A search for decays of new particles to a Higgs boson and a $W$ or $Z$ boson is described. Focus is put on a search for heavy resonances (resonance mass greater than 1 TeV) where the $W/Z$ and Higgs boson decay hadronically and the Higgs decays to $b\bar{b}$ in particular. 79.8 fb$^{-1}$ of proton-proton ($pp$) collision data at $\sqrt{s} = 13$ collected with the ATLAS detector at the CERN Large Hadron Collider between 2015 and 2017 is utilized in the search. In this analysis, narrow simulated resonances are smeared to larger widths in order to compare the significance of signals with regard to width. In all cases, wider signals are found to have lower significance.
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I. INTRODUCTION

A. The Standard Model

The Standard Model of particle physics is the theory, developed over the last century, that classifies the known elementary particles and describes their interactions by the fundamental forces (excluding gravity). It includes 6 quarks and 6 leptons (and their antiparticles), as well as 4 gauge bosons and a scalar boson, the Higgs boson. These particles have no substructure and cannot be split further [2].

Fermions

Fermions are generally characterized as having spin $\frac{1}{2}$ and include quarks and leptons. They are divided into 3 generations, as shown in Figure 1. The first generation is composed of the lightest particles that make up stable matter. The third generation is composed of the heaviest and least stable particles, which quickly decay into generation I and II particles. Quarks are differentiated from leptons because leptons do not experience strong force interactions or color charge, a property related to the strong interaction [2].

Quarks are bound together via the strong interaction to compose particles called hadrons, which are generally classified either as baryons or mesons. Baryons have half-integer spin and are composed of 3 quarks, while mesons have integer spin and are composed of a quark-antiquark pair [3].
Bosons

Gauge bosons are elementary particles with nonzero integer spin that are responsible for propagating the fundamental forces. The photon is the force carrier of the electromagnetic force, while the gluon, which exists in 8 distinct types, mediates the strong interaction. The $W$ and $Z$ bosons, which carry the weak interaction, are most relevant to this project. While the other gauge bosons are massless, $W$ and $Z$ bosons have masses of approximately 91.188 GeV and 80.385 GeV respectively. The $W$ boson exists in two types, denoted $W^+$ and $W^-$, based on its electric charge. The $W^+$ and $W^-$ boson are each other’s antiparticle. The $Z$ boson, however, has no electric charge and thus has no antiparticle. $W$ and $Z$ bosons are referred to collectively as $V$ bosons in this search. Gravity is not currently explained by the Standard Model, but a particle called the graviton is hypothesized to carry the gravitational force.

The Higgs boson, first observed in 2012 by the ATLAS and CMS experiments at CERN, is the only scalar boson. It has 0 spin and a mass of approximately 125.09 GeV. The Higgs boson is responsible for propagating the Higgs field, which gives mass to massive particles [2, 3]. Several theories attempting to resolve issues with the Standard Model predict the existence of particles that exhibit coupling with the Higgs boson [4].

B. CERN and the LHC

The European Organization for Nuclear Research (CERN), founded in 1954, is a research organization that builds and operates several particle accelerators and one particle decelerator near Geneva, Switzerland. In September 2008, CERN started up the Large Hadron Collider (LHC), which sits on the Franco-Swiss border near Geneva and is currently the world’s largest particle accelerator [5]. The LHC consists of a ring, 27 km in circumference, of superconducting magnets kept at less than 2°C above absolute zero. The magnets direct the paths of two beams of protons

![Overall view of the LHC experiments.](image-url)

FIG. 2: Main LHC experiments [6]
traveling in separate beam pipes in opposite directions along the circular path. Once they have been accelerated to nearly the speed of light, bunches of protons are made to collide inside of the detectors. As depicted in Figure 2, the main LHC experiments are ATLAS, CMS, ALICE, and LHCb. ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid) are the two general-purpose detectors at the LHC that studies a wide range of physics. ALICE (A Large Ion Collider Experiment) studies strongly interacting matter at high energy densities using lead ion collisions, while LHCb (Large Hadron Collider beauty) studies the bottom ($b$) quark and interactions between hadrons containing it [7].

