Search for single production of a vector-like quark via a heavy gluon in the $4b$ final state with the ATLAS detector in $pp$ collisions at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration

Abstract

A search is performed for the process $pp \rightarrow G^* \rightarrow B_H\bar{b}/\bar{B}_Hb \rightarrow Hb\bar{b} \rightarrow b\bar{b}b\bar{b}$, predicted in composite Higgs scenarios, where $G^*$ is a heavy colour octet vector resonance and $B_H$ a vector-like quark of charge $-1/3$. The data were obtained from $pp$ collisions at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of 19.5 fb$^{-1}$, recorded by the ATLAS detector at the LHC. The largest background, multijet production, is estimated using a data-driven method. No significant excess of events with respect to Standard Model predictions is observed, and upper limits on the production cross section times branching ratio are set. Comparisons to the predictions from a specific benchmark model are made, resulting in lower mass limits in the two-dimensional mass plane of $m_{G^*}$ vs. $m_{B_H}$. 

© 2016 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.
1 Introduction

Composite Higgs [1–4] models interpret the Higgs boson discovered at the Large Hadron Collider (LHC) [5] as a pseudo-Goldstone boson resulting from spontaneous symmetry breaking in a new strongly coupled sector, thus addressing the naturalness problem, the extreme fine tuning required in the Standard Model (SM) to cancel quadratically divergent radiative corrections to the Higgs boson mass. A generic prediction of these models is the existence of massive vector-like quarks (VLQ). These VLQs are expected to mix mainly with the third family of quarks of the SM [6–8], leading to partial compositeness. Colour octet resonances (massive gluons) also occur naturally in these models [6, 7, 9, 10].

Searches for vector-like quarks in the ATLAS and CMS experiments, in both the pair and single production processes [11–22], constrain their mass to be above 700–900 GeV. This analysis is a search for single production of a vector-like quark $B_H$ of charge $-1/3$ via the $s$-channel exchange of a heavy colour octet vector resonance $G^*$, using data recorded by the ATLAS detector at the LHC. The search is performed for the process of $Hb\bar{b}$ production through $pp \rightarrow G^* \rightarrow B_H\bar{b}/B_Hb \rightarrow Hb\bar{b} \rightarrow b\bar{b}b\bar{b}$ (see Fig. 1),\footnote{Charge conjugate states are implied in the following text.} based on Ref. [23] and using the benchmark model of Ref. [9]. This simplified minimal composite Higgs model has a composite sector with a global $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_Y$ symmetry and an elementary sector which contains the SM particles but not the Higgs boson. Physical states of the composite sector include the heavy gluon $G^*$, a composite Higgs boson and heavy vector-like quarks of charge $5/3$, $2/3$, $-1/3$ and $-4/3$. Among these heavy quarks, there is one singlet of charge $2/3$ which mixes with the right-handed top quark of the SM with an angle $\theta_{tR}$, and similarly one singlet of charge $-1/3$ which mixes with the right-handed bottom quark of the SM with an angle $\theta_{bR}$. After mixing between the gluons from the elementary and composite sectors by an angle $\theta_s$, the physical state of the heavy gluon has a coupling $g_c \cos \theta_s$ to composite states, where $g_c = g_s / \sin \theta_s$ and $g_s$ is the coupling of the SM gluon. The other parameters of the model are the composite fermion masses, assumed to be universal, the heavy gluon mass $m_{G^*}$ and two Yukawa couplings $Y_T$ and $Y_B$. In a large part of the parameter space, the lightest of the new heavy quarks is $B_H$, of charge $-1/3$, and in this model it decays exclusively to $Hb$. In Ref. [23], the condition $m_{B_H} = m_{G^*}/2$ is applied, with the result that pair production of the heavy partners is kinematically forbidden and the width of $G^*$ is consequently not too large. In the search presented here, the phase space is extended to $m_{B_H} \geq m_{G^*}/2$. When $m_{B_H} \leq m_{G^*}/2$, present results on pair production of vector-like quarks can be recast in a model with a massive colour octet [24].

For high masses of the $G^*$ and $B_H$ resonances, the Higgs boson is highly boosted and the decay products are reconstructed in a single large-radius (large-$R$) jet in the detector, whereas for lower masses the four $b$-quarks are reconstructed as separate small-radius jets. The analysis uses two sets of selection criteria to target these two cases.
Figure 1: Feynman diagram of the signal process $qar{q} \rightarrow G^* \rightarrow B_H \bar{b} \rightarrow Hb \bar{b} \rightarrow bar{b}b\bar{b}$.

2 The ATLAS detector

The ATLAS detector, located at the LHC, is described in detail in Ref. [25]. It covers nearly the full solid angle around the collision point. The inner detector is surrounded by a solenoid that produces a 2 T axial magnetic field. The tracks of charged particles are reconstructed with a high-granularity silicon pixel and microstrip detector for $|\eta| < 2.5$. A straw-tube transition radiation detector extends the tracking to larger radii and provides electron/pion discrimination. The electromagnetic calorimeter consists of a barrel and end-cap lead/liquid-argon (LAr) sections with an accordion geometry covering $|\eta| < 3.2$, preceded by a thin presampler, covering $|\eta| < 1.8$, which allows corrections for fluctuations in upstream energy losses. A copper/LAr electromagnetic calorimeter covers the very forward angles. Hadronic calorimetry is installed in the barrel region, $|\eta| < 1.7$, using steel as the absorber and scintillator tiles as the active material. In the endcaps, copper/LAr calorimeters cover $1.5 < |\eta| < 3.2$ followed by a forward calorimeter based on tungsten absorbers in LAr as sensitive medium, up to $|\eta| = 4.9$. Surrounding the hadronic calorimeters are large toroidal magnets whose magnetic fields deflect the trajectories of charged particles exiting the barrel and end-cap calorimeters. The muon spectrometer uses monitored drift tubes for tracking in $|\eta| < 2.7$ with cathode strip chambers in the innermost station for $|\eta| > 2.0$. A dedicated muon trigger is provided by resistive plate chambers in the barrel and thin-gap chambers in the end-cap, covering $|\eta| < 2.4$.

