$^{46}$, F. Beiseiegel$^{24}$, A.S. Bell$^{94}$, G. Bella$^{161}$, L. Bellagamba$^{23b}$, A. Bellerive$^{34}$, P. Bello$^{9}$, K. Beloborodov$^{12b,122a}$, K. Belotskiy$^{112}$, N.L. Belyaev$^{112}$, D. Benchekroun$^{35a}$, N. Benekos$^{10}$, Y. Benhammou$^{161}$, D.P. Benjamin$^{6}$, M. Benoit$^{54}$, J.R. Bensinger$^{26}$, S. Bentvelsen$^{120}$, L. Beresford$^{135}$, M. Beretta$^{51}$, D. Berge$^{46}$, E. Bergeaas Kuutmann$^{72}$, N. Berger$^{5}$, B. Bergmann$^{142}$, L.J. Bergsten$^{66}$, J. Beringer$^{18}$, S. Berlendis$^{7}$, N.R. Bernard$^{102}$, G. Bernardi$^{136}$, C. Bernius$^{153}$, T. Berry$^{93}$, P. Berta$^{59}$, C. Bertella$^{15a}$, I.A. Bertram$^{89}$, G.J. Besjes$^{40}$, O. Bessidskaia Bylund$^{182}$, N. Besson$^{145}$, A. Bethani$^{100}$, S. Bethke$^{115}$, A. Betts$^{24}$, A.J. Bevan$^{92}$, J. Beyer$^{115}$, R. Bi$^{39}$, R.M. Bianchi$^{139}$, O. Bijbels$^{114}$, D. Biedermann$^{19}$, R. Bielski$^{36}$, K. Bierwagen$^{99}$, N.V. Biesuz$^{71a,71b}$, M. Biglietti$^{74a}$, T.R.V. Billoud$^{109}$, M. Bindi$^{53}$, A. Bิงกล$^{120}$, C. Bin$^{72a,72b}$, S. Biondi$^{23b,23a}$, M. Birman$^{180}$, T. Bisan$^{53}$, J.P. Biswal$^{161}$,
2 Department of Physics, SUNY Albany, Albany NY; United States of America.
3 Department of Physics, University of Alberta, Edmonton AB; Canada.
4(a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.
5 LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
7 Department of Physics, University of Arizona, Tucson AZ; United States of America.
8 Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
9 Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
10 Physics Department, National Technical University of Athens, Zografou; Greece.
11 Department of Physics, University of Texas at Austin, Austin TX; United States of America.
12(a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (c) Department of Physics, Bogazici University, Istanbul; (d) Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.
13 Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
14 Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
15(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing; (d) University of Chinese Academy of Science (UCAS), Beijing; China.
16 Institute of Physics, University of Belgrade, Belgrade; Serbia.
17 Department for Physics and Technology, University of Bergen, Bergen; Norway.
18 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.
19 Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
20 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
21 School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
22 Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota; Colombia.
23(a) INFN Bologna and Universita’ di Bologna, Dipartimento di Fisica; (b) INFN Sezione di Bologna; Italy.
24 Physikalisches Institut, Universität Bonn, Bonn; Germany.
25 Department of Physics, Boston University, Boston MA; United States of America.
26 Department of Physics, Brandeis University, Waltham MA; United States of America.
27(a) Transilvania University of Brașov, Brașov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara; Romania.
28(a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
29 Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
31 California State University, CA; United States of America.
32 Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
33(a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (c) School of Physics, University of the
INFN Sezione di Lecce; Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
INFN Sezione di Milano; Dipartimento di Fisica, Università di Milano, Milano; Italy.
INFN Sezione di Napoli; Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
INFN Sezione di Pavia; Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
INFN Sezione di Roma; Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
INFN Sezione di Roma Tre; Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
INFN-TIFPA; Università degli Studi di Trento, Trento; Italy.
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.
University of Iowa, Iowa City IA; United States of America.
Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
Joint Institute for Nuclear Research, Dubna; Russia.
Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; Universidade Federal de São João del Rei (UFSJ), São João del Rei; Instituto de Física, Universidade de São Paulo, São Paulo; Brazil.
KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
Graduate School of Science, Kobe University, Kobe; Japan.
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
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.
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, Egham; United Kingdom.
Department of Physics and Astronomy, University College London, London; United Kingdom.
Louisiana Tech University, Ruston LA; United States of America.
Fysiska institutionen, Lunds universitet, Lund; Sweden.
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.
Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
Institut für Physik, Universität Mainz, Mainz; Germany.
Física, Universidade do Minho, Braga; (f) Universidad de Granada, Granada (Spain); (g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal.

141 Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

142 Czech Technical University in Prague, Prague; Czech Republic.

143 Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

144 Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

145 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

146 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

147 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

148 Department of Physics, University of Washington, Seattle WA; United States of America.

149 Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

150 Department of Physics, Shinshu University, Nagano; Japan.

151 Department Physik, Universität Siegen, Siegen; Germany.

152 Department of Physics, Simon Fraser University, Burnaby BC; Canada.

153 SLAC National Accelerator Laboratory, Stanford CA; United States of America.

154 Physics Department, Royal Institute of Technology, Stockholm; Sweden.

155 Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

156 Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

157 School of Physics, University of Sydney, Sydney; Australia.

158 Institute of Physics, Academia Sinica, Taipei; Taiwan.

159 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.

160 Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

161 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

162 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

163 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

164 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.

165 Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

166 Tomsk State University, Tomsk; Russia.

167 Department of Physics, University of Toronto, Toronto ON; Canada.

168 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON; Canada.

169 Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

170 Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

171 Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

172 Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

173 Department of Physics, University of Illinois, Urbana IL; United States of America.

174 Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

175 Department of Physics, University of British Columbia, Vancouver BC; Canada.

176 Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

177 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid; Spain.
Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
Also at Joint Institute for Nuclear Research, Dubna; Russia.
Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
Also at Louisiana Tech University, Ruston LA; United States of America.
Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
Also at Manhattan College, New York NY; United States of America.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
Also at National Research Nuclear University MEPhI, Moscow; Russia.
Also at Physics Department, An-Najah National University, Nablus; Palestine.
Also at Physics Dept, University of South Africa, Pretoria; South Africa.
Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
Also at School of Physics, Sun Yat-sen University, Guangzhou; China.
Also at The City College of New York, New York NY; United States of America.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
Also at TRIUMF, Vancouver BC; Canada.
Also at Universita di Napoli Parthenope, Napoli; Italy.
* Deceased