C. The ATLAS Detector

The ATLAS detector is a 46 m long, 25 m diameter general purpose particle detector composed of a magnet system, a muon spectrometer, calorimeters, and an inner detector. The magnet system is made up of a 5.3 m long solenoid magnet and several toroidal magnets. Its purpose is to provide the magnetic field necessary to make momenta measurements. The muon spectrometer is the outermost part of the ATLAS detector. It measures the momenta and direction of the muons, which are the only particles which are not stopped by the calorimeters.

The calorimeters, located between the inner detector and the muon spectrometer, are used mainly to measure the particle energies. The hadronic calorimeter absorbs energy from particles that interact via the strong interaction, namely hadrons, while the electromagnetic calorimeter detects particles that interact via the electromagnetic force, such as electrons and photons. The calorimeter is composed of metal absorbers and sensing elements. In parts of the calorimeter, this sensing element is liquid argon (denoted LAr in Figure 3). The outer parts of the calorimeter use scintillating plastic tiles to detect particles (labeled tile calorimeters in Figure 3).

The inner detector consists of a pixel detector, semiconductor tracker (SCT) system, and a transition radiation tracker (TRT). The pixel detector is made up of silicon pixels and, being closest to the interaction point, has the highest granularity. The SCT is similar to the pixel detector but is composed of silicon strips. The TRT utilizes straw detectors, which are cylindrical tubes 4 mm in diameter that contribute to measuring the momentum of particles [8].

Every type of particle has its own signature based on which parts of the detector it does and does not interact with. For example, electrons are stopped by the electromagnetic calorimeter, but neutrons do not interact until they reach the hadronic calorimeter. Figure 4 depicts this.

ATLAS utilizes a trigger system in order to reduce the flow of data from the detector to manageable levels. This system selects events that contain characteristics that might lead to new discoveries and discards the rest. It selects about 100 interesting events per second out of 1000 million total [9].
D. Heavy $VH \rightarrow q\bar{q}b\bar{b}$ Resonances

Resonance is a term typically used to describe the peaks observed in the cross sections of scattering experiments. These peaks correspond to particles that decay strongly and are extremely short lived, usually with lifetimes less than $10^{-23}$ seconds. The resonance is usually characterized
by the energy at which the peak occurs, and the energy uncertainty is reflected in the width of the resonance [11]. In this search, focus is put on resonances with mass greater than 1 TeV, hence the term heavy resonance.

Recently, there have been attempts to address deficiencies in the Standard Model, such as sensitivity of the Higgs boson mass to radiative corrections. A significant number of theories attempting to resolve this issue, including composite Higgs models, predict the existence of particles that are expected to couple with the Higgs Boson [12]. This search looks for an unknown resonance, $Y$, decaying into a Higgs boson and a $W$ or $Z$ boson, which both decay hadronically. This decay is depicted in Figure 5. Given its assumed decay modes, the particle $Y$ must be a boson [4].

II. DATA AND MONTE CARLO SAMPLES

This analysis utilizes 79.8 fb$^{-1}$ of proton-proton ($pp$) collision data at $\sqrt{s} = 13$ collected by the ATLAS detector between 2015 and 2017. Only data collected during stable beam conditions with functional detector systems were considered. The background estimation is performed using data as described in Section V.C.

Signals utilized in this analysis are modeled with Monte Carlo (MC) simulation. Signal events were generated with Madgraph5_aMC@NLO 2.2.2 interfaced to Pythia 8.186 for parton shower and hadronization [12]. The analysis includes narrow $WH \rightarrow qq\bar{b}b$ and $ZH \rightarrow qq\bar{b}b$ samples with resonance masses of 1 TeV, 3.5 TeV, and 5 TeV.