A three-level trigger system, consisting of a hardware Level-1 trigger and two software-based trigger levels reduce the event rate to be recorded to less than about 400 Hz.

---

2 ATLAS experiment uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre 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 $\eta = -\ln \tan(\theta/2)$. The distance in $\eta-\phi$ space is referred to as $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. 

3
3 Data and simulation

Data used in this analysis correspond to an integrated luminosity of $19.5 \text{ fb}^{-1}$ of $pp$ collisions collected at the LHC at a centre-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$, with all the essential elements of the ATLAS detector were fully operational and stable.

Simulated signal and background samples are produced by Monte Carlo (MC) event generators and passed through a Geant 4 [26] simulation of the ATLAS detector [27]. Additional events from the same and neighbouring bunch crossings (pile-up) are included by adding simulated diffractive and non-diffractive $pp$ collisions to hard-scattering events. The pile-up rate is reweighted in accordance with the luminosity profile of the recorded data. All simulated events are then reconstructed using the same reconstruction software as the data.

Signal samples based on the model discussed in Ref. [23] are generated with MadGraph5 aMC@NLO [28], using CTEQ6L1 [29] parton distribution functions (PDFs), in the mass region $m_{G^*}/2 \leq m_{BH} < m_{G^*}$, with $1 \text{ TeV} < m_{G^*} < 3 \text{ TeV}$, in steps of 250 GeV in $m_{G^*}$ and in steps of 125 GeV in $m_{BH}$. The Higgs boson mass is set to 126 GeV and its branching ratio $\text{BR}(H \rightarrow b\bar{b})$ to 56.1% [30]. The parameters of the model are set as in Ref. [23]: $g_c = 3$, $Y_T = Y_B = 3$, $\sin \theta_t = \sin \theta_b = 0.6$.

The event selection requires at least two $b$-jets in the final state. Multijet events from strong interactions have a large cross section and are the dominant background. Due to the large number of events required to simulate this background and the difficulty of modelling it accurately, it is evaluated using a data-driven method, as described in Section 6. Other background contributions include top-pair and single-top-quark production, generated with Powheg-Box [31–33] interfaced to Pythia [34] using CT10 PDFs [35]. The $t\bar{t}$ sample is normalised to the theoretical calculation performed at next-to-next-to-leading order (NNLO) including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms with Top++2.0 [36, 37], giving an inclusive cross section of $253^{+13}_{-15} \text{ pb}$ [38]. Samples of $t\bar{t} + Z$ and $t\bar{t} + H$ events are generated with Pythia and CTEQ6L1 PDFs. The Sherpa [39] generator, with CT10 PDFs, is used to simulate $W/Z + \text{jets}$ samples with leptonic decay of the vector bosons. Sherpa is also used to generate $Z + \text{jets}$ events, with $Z \rightarrow b\bar{b}$, where the extra jets are produced inclusively. Contributions from diboson backgrounds—WW, WZ and ZZ—are estimated to be negligible.

4 Object reconstruction

The final state consists of four jets from $b$-quarks ($b$-jets), two of which come from the Higgs boson decay. If the Higgs boson is sufficiently boosted, having a transverse momentum $p_T \gtrsim 300 \text{ GeV}$, the two $b$-jets may be merged into a single jet with a large radius parameter (large-$R$ jet) and therefore two different jet definitions are used.

Jets with smaller radius parameter, or small-$R$ jets, are reconstructed from calibrated calorimeter energy clusters [40, 41] using the anti-$k_t$ algorithm [42] with a distance parameter $R = 0.4$. The high $p_T$ threshold used in the event selection ensures that the contamination of jets from pile-up is small. To ensure high-quality reconstruction of central jets while rejecting most jets not coming from hard-scattering events, criteria as described in Ref. [43] are applied. Jets are corrected for pile-up by a jet-area subtraction method and calibrated by a jet energy scale factor [44]. They are required to have $p_T > 50 \text{ GeV}$ and $|\eta| < 2.5$. 


Small-$R$ jets are identified as containing a $b$-hadron ($b$-tagged) by a multivariate algorithm [45]. This algorithm was configured to give a $b$-tagging efficiency of 70% in simulated $t\bar{t}$ events, with a mistag probability of about 1% for gluon and light-quark jets and of about 20% for $c$-quark-initiated jets. The $b$-tagging efficiency in simulated events is corrected to account for differences observed between data and simulation.

Large-$R$ jets are reconstructed using the anti-$k_t$ algorithm with $R = 1.0$. Jet trimming [46, 47] is applied to reduce the contamination from pile-up and underlying-event activity: subjets are formed using the $k_t$ algorithm [48] with $R = 0.3$ and subjets with $p_T^{\text{subj}}/p_T^{\text{jet}} < 5\%$ are removed.