Statistics for the $WH \rightarrow qq\bar{b}b$ signals and data appear in Figure 6.
FIG. 6: Statistics for the data and $WH \rightarrow q\bar{q}b\bar{b}$ signals
III. SEARCH STRATEGY

In this search, we look for the decay of a new boson $Y$ to a Higgs boson and a $W$ or $Z$ boson, which decay hadronically. This search is sensitive to resonance masses above 1 TeV. 79.8 fb$^{-1}$ of $pp$ collision data is utilized in the search.

At 125 GeV, the branching ratio of the $H \to bb$ channel is approximately 57% (See Figure 7). Because this decay mode is so common, Higgs bosons can be identified through the use of $b$-tagging, a method used to identify jets with characteristics matching those of a $b$-jet. In this analysis, the Higgs and $V$ bosons are expected to have a very high kinetic energy and $p_t$ because the resonances being searched for are much more massive than their final decay products. The hadronic jets are expected to have high $p_t$ for the same reason. These objects are referred to as boosted. In a decay to two quarks, the angular separation of the quarks is related by the equation

$$\Delta R = \sqrt{\Delta \Phi^2 + \Delta \eta^2} \approx \frac{2m}{p_t}$$

where $\eta$ is the pseudorapidity and $\Phi$ is the azimuthal angle.\(^2\) It can be observed that as the $p_t$ becomes very large, the angle between the two quarks becomes small. Since the angle between the boosted $b$-jets is expected to be small, Higgs candidates are identified by reconstructing large-$R$ jets (large radius jets; see Section IV) and searching for those that contain $b$-jets. This technique is known as the boosted regime\(^1\).

\(^1\) Transverse momentum; the component of a particle’s momentum perpendicular to the beam axis ($p_t = p \sin \theta$)

\(^2\) The ATLAS coordinate system is implemented with its origin at the nominal interaction point in the center of the detector and the z-axis along the beam pipe. The x-axis points from the interaction to 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 $\eta = -\ln \tan \theta/2$ [12].

FIG. 7: Higgs Branching Ratios [13]
The $W$ and $Z$ bosons have hadronic branching ratios of approximately 67.60% and 69.91% respectively [15]. Boosted $V$ bosons are identified using substructure techniques that search for the proper two-prong structure within the large-$R$ jet [14].

**IV. EVENT RECONSTRUCTION AND SELECTION**

**A. Reconstruction**

Hadronically decaying $V$ boson and Higgs boson candidates are identified and reconstructed using the anti-$k_t$ jet clustering algorithm with radius $R = 1.0$. The anti-$k_t$ algorithm is a soft-resilient jet algorithm that produces conical jets and determines the exact shape of each jet based only on hard particles (i.e. soft radiation particles do not modify the shape of the jet) [17]. The large-$R$ jets are reconstructed from topological clusters of calorimeter energy [12]. They also trimmed in order to diminish the effects of pile-up and soft radiation, as shown in Figure 8. In order to accomplish this, the constituents of each large-$R$ jet are reclustered into subjets with radius $R = 0.2$, removing subjets with $p_T$ that is less than 5% of the original large-$R$ jet ($p_T^{\text{subj}} / p_T^{\text{jet}} < 5\%$) [18]. The jets are further required to have $p_T > 200$ GeV, since the final state particles are expected to have high kinetic energy and thus high $p_T$. The mass of the final large-$R$ jets is calculated using a combination of tracking and calorimeter information, defined by the equation

$$m_J \equiv w_{\text{calo}} \times m_J^{\text{calo}} + w_{\text{track}} \times (m_J^{\text{track}} \frac{p_T^{\text{calo}}}{p_T^{\text{track}}})$$  \hspace{1cm} (2)$$

where $m_J^{\text{calo}}$ ($p_T^{\text{calo}}$) is the calorimeter estimate of jet mass ($p_T$) and $m_J^{\text{track}}$ ($p_T^{\text{track}}$) is the jet mass ($p_T$) estimated using the associated track jets with $p_T > 0.4$ GeV. $w_{\text{calo}}$ and $w_{\text{track}}$ are $p_T^{\text{calo}}$-dependent functions used to optimize the combined mass resolution [12].

Track jets, jets identified and measured by the ATLAS inner detector, are used in the identification of $b$-jets. Track jets are constructed from charged particle tracks with $p_T > 0.4$ GeV and $|\eta| < 2.5$. In order to determine which track jets are $b$-jets, a multivariate tagging algorithm, MV2c10, is used. This algorithm combines the output of several vertexing and impact parameter tagging algorithms that identify $b$-hadrons by reconstructing an inclusive displaced secondary vertex and exploiting their unusually long lifetime respectively. The $b$-tagging requirements result in an $b$-jet efficiency of 77% with a misidentification rate of about 2% for light-flavor jets and 24% for charm jets [12, 19]. In this analysis, events with MV2c10 > 0.3706 (out of 1) are considered $b$-jet candidates.
Leptons ($\ell$) are used in a veto to ensure the independence of the data selected for analysis with respect to heavy $VH$ resonance searches in non-fully hadronic final states. This implies that events with leptons are not included in the analysis. Additionally, events selected for the analysis must have at least two large-$R$ jets with $|\eta| < 2.0$ and invariant mass $m_J > 50$ GeV. The two leading $p_T$ large-$R$ jets within the event must have $p_T$ greater than 450 GeV and 250 GeV respectively [12]. This is because the Higgs boson is more massive than either the $W$ or $Z$ boson, and its decay products are expected to be more energetic. Hence, the leading $p_T$ large-$R$ jet will be tested for Higgs candidacy and the subleading large-$R$ jet will be tested for $V$ boson candidacy. These cuts are summarized in Table I.

### Table I: Summary of cuts

<table>
<thead>
<tr>
<th>Selection</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjets (trimming process)</td>
<td>$p_T^{\text{subjet}} / p_T^{\text{jet}} &gt; 5%$</td>
</tr>
<tr>
<td>Large-$R$ jets</td>
<td>$p_{T,\text{Leading}} &gt; 450$ GeV, $p_{T,\text{Subleading}} &gt; 250$ GeV, $m_J &gt; 50$ GeV, $</td>
</tr>
<tr>
<td>Track jets</td>
<td>$p_t &gt; 0.4$ GeV, $</td>
</tr>
<tr>
<td>Lepton Veto</td>
<td>Remove events with leptons</td>
</tr>
<tr>
<td>Higgs cuts</td>
<td>95 GeV $&lt; m_J &lt; 145$ GeV, MV2c10 $&gt; 0.3706$</td>
</tr>
<tr>
<td>W/Z tagging</td>
<td>95 GeV $&lt; m_J &lt; 105$ GeV, $D_2$ cuts</td>
</tr>
</tbody>
</table>

**B. Selection**

Higgs and $V$ boson candidates are determined using methods dictated in Section VA and Section VB. For events with both a Higgs candidate and a $V$ boson candidate, the $Y$ resonance is reconstructed. A 4-vector is formed for the Higgs and the $V$ boson candidates, and the two are added using vector addition. Information about the $Y$ resonance can then be used.

### V. RESONANCE RECONSTRUCTION

For each event that passes selection, the leading $p_T$ large-$R$ jet is tested for Higgs boson candidacy. Large-$R$ jets with 95 GeV $< m_J < 145$ GeV are considered. The events are then classified into two signal regions and one control region based on the number of $b$-jets tagged within the large-$R$ jet. Events in which 1 or both of the leading $p_T$ track jets within the leading large-$R$ jet are $b$-tagged are considered Higgs candidates and are utilized in the analysis. These events fall in the “1-tag” (denoted SR1) and “2-tag” (denoted SR2) regions respectively. Figure 9 shows the mass distribution of the Higgs candidates. Events in which the leading $p_T$ large-$R$ jet passes the mass requirements but has no $b$-tagged track jets fall in the control region (denoted CR0). This region is used in the background determination [4]. Figure 10 depicts these regions.
FIG. 9: Higgs candidate mass distribution for signals

(a) WH → qqb̄b signals

(b) ZH → qqb̄b signals

FIG. 10: Signal regions and control region. The sideband, which is not utilized in this analysis, has similar expected event yield to the signal region. [12]