Leptons are vetoed in this analysis to reduce background involving leptonically decaying vector bosons. Electron candidates with $p_T > 7$ GeV are identified in the range $|\eta| < 2.47$ from energy clusters in the electromagnetic calorimeter, matched to a track in the inner detector. Requirements of ‘medium’ quality, as defined in Ref. [49], are applied together with two isolation criteria: the scalar sum of the transverse momentum (energy) within a radius $\Delta R = 0.2$ around the electron candidate has to be less than 15% (14%) of the electron $p_T (E_T)$. Muons with $p_T > 7$ GeV and $|\eta| < 2.4$ are reconstructed from matched tracks in the muon spectrometer and the inner detector. Quality criteria are applied, as described in Ref. [50], and an isolation requirement is applied: the scalar sum of the transverse momentum of tracks within a radius $\Delta R = 0.2$ around the muon candidate has to be less than 10% of the muon $p_T$.

5 Event selection

5.1 Event preselection

Events in the signal region are first preselected according to the following criteria (see end of Section 5.2 for the signal region definition).

- They must satisfy a combination of six triggers requiring multiple jets and $b$-jets for various $p_T$ thresholds, where $b$-jets are identified by a dedicated online $b$-tagging algorithm. This combination of triggers is $> 99\%$ efficient for signal events passing the offline selection, across the $B_H$ and $G^*$ mass ranges considered in this analysis.
- They are vetoed if they contain reconstructed isolated leptons ($e$ or $\mu$) in order to reduce the contribution from $W/Z +$ jets and $t\bar{t}$ backgrounds.
- At least three small-$R$ $b$-tagged jets must be present in the signal region.
- The invariant mass of the system composed of all selected $R = 0.4$ jets is required to be greater than 600 GeV.

Two event topologies are considered for the signal, depending on the boost of the Higgs boson. Highly boosted Higgs bosons are reconstructed using large-$R$ jets as described in Section 4 and this topology corresponds to the merged scenario (see Section 5.2). If no large-$R$ jet is found, an attempt is made to reconstruct the Higgs boson from two small-$R$ jets (see Section 5.3). The acceptance times reconstruction efficiency for the combined yields of the two topologies varies from 5% to 20% depending on the masses of the $G^*$ and $B_H$. 

5
5.2 Merged selection

The signal region for the merged case consists of the following requirements.

- A large-\(R\) jet must be present with \(p_T > 300\) GeV and \(|\eta| < 2.0\) and mass in the range [90, 140] GeV. The mass window was optimised based on the signal sensitivity. If more than one such large-\(R\) jet is present, the Higgs candidate is chosen to be the one with mass closest to 126 GeV. At least one \(b\)-tagged jet must be matched to it within a distance \(\Delta R = 1.0\).

- There must be at least two additional \(b\)-tagged jets separated from the Higgs boson candidate, \(\Delta R (H, j) > 1.4\). The two with the highest \(p_T\) are used to reconstruct the \(G^*\) and \(B_H\) candidates.

Once the Higgs boson candidate has been identified as above, there remains an ambiguity in assigning the other jets to the vector-like quark \(B_H\). The four-momentum of the \(B_H\) candidate is reconstructed as the four-momentum sum of the Higgs boson candidate and either the next-to-leading-\(p_T\) (category 1) or the leading-\(p_T\) (category 2) \(b\)-jet away from it, depending on the assumed mass difference between \(G^*\) and \(B_H\). For large \(G^*-B_H\) mass difference, the \(B_H\) and \(b\)-quark from \(G^*\) splitting have high momentum and therefore the jet from the subsequent \(B_H\) decay is likely to be the next-to-leading jet. For a small mass difference the opposite is true since in this latter case the \(B_H\) decay products are more boosted than the \(G^*\) splitting products. For each \((m_{G^*}, m_{B_H})\) pair, the category which has the higher probability that the correct pairing is formed is chosen, based on the simulated signal events. Finally, the \(G^*\) four-momentum is reconstructed as the four-momentum sum of the Higgs boson jet and the two leading-\(p_T\) \(b\)-jets not matched to the Higgs boson candidate.

Different signal regions are defined for the different \((m_{G^*}, m_{B_H})\) mass pair hypotheses. They are characterised by the choice of category defined above as well as by lower cuts on the reconstructed masses of \(G^*\) and \(B_H\) candidates. Five inclusive signal regions were defined, with the minimum mass of the \(G^*\) candidate ranging from 0.8 to 1.8 TeV and of the \(B_H\) candidate from 0.5 to 1 TeV; these are shown in Table 1. For each mass pair considered, the signal region that gives the maximum signal sensitivity, the ratio of the expected number of signal events to the square root of the number of background events, is chosen.

<table>
<thead>
<tr>
<th>Category 1</th>
<th>Category 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower cut on reconstructed (m_{G^*}) and (m_{B_H}) [TeV]</td>
<td>((1.0, 0.5))</td>
</tr>
</tbody>
</table>

Table 1: Signal region definitions: category 1 (2) refers to the case where the next-to-leading-\(p_T\) (leading-\(p_T\)) jet not associated with the Higgs boson is assumed to be from the \(B_H\) decay.

5.3 Resolved selection

Events in the resolved signal region are required to satisfy the following criteria.

- In order to be able to later combine the results with the merged channel, events are required to fail the merged selection criteria.
• Events are required to have exactly four small-$R$ jets with $p_T > 50$ GeV and $|\eta| < 2.5$, with at least three of these jets being $b$-tagged. The Higgs boson candidate is reconstructed using the two jets with invariant mass nearest to 126 GeV. The invariant mass is required to be in the interval $[90, 140]$ GeV and the transverse momentum of the dijet system $p_T(jj) > 200$ GeV.

The four-momentum of the $B_H$ candidate is reconstructed from the four-momentum sum of the Higgs candidate and either the leading or the next-to-leading-$p_T$ jet away from the Higgs boson jets, depending on the $G^*-B_H$ mass splitting. As in the merged case, for each pair of masses considered the category is chosen to be the one with the lower mis-assignment rate of jets, based on samples of simulated signal events. Inclusive signal regions are defined by lower minimum mass values identical to the merged case, and shown in Table 1. Each mass pair is assigned to the same SR for the merged and resolved analysis. The four-momentum of the $G^*$ candidate is reconstructed from the four-momentum sum of the four jets in the event.

6 Modelling of the multijet background

The ‘ABCD’ data-driven method is used to estimate the multijet background. For each of the ten signal regions, three control regions orthogonal to the signal region are defined: region B has all the signal region selection criteria mentioned in Section 5 applied, including the lepton vetoes and lower cuts on the masses of $B_H$ and $G^*$ candidates, but the Higgs boson candidate mass is required to be outside the interval $[90, 140]$ GeV; region C has all the signal region selection requirements, but requires exactly two jets to be $b$-tagged; and region D has the Higgs boson candidate outside the Higgs boson mass window and exactly two $b$-tagged jets. In regions C and D, only one of the two jets not associated with the Higgs boson candidate is $b$-tagged. The number of multijet (MJ) events expected in the signal region (SR) is then evaluated according to

$$N_{SR}^{MJ} = N_B/N_D \times N_C,$$

where $N_X$ is the number of events in region X, after having removed the top-quark, diboson and other electroweak background contributions as determined from MC simulations.

This estimate assumes that no bias results from the choice of control regions. To evaluate and potentially correct for the effect of any biases, a re-weighting is performed on two kinematic distributions, the leading-jet $p_T$ and the $\Delta R$ between the reconstructed Higgs boson candidate and the leading jet not associated with it. Control regions C and D (B and D) are re-weighted, using a method similar to Ref. [51], to have the same shape as in control region B (C) with weights obtained from $N_B/N_D (N_B/N_D)$ per bin. The effect of this re-weighting is found to be negligible and therefore no correction is applied.

A validation region is defined as the 15 GeV sideband regions outside the Higgs boson candidate mass window for each signal region. The contribution from multijet background is estimated as above, but with the control regions B and D excluding these validation regions and region C now being the two sidebands. It is then compared to the number of observed data events, after adding back the simulation-based background, in these regions. Table 2 shows that the expected and observed numbers of events agree well in the validation regions for the merged- and resolved-channel signal regions.
Table 2: Expected and observed numbers of events in the validation regions (VR) associated to their respected signal regions for the merged and resolved channels. Only the statistical error is shown.

<table>
<thead>
<tr>
<th></th>
<th>VR1</th>
<th>VR2</th>
<th>VR3</th>
<th>VR4</th>
<th>VR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Merged</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td>563 ± 16</td>
<td>213 ± 10</td>
<td>1680 ± 29</td>
<td>135 ± 8</td>
<td>45 ± 4</td>
</tr>
<tr>
<td>Observed</td>
<td>558</td>
<td>184</td>
<td>1666</td>
<td>137</td>
<td>35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>VR1</th>
<th>VR2</th>
<th>VR3</th>
<th>VR4</th>
<th>VR5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resolved</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td>1065 ± 21</td>
<td>337 ± 11</td>
<td>3758 ± 50</td>
<td>242 ± 10</td>
<td>63 ± 5</td>
</tr>
<tr>
<td>Observed</td>
<td>1073</td>
<td>324</td>
<td>3906</td>
<td>238</td>
<td>56</td>
</tr>
</tbody>
</table>

7 Systematic uncertainties

Systematic uncertainties from several sources affect the expected numbers of background and signal events. Table 3 shows the estimated size of the different components.

The statistical uncertainty in the data control regions used for the estimation of the multijet background is considered as part of the statistical error.

There is an uncertainty in the number of background events due to the difference between the observed and estimated numbers of events in each of the validation regions. In each validation region, if the observed number of events is compatible with the estimated number within one standard deviation (calculated as the sum in quadrature of the relative statistical errors of the two), this standard deviation is considered to be the background estimation uncertainty. Otherwise, the background uncertainty is considered to be the fractional difference between the observed and estimated numbers of events. This is the largest uncertainty, ranging from 5% in SR1 to 27% in SR5 for the merged case, and from 3.5% in SR1 to 16% in SR5 for the resolved case.

The $t\bar{t}$ contribution dominates the simulation-based background. The theoretical uncertainty on its cross section is taken to be 6%, as discussed in Section 3.

Uncertainties due to the calibration and modelling of the detector affecting the simulation-based background estimates in the control and signal regions are principally due to the jet energy scale (JES) and jet energy resolution (JER). JES uncertainties for small-$R$ jets include contributions from detector reconstruction and from different physics modelling and evaluation methods [52]. Uncertainties leading to a higher (lower) yield than the nominal value are added in quadrature to the total JES up (down) uncertainty. To evaluate the impact of JER for small-$R$ jets, energies of simulated jets are smeared to be consistent with the JER measured in data. The JER systematic uncertainty is the difference between the nominal and smeared values.

JES uncertainties for large-$R$ jets in the central region are evaluated as described in Ref. [47]. The jet mass scale (JMS) uncertainty is 4–5% for $p_T \lesssim 700$ GeV and increases linearly with $p_T$ to about 8% in the range $900 \lesssim p_T \lesssim 1000$ GeV.

The total uncertainty in the measured $b$-tagging efficiency was evaluated in Ref. [53] and is $p_T$ and $\eta$ dependent. For high-$p_T$ jets, the systematic uncertainty is derived from simulation. It is estimated here
for the simulation-based backgrounds, accounting for the statistical uncertainty, the error on the generator-dependent scale factors, the track momentum scale, resolution and efficiency systematic uncertainties, and the extrapolation uncertainties for light jets. It is at or below the percent level and always dominated by the background estimation.