B. V Boson Selection

The subleading $p_T$ large-$R$ jet in each event is tested for $V$ boson candidacy. Large-$R$ jets with $65 \, \text{GeV} < m_J < 105 \, \text{GeV}$ are considered. For the jet to be considered a $V$ boson candidate, it must also pass a substructure cut. This selection is based on the variable $D_2$, which exploits energy correlation functions to tag boosted objects with two-prong decay structures [12].
The $D_2$ is calculated as follows:

$$D_2^{3=1} = E_{CF3} \left( \frac{E_{CF1}}{E_{CF2}} \right)^3 $$

where

$$E_{CF1} = \sum_{i} p_{T,i}$$

$$E_{CF2} = \sum_{ij} p_{T,i} p_{T,j} \Delta R_{ij}$$

$$E_{CF3} = \sum_{ijk} p_{T,i} p_{T,j} p_{T,k} \Delta R_{ij} \Delta R_{jk} \Delta R_{ki}.$$ 

The $E_{CF}$ equations are energy correlation functions based on the angular separation $\Delta R$ between subjets and the $p_T$ of individual subjets [14]. This selection is dependent on whether the large-$R$ jet is a $W$ or $Z$ boson candidate. The $V$-jet tagging efficiency is approximately 50% with a misidentification rate of about 2% [12]. Figure 11 shows the mass distributions of the selected $V$ boson candidates.

**C. Background Estimation**

The predominant background (approximately 90%) for the signal originates from multijet events [12]. This multijet background is modeled directly from data. The control region described in Section VA, which consists of about 99% multijet events, is used to model the background in the signal (SR1 and SR2) regions. The control region is normalized to the 1-tag and 2-tag regions separately, as seen in the plots in Section VI.
VI. ANALYSIS

In order to test if $VH \rightarrow qqbb$ signals of different widths are detectable, the $WH \rightarrow qqbb$ and $ZH \rightarrow qqbb$ signals are smeared using a smearing function. This step is performed due to the lack of generated signals with greater width, which corresponds to a shorter lifetime of the particle. Each signal is assumed to be a relativistic Breit-Wigner distribution, defined by the equation

$$
\sigma_2(E; \mu, \Gamma) = \frac{\mu \Gamma}{\pi} \frac{1}{(E^2 - \mu^2)^2 + (\mu \Gamma)^2},
$$

(4)

where $E > 0$ is the energy of the resonance, $\mu > 0$ is the mass of unstable particle and $\Gamma > 0$ is the width of the resonance [20]. For each signal, the resonance width $\Gamma$ is increased by 5% and 10%, and the smeared signals are compared to the original. As depicted in Figures 14-25 below, the smeared signals are flatter in shape. The significance of each signal and smeared signal is then calculated using the asymptotic formula

$$
s = \sqrt{2(n_s + n_b) \ln(1 + \frac{n_s}{n_b}) - 2n_s}
$$

(5)

where $n_s$ is the number of signal events and $n_b$ is the number of background events. The significance is calculated around each peak, utilizing a mass window from 1.0-1.7 TeV for the 1.2 TeV signals, 3.0-4.0 GeV for 3.5 TeV signals, and 4.5-5.5 TeV for the 5 TeV signals. For the 1.2 TeV signals, the because the ATLAS trigger system is not efficient in this range [21]. The significance of each signal and smeared signal is given in Table II. These numbers are not normalized.

There are a few observations that can be made from this data. The significance of the narrower (original) signal is consistently higher than that of the wider signals. This is because as the signal becomes wider and flatter, it approaches the shape of the background and is thus less significant. Additionally, the 1.2 TeV signals have markedly lower significance than the 3.5 and 5 TeV signals.