The predicted signal is not confined to the signal region: it could also constitute a fraction of the observed data in the control regions. The effect of this potential contamination on the statistical procedure is described in Section 8.

Systematic uncertainties due to detector effects also affect the VLQ signal yields. Theoretical uncertainties in the signal cross section due to the choice of PDFs are estimated from CTEQ6.6 with its 22 eigenvector sets [29].

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
<th>SR4</th>
<th>SR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background estimation</td>
<td>5%</td>
<td>15%</td>
<td>2.8%</td>
<td>10%</td>
<td>27%</td>
</tr>
<tr>
<td>$t\bar{t}$ cross section</td>
<td>+1.0% −1.1%</td>
<td>+0.8% −0.9%</td>
<td>+1.2% −1.4%</td>
<td>+0.8% −0.9%</td>
<td>+0.6% −0.7%</td>
</tr>
<tr>
<td>JER small-R</td>
<td>+0.29%</td>
<td>+0.15%</td>
<td>+0.01%</td>
<td>−0.32%</td>
<td>+0.20%</td>
</tr>
<tr>
<td>JES small-R</td>
<td>+0.9% −0.8%</td>
<td>+1.6% −0.7%</td>
<td>+1.0% −1.0%</td>
<td>+0.9% −1.0%</td>
<td>+1.5% −1.0%</td>
</tr>
<tr>
<td>JES/JMS large-R</td>
<td>+0.31% −1.5%</td>
<td>+1.3% −1.5%</td>
<td>+0.13% −1.9%</td>
<td>+0.9% −0.8%</td>
<td>+1.6% −0.20%</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>+0.18% −0.18%</td>
<td>+0.23% −0.33%</td>
<td>+0.24% −0.18%</td>
<td>&lt; 0.01%</td>
<td>+1.6% &lt; 0.01%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Data/MC statistical (CR)</td>
<td>2.2%</td>
<td>4%</td>
<td>1.3%</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td>Total (stat.)</td>
<td>2.7%</td>
<td>5%</td>
<td>1.5%</td>
<td>6%</td>
<td>10%</td>
</tr>
<tr>
<td>Total (syst.)</td>
<td>6%</td>
<td>15%</td>
<td>4%</td>
<td>11%</td>
<td>28%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
<th>SR4</th>
<th>SR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background estimation</td>
<td>3.5%</td>
<td>6%</td>
<td>4%</td>
<td>8%</td>
<td>16%</td>
</tr>
<tr>
<td>$t\bar{t}$ cross section</td>
<td>+0.24% −0.27%</td>
<td>+0.20% −0.23%</td>
<td>+0.31% −0.4%</td>
<td>+0.23% −0.26%</td>
<td>+0.17% −0.20%</td>
</tr>
<tr>
<td>JER small-R</td>
<td>+0.17%</td>
<td>+0.32%</td>
<td>+0.18%</td>
<td>−0.37%</td>
<td>−0.5%</td>
</tr>
<tr>
<td>JES small-R</td>
<td>+0.8% −0.6%</td>
<td>+0.7% −0.6%</td>
<td>+0.6% −0.7%</td>
<td>+0.8% −0.7%</td>
<td>+1.0% −0.8%</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>+0.5% −0.4%</td>
<td>+0.5% −0.30%</td>
<td>+0.5% −0.4%</td>
<td>+0.4% −0.4%</td>
<td>+0.7% −0.7%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.13%</td>
<td>0.13%</td>
<td>0.15%</td>
<td>0.15%</td>
<td>0.11%</td>
</tr>
<tr>
<td>Data/MC statistical (CR)</td>
<td>1.6%</td>
<td>2.7%</td>
<td>1.0%</td>
<td>3.3%</td>
<td>6%</td>
</tr>
<tr>
<td>Total (stat.)</td>
<td>2.1%</td>
<td>4%</td>
<td>1.0%</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td>Total (syst.)</td>
<td>4%</td>
<td>7%</td>
<td>4%</td>
<td>8%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Table 3: Systematic and statistical uncertainties on the total background in each of the signal regions for the merged and resolved analyses. The background estimation uncertainties have been scaled by the ratio of the multijet contribution to the total background estimation in order to get the relative error on the total background.
8 Results

After applying all selection criteria in the signal regions, the multijet background in the Higgs boson candidate mass window is evaluated according to Eq. (1). Mass distributions of reconstructed Higgs boson candidates are shown in Fig. 2 for the merged and resolved cases in SR3. The observed data and the background predictions are consistent within statistical and systematic uncertainties.

Figure 2: Observed (black points) and expected (red band) distribution of the reconstructed Higgs boson candidate mass in signal region 3 for the (a) merged and (b) resolved cases. The normalisation of region C is applied as an overall factor, and not bin-by-bin, for the Higgs boson candidate mass window. The red error bands represent the systematic uncertainty on the expected background. The distribution from a signal with $m_G = 1$ TeV and $m_{B_H} = 0.75$ TeV is also shown for the parameters listed in Section 3. The lower panels show the ratio of the observed number of events in data to the expected background.

For each pair of mass points considered, the expected signal yield, based on the benchmark model, is evaluated in the corresponding signal region. These yields result from the signal $\sigma \times (A \times \epsilon)$, where $\sigma$ is the cross section including all the branching fractions and $(A \times \epsilon)$ is the acceptance times reconstruction efficiency of the signal selection cuts. The amount of contamination, defined as the expected ratio of the number of signal events in control regions B, C, or D to that in the signal region, is also estimated.

Table 4 shows the expected and observed background event yields in each of the signal regions for the merged and resolved cases. No significant excess of data events is found compared to the expected SM background. Upper limits at the 95% confidence level (CL), using the CL$_S$ prescription [54] and RooStats [55], are set on the cross section times the branching fraction of a signal, combining results from the merged and resolved analyses. To account for possible contamination of the control regions by signal, an iterative procedure is used: a 95% CL limit is first obtained assuming no contamination in the control regions. The contamination in regions B, C, D is then calculated, assuming a signal corresponding
to that limit, and the multijet background is then re-evaluated. The procedure is repeated until it converges
to a stable value. Expected and observed limits on the cross section \( \sigma(pp \to G^* \to B_H b) \times \text{BR}(B_H \to Hb) \) \( \times \text{BR}(H \to b\bar{b}) \), where \( \sigma(pp \to G^* \to B_H b) \) represents the cross section of the process \( pp \to G^* \to B_H \bar{b} \) and its complex conjugate, as well as the theoretical cross section for the benchmark model, with its theoretical uncertainty, are shown in Table 5. Limits for the particular cases where \( m_{B_H} = m_{G^*}/2 \) and \( m_{B_H} = m_{G^*} - 250 \text{ GeV} \) are shown in Figs. 3 and 4.

<table>
<thead>
<tr>
<th>Background</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
<th>SR4</th>
<th>SR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multijet</td>
<td>1104 ± 27</td>
<td>398 ± 16</td>
<td>3372 ± 49</td>
<td>259 ± 12</td>
<td>85 ± 7</td>
</tr>
<tr>
<td>( t\bar{t}/\text{top} )</td>
<td>107 ± 4</td>
<td>30.0 ± 2.3</td>
<td>398 ± 8</td>
<td>18.3 ± 1.9</td>
<td>4.2 ± 1.0</td>
</tr>
<tr>
<td>( W/Z + \text{jets} )</td>
<td>10.5 ± 1.3</td>
<td>4.4 ± 0.9</td>
<td>30.1 ± 1.9</td>
<td>2.6 ± 0.8</td>
<td>0.8 ± 0.5</td>
</tr>
<tr>
<td><strong>Total BG</strong></td>
<td>1222 ± 33 ± 70</td>
<td>432 ± 20 ± 60</td>
<td>3800 ± 60 ± 150</td>
<td>280 ± 16 ± 30</td>
<td>90 ± 9 ± 25</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>1310</td>
<td>456</td>
<td>3827</td>
<td>287</td>
<td>89</td>
</tr>
</tbody>
</table>

**Resolved**

<table>
<thead>
<tr>
<th>Background</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
<th>SR4</th>
<th>SR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multijet</td>
<td>1985 ± 34</td>
<td>639 ± 18</td>
<td>8580 ± 90</td>
<td>523 ± 18</td>
<td>141 ± 9</td>
</tr>
<tr>
<td>( t\bar{t}/\text{top} )</td>
<td>64.2 ± 3.2</td>
<td>17.7 ± 1.8</td>
<td>353 ± 8</td>
<td>15.4 ± 1.6</td>
<td>3.3 ± 0.7</td>
</tr>
<tr>
<td>( W/Z + \text{jets} )</td>
<td>35.0 ± 3.3</td>
<td>12.7 ± 1.8</td>
<td>142 ± 6</td>
<td>12.8 ± 2.2</td>
<td>2.6 ± 0.4</td>
</tr>
<tr>
<td><strong>Total BG</strong></td>
<td>2080 ± 40 ± 80</td>
<td>669 ± 25 ± 50</td>
<td>9080 ± 90 ± 340</td>
<td>551 ± 23 ± 50</td>
<td>147 ± 12 ± 25</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>2106</td>
<td>706</td>
<td>8927</td>
<td>568</td>
<td>122</td>
</tr>
</tbody>
</table>

Table 4: Observed data and background yields in the different signal regions for the merged and resolved cases. The first error is statistical and the second is systematic, while for individual background contributions only the statistical error is shown. Statistical errors on the numbers of data events in the control regions used to estimate the multijet background are included in the total statistical error. The row \( t\bar{t}/\text{top} \) includes \( t\bar{t} \), single-top and \( t\bar{t} + V/H \) backgrounds while \( W/Z + \text{jets} \) includes leptonic and hadronic decays of the vector boson.
<table>
<thead>
<tr>
<th>$m_{B_H}$ [TeV]</th>
<th>$m_{G^*}$ [TeV]</th>
<th>$\sigma(pp \rightarrow G^* \rightarrow B_H b) \times BR(B_H \rightarrow H b) \times BR(H \rightarrow b\bar{b})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.0</td>
<td>$62^{+62}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$68^{+8}_{-4}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$62^{+58}_{-24}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$61^{+75}_{-23}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$71^{+110}_{-29}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$74^{+6}_{-4}$</td>
</tr>
<tr>
<td>1.875</td>
<td>1.0</td>
<td>$72^{+48}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$51^{+36}_{-17}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$57^{+52}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$61^{+72}_{-24}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$65^{+82}_{-26}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$66^{+6}_{-4}$</td>
</tr>
<tr>
<td>1.75</td>
<td>1.0</td>
<td>$66^{+42}_{-23}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$66^{+104}_{-50}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$66^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$66^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td>1.625</td>
<td>1.0</td>
<td>$66^{+42}_{-23}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$66^{+104}_{-50}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$66^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$66^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td>1.50</td>
<td>1.0</td>
<td>$66^{+42}_{-23}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$66^{+104}_{-50}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$66^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$66^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td>1.375</td>
<td>1.0</td>
<td>$66^{+42}_{-23}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$66^{+104}_{-50}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$66^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$66^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td>1.25</td>
<td>1.0</td>
<td>$66^{+42}_{-23}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$66^{+104}_{-50}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$66^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$66^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td>1.125</td>
<td>1.0</td>
<td>$66^{+42}_{-23}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$66^{+104}_{-50}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$66^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$66^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$66^{+55}_{-21}$</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>$163^{+104}_{-50}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$163^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$163^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$163^{+53}_{-19}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$163^{+55}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$163^{+55}_{-18}$</td>
</tr>
<tr>
<td>0.875</td>
<td>1.0</td>
<td>$163^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$163^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$163^{+53}_{-19}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$163^{+55}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$163^{+55}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$163^{+55}_{-18}$</td>
</tr>
<tr>
<td>0.75</td>
<td>1.0</td>
<td>$163^{+49}_{-22}$</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>$163^{+43}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>$163^{+53}_{-19}$</td>
</tr>
<tr>
<td></td>
<td>1.75</td>
<td>$163^{+55}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>$163^{+55}_{-18}$</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>$163^{+55}_{-18}$</td>
</tr>
</tbody>
</table>