![FIG. 12: 1-tag data with background](image1.png)

![FIG. 13: 2-tag data with background](image2.png)
Events

1
10
2
10
3
10
4
10
5
10
6
10 Background
Data
WH, m(Y) = ... = 36.1 fb⁻¹

∫
Mass [GeV]
3000 3200 3400 3600 3800 4000
Data/Background

0.4
0.6
0.8
1
1.2
1.4
1.6
79.8

FIG. 14: 1.2 TeV WH → qq̄b̄ signal with 1-tag data

FIG. 15: 1.2 TeV WH → qq̄b̄ signal with 2-tag data

FIG. 16: 3.5 TeV WH → qq̄b̄ signal with 1-tag data

FIG. 17: 3.5 TeV WH → qq̄b̄ signal with 2-tag data
FIG. 18: 5 TeV $WH \rightarrow qqb\bar{b}$ signal with 1-tag data

FIG. 19: 5 TeV $WH \rightarrow qqb\bar{b}$ signal with 2-tag data

FIG. 20: 1.2 TeV $ZH \rightarrow qqb\bar{b}$ signal with 1-tag data

FIG. 21: 1.2 TeV $ZH \rightarrow qqb\bar{b}$ signal with 2-tag data
FIG. 22: 3.5 TeV $ZH \rightarrow q\bar{q}b\bar{b}$ signal with 1-tag data

FIG. 23: 3.5 TeV $ZH \rightarrow q\bar{q}b\bar{b}$ signal with 2-tag data

FIG. 24: 5 TeV $ZH \rightarrow q\bar{q}b\bar{b}$ signal with 1-tag data

FIG. 25: 5 TeV $ZH \rightarrow q\bar{q}b\bar{b}$ signal with 2-tag data
<table>
<thead>
<tr>
<th>Decay</th>
<th>Resonance Mass (TeV)</th>
<th>Region</th>
<th>Smear (% distribution width)</th>
<th>Significance</th>
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</thead>
<tbody>
<tr>
<td>WH 1.2</td>
<td>SR1</td>
<td>0</td>
<td>35.3528</td>
<td></td>
</tr>
<tr>
<td>WH 3.5</td>
<td>SR1</td>
<td>0</td>
<td>273.451</td>
<td></td>
</tr>
<tr>
<td>WH 5</td>
<td>SR1</td>
<td>0</td>
<td>248.628</td>
<td></td>
</tr>
<tr>
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<td>SR1</td>
<td>0</td>
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<td></td>
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<td></td>
</tr>
<tr>
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<td>SR1</td>
<td>0</td>
<td>326.138</td>
<td></td>
</tr>
<tr>
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<td>SR1</td>
<td>5</td>
<td>34.2042</td>
<td></td>
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<td>248.056</td>
<td></td>
</tr>
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<td>5</td>
<td>225.089</td>
<td></td>
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</tr>
<tr>
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<td>193.066</td>
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</tr>
<tr>
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<td>5</td>
<td>100.051</td>
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</tr>
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<td>SR2</td>
<td>5</td>
<td>426.660</td>
<td></td>
</tr>
<tr>
<td>WH 5</td>
<td>SR2</td>
<td>5</td>
<td>392.912</td>
<td></td>
</tr>
<tr>
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<td>5</td>
<td>334.174</td>
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</tr>
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<td>305.417</td>
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<tr>
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<td>305.417</td>
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<tr>
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<td>SR2</td>
<td>10</td>
<td>96.9684</td>
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<tr>
<td>WH 5</td>
<td>SR2</td>
<td>10</td>
<td>362.989</td>
<td></td>
</tr>
</tbody>
</table>

TABLE II: Significance of $WH \rightarrow q\bar{q}b\bar{b}$ and $ZH \rightarrow q\bar{q}b\bar{b}$ signals
VII. CONCLUSION

In this analysis, several $VH \rightarrow qqbb$ resonance signals are reconstructed and smeared to increase their width. This simulates a comparison between resonances with different lifetimes. The original signals and the smeared signals are compared and their significance is determined in relation to the estimated background. It is observed that wider signals consistently have lower significance. Furthermore, the resonances with higher mass tended to have higher significance than lower mass signals. It is concluded that signals of a range of different widths are detectable using our analysis techniques. However, signals of larger widths, which correspond to resonances with shorter lifetimes, are less distinguishable from background.

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