Table 5: Combined limits, in fb, on $\sigma(pp \rightarrow G^* \rightarrow B_H b) \times BR(B_H \rightarrow H b) \times BR(H \rightarrow b\bar{b})$. First and second entries in each cell give the expected and observed limits respectively. The third entry gives the cross section in fb predicted by the benchmark model. Red cells are excluded and green cells are not excluded at 95% C.L. Cases where $m_{G^*} > 2m_{B_H}$ are not considered in this analysis and are marked in yellow.
Figure 3: Observed (solid) and expected (dashed) 95% C.L. upper limits on the cross section $\sigma \left( pp \rightarrow G^* \rightarrow B_H b \right) \times \text{BR} \left( B_H \rightarrow Hb \right) \times \text{BR} \left( H \rightarrow b\bar{b} \right)$ for VLQ mass points with $m_{B_H} = m_{G^*}/2$, from the combined merged and resolved analyses, as well as the theoretical prediction based on parameters given in Section 3. The uncertainty band around the theory cross section reflects the uncertainty in the CTEQ6.6 PDFs.
A search for a heavy gluon and a charge $-1/3$ vector-like quark in the process $pp \rightarrow G^* \rightarrow B_H \bar{b}$, with $B_H \rightarrow bH$ and $H \rightarrow \bar{b}b$, has been performed using an integrated luminosity of 19.5 fb$^{-1}$ of $pp$ collision data recorded at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC. The main background, multijet production, is estimated with a data-driven technique. Five signal regions are defined based on the choice of jet assignment to the $B_H$ candidate and on lower mass requirements for the reconstructed $G^*$ and $B_H$. No significant excess over the SM predictions is observed and upper limits have been set at the 95% confidence level on the total cross section times branching ratio in the two-dimensional plane of $m_{G^*}$ vs. $m_{B_H}$ with $m_{G^*} \leq 2m_{B_H}$. Using a benchmark model presented in Ref. [23], a lower limit of 2.0 TeV on the $G^*$ mass is obtained when $m_{G^*} = 2m_{B_H}$. 

9 Conclusion
Acknowledgements

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; BMWFW 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-DSM/IRFU, France; GNSF, Georgia; 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; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, 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, 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; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and 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) and in the Tier-2 facilities worldwide.
References


The ATLAS Collaboration

G. Aad$^{85}$, B. Abbott$^{112}$, J. Abdallah$^{150}$, O. Abidin$^{11}$, B. Abeloo$^{116}$, R. Aben$^{106}$, M. Abolins$^{90}$, O.S. AbouZeid$^{196}$, H. Abramowicz$^{152}$, H. Abreu$^{151}$, R. Abreu$^{115}$, Y. Abulaiti$^{145a,145b}$, B.S. Acharya$^{163a,163b}$, L. Adamczyk$^{38a}$, D.L. Adams$^{25}$, J. Adelman$^{107}$, S. Adomeit$^{99}$, T. Adye$^{130}$, A.A. Affolder$^{74}$, T. Agatonovic-Jovin$^{13}$, J. Agricola$^{54}$, J.A. Aguilar-Saavedra$^{125a,125f}$, S.P. Ahlen$^{22}$, F. Ahmadov$^{65}$, G. Aielli$^{132a,132b}$, H. Akerstedt$^{145a,145b}$, T.P.A. Åkesson$^{81}$, A.V. Akimov$^{95}$, G.L. Alberghi$^{103a,103b}$, A. Aloisio$^{103a,103b}$, T. Alexander$^{152}$, T. Alexopoulos$^{10}$, M. Albroo$^{112}$, G. Alimonti$^{91a}$, L. Aliò$^{85}$, J. Alison$^{31}$, S.P. Alkins$^{35}$, B.M.M. Allbrooke$^{148}$, B.W. Allen$^{115}$, P.P. Allport$^{18}$, A. Aloisio$^{103a,103b}$, A. Alonso$^{135}$, J. Alper$^{16}$, S. Albrand$^{26b}$, M.G. Alviggi$^{30}$, C. Amelung$^{152}$, N. Amram$^{9}$, C.F. Anders$^{131a,131b}$, N. Anjos$^{9}$, 9, L. Aperio Bella$^{142}$, M. Arratia$^{28}$, A. Ashkenazi$^{152}$, 140, A.E. Baas$^{58a}$, P. Bagiacchi$^{128}$, P. Balek$^{28}$, T. Balestri$^{74}$, A. Annovi$^{31}$, F. Bertolucci$^{122}$, A. Alonso$^{23}$, G. Amundsen$^{23}$, K. Augsten$^{124}$, W. Bhimji$^{123a,123b}$, M. Bindi$^{147}$, O. Bessidskaia Bylund$^{131a,131b}$, L. Barak$^{90}$, L. Barakova$^{98}$, E. Banas$^{39}$, E. Banas$^{39}$, L. Banerjee$^{172}$, A.E. Bannoura$^{174}$, L. Barak$^{30}$, E.L. Barberio$^{38}$, D. Barberis$^{50a,50b}$, M. Barbero$^{83}$, T. Barillari$^{100}$, M. Barisonzi$^{163a,163b}$, T. Barklow$^{142}$, N. Barlow$^{28}$, S.L. Barnes$^{84}$, B.M. Barnett$^{130}$, R.M. Barnett$^{15}$, Z. Barnovska$^{16}$, A. Baroncelli$^{133a}$, G. Barone$^{23}$, A.J. Bart$^{119}$, L. Barranco Navarro$^{166}$, F. Barreiro$^{82}$, J. Barreiro Guimarães da Costa$^{33a}$, R. Bartoldus$^{142}$, A.E. Barton$^{72}$, P. Bartos$^{143a}$, A. Basalaev$^{122}$, A. Bassalat$^{116}$, A. Basile$^{164}$, R. Becchere$^{123a,123b}$, P. Bechtle$^{21}$, H.P. Beck$^{17a}$, K. Becker$^{119}$, M. Becker$^{83}$, M. Beckingham$^{169}$, C. Becot$^{109}$, A.J. Beddall$^{19a}$, A. Beddall$^{19b}$, V.A. Bednyakov$^{65}$, M. Bedognetti$^{106}$, C.P. Bee$^{147}$, L.J. Beemster$^{106}$, T.A. Beermann$^{30}$, M. Begel$^{25}$, J.K. Behr$^{119}$, C. Belanger-Champagne$^{87}$, A.S. Bell$^{78}$, W.H. Bell$^{40}$, G. Bella$^{25}$, L. Bellagamba$^{30a}$, A. Bellerive$^{29}$, M. Bellomo$^{46}$, K. Belotskii$^{97}$, O. Beltramello$^{30}$, N.L. Belyaev$^{99}$, O. Benary$^{158b}$, F. Berghaus$^{20a,20b}$, D. Berlends$^{22}$, J.P. Bernardo$^{20}$, D.M. Bjorgaard$^{45}$, C.W. Black$^{149}$, J.E. Black$^{142}$, K.M. Black$^{22}$, D. Blackburn$^{137}$, R.E. Blair$^{10}$, J.-B. Blanchard$^{135}$,
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, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul,Turkey; (d) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (also affiliated with PKU-CHEP); (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and
CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Department of Physics, Kyushu University, Fukuoka, Japan
71 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
72 Physics Department, Lancaster University, Lancaster, United Kingdom
73 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
75 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
76 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
77 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
78 Department of Physics and Astronomy, University College London, London, United Kingdom
79 Louisiana Tech University, Ruston LA, United States of America
80 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
81 Fysiska institutionen, Lunds universitet, Lund, Sweden
82 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
83 Institut für Physik, Universität Mainz, Mainz, Germany
84 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
85 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
86 Department of Physics, University of Massachusetts, Amherst MA, United States of America
87 Department of Physics, McGill University, Montreal QC, Canada
88 School of Physics, University of Melbourne, Victoria, Australia
89 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
91 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
94 Group of Particle Physics, University of Montreal, Montreal QC, Canada
95 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
97 National Research Nuclear University MEPhI, Moscow, Russia
98 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
101 Nagasaki Institute of Applied Science, Nagasaki, Japan
102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
103 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
107 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
109 Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCP TM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohammed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
Department of Physics, University of Washington, Seattle WA, United States of America
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
(a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
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
Department of Physics, University of Toronto, Toronto ON, Canada
(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, 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 MA, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, 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 WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität

34
Wuppertal, Wuppertal, Germany

175 Department of Physics, Yale University, New Haven CT, United States of America

176 Yerevan Physics Institute, Yerevan, Armenia

177 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

d Also at Department of Physics, King’s College London, London, United Kingdom
b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
c Also at Novosibirsk State University, Novosibirsk, Russia
d Also at TRIUMF, Vancouver BC, Canada
e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America
f Also at Department of Physics, California State University, Fresno CA, United States of America
g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
h Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain
i Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
j Also at Tomsk State University, Tomsk, Russia
k Also at Universita di Napoli Parthenope, Napoli, Italy
l Also at Institute of Particle Physics (IPP), Canada
m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
n Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
o Also at Louisiana Tech University, Ruston LA, United States of America
p Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
q Also at Graduate School of Science, Osaka University, Osaka, Japan
r Also at Department of Physics, National Tsing Hua University, Taiwan
s Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
t Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
u Also at CERN, Geneva, Switzerland
v Also at Georgian Technical University (GTU), Tbilisi, Georgia
w Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
x Also at Manhattan College, New York NY, United States of America
y Also at Hellenic Open University, Patras, Greece
z Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
aa Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
ab Also at School of Physics, Shandong University, Shandong, China
ac Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
ad Also at Section de Physique, Université de Genève, Geneva, Switzerland
ae Also at International School for Advanced Studies (SISSA), Trieste, Italy
af Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
ag Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
ah Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
ai Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
aj Also at National Research Nuclear University MEPhI, Moscow, Russia
ak Also at Department of Physics, Stanford University, Stanford CA, United States of America
al Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest,
Hungary

\textsuperscript{am} Also at Flensburg University of Applied Sciences, Flensburg, Germany

\textsuperscript{an} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

\textsuperscript{ao} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

* Deceased