Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Abstract

We present a search for Higgs boson pair production, with the $b\bar{b}b\bar{b}$ final state. This analysis uses the full 2015 and 2016 data collected collected by the ATLAS Collaboration at $\sqrt{s} = 13$ TeV, corresponding to 3.2 ± 0.2 fb^{-1} of 2015 and 32.9 ± 1.1 fb^{-1} of 2016 pp collision data. Improvements with respect to the previous analysis are mainly in the boosted regime, where the resonance signal is between 2500 GeVand 3000 GeV. The data is found to be compatible with the Standard model, and no signs of new physics have been observed. The results are interpreted in the context of the bulk Randall-Sundrum warped extra dimension model with a Kaluza-Klein graviton decaying to hh, with the coupling $k/\bar{M}_{\mathrm{Pl}}$, chosen to be in the allowed range $1.0 - 2.0$. The results are also interpreted with the Type 2 two-Higgs doublet model (2HDM) where the neutral heavy CP-even H scalar decays to hh.

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Everything is meaningless.
Even the sentence above.

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THANKS TO EVERYONE THE ATLAS COLLABORATION, who has supported this remarkable program and has contributed to every bit of the result in my thesis. Sir Issac Newton said he was standing on the gaint's showlders to see far and deep into the nature. Similarly. I am standing on the ATLAS(member)'s showlders–it's eight stories high so I hope ATLAS doesn't shrug. Without the excellent work on detector design, commisioning, operational works, reconstruction, data processing, performance studies and recommendations, software support, computing support, and analysis discussions and guidance, I could not have completed this thesis. I truely and sincerely thank all ATLAS members for their contributions.

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Introduction

Why do we look for $hh \to 4b$?

There are two types of analysis in particle physics. The first one is measurement, which yeilds a observable with an uncertainty. This could either imrpove our current knowledge, or show some inconsistency. The other type is search, which generally assumes some new physics model and try to justfy in data wether the new model is justified in some observables. A successful search turns the subject into a measurement, yet a null search result will set a new limit for a given physics model.

After Run 1 of the LHC, with the existence of the Higgs now firmly established, the focus shifted to searches for physics beyond the Standard Model. In particular, searches for high mass resonances benefit from the LHC's increase to $\sqrt{s} = 13$ TeV in Run 2. The cross section for a generic gluon-initiated resonance with a mass of 2 TeV increases tenfold in Run 2, making searches for high mass resonances a high priority. The newly discovered Higgs can be used as a tool in these searches. After the discovery, the Higgs boson provides a large swath of unmeasured phase space where new physics could be discovered. Higgs pair production in the Standard Model has a low cross section that requires large datasets (on the order of the LHC's lifetime) for full measurement. However, new physics can modify this cross section, especially through new resonances which decay to two Higgs bosons. Such high mass resonances also produce difficult to recognize final state topologies due to the merging of decay products from high momentum Higgs bosons. A search for Higgs pair production in the $HH \rightarrow b\bar{b}b\bar{b}$ final state was performed with 3.2fb^{-1} collected with ATLAS at $\sqrt{s} = 13$ TeV in 2015. The results are presented in this dissertation with a focus on a dedicated signal region for boosted final states. This signal region uses new techniques for recognizing jet substructure and b-tagging to the improve signal acceptance of high mass resonances.

The discovery of the Standard Model (SM) Higgs boson (h)[?,?] at the Large Hadron Collider (LHC) motivates searches for new physics using the Higgs boson as a probe. In particular, many models predict cross sections for Higgs boson pair production that are significantly greater than the SM prediction. Resonant Higgs boson pair production is predicted by models such as the bulk Randall–Sundrum model[?,?], which features spin-2 Kaluza–Klein gravitons, G^*_{KK}, that subsequently decay to a pair of Higgs bosons. Extensions of the Higgs sector, such as two-Higgs-doublet models[?,?], propose the existence of a heavy spin-0 scalar that can decay into $h$pairs. Enhanced non-resonant Higgs boson pair production is predicted by other models, for example those featuring light coloured scalars[?] or direct $t\bar{t}hh$ vertices[?,?].

Previous searches for Higgs boson pair production have all yielded null results. In the $b\bar{b}b\bar{b}$channel, ATLAS searched for both non-resonant and resonant production in the mass range of 400–3000 GeV using 3.2 fb^{-1} of 13 TeV data[?] collected during 2015. CMS searched for the production of resonances with masses of 750–3000 GeV[?] using 13 TeV data and with masses 270–1100 GeV with 8 TeV data[?]. Using 8 TeV data, ATLAS has examined the $b\bar{b}b\bar{b}$[?], $b\bar{b}\gamma\gamma$[?], $b\bar{b}\tau^+\tau^-$ and $W^+W^-\gamma\gamma$ channels, all of which were combined in Ref.[?]. CMS has performed searches using 13 TeV data for the $b\bar{b}\tau^+\tau^-$[?] and $bb\ell\nu\ell\nu$[?] final states, and used 8 TeV data to search for $b\bar{b}\gamma\gamma$[?] in addition to a search in multilepton and multilepton+photons final states[?].

The analyses presented in this paper exploit the dominant $h \to b\bar{b}$ decay mode to search for Higgs boson pair production in both resonant and non-resonant production. Two analyses are presented, which are complementary in their acceptance, each employing a unique technique to reconstruct the Higgs boson. The "resolved" analysis is used for hh systems in which the Higgs bosons have Lorentz boosts low enough that four b-jets can be reconstructed. The "boosted" analysis is used for those hh systems in which the Higgs bosons have higher Lorentz boosts, which prevents the Higgs boson decay products from being resolved in the detector as separate b-jets. Instead, each Higgs boson candidate consists of a single large-radius jet, and b-decays are identified using smaller-radius jets built from charged-particle tracks.

Both analyses were re-optimized with respect to the former ATLAS publication[?]; an improved algorithm to pair b-jets to Higgs boson candidates is used in the resolved analysis, and in the boosted analysis an additional signal-enriched sample is utilized. The dataset comprises the 2015 and 2016 data, corresponding to 27.5 fb^{-1} for the resolved analysis and 36.1 fb^{-1} for the boosted analysis, with the difference due to the trigger selections used. The results are obtained using the resolved analysis for a resonance mass between 260 and 1400 GeV, and the boosted analysis between 800 GeV and 3000 GeV. The main background is multijet production, which is estimated from data; the sub-leading background is $t\bar{t}$, which is estimated using both data and simulations. The two analyses employ orthogonal selections, and a statistical combination is performed in the mass range where they overlap. The final discriminants are the four-jet and dijet mass distributions in the resolved and boosted analyses, respectively. Searches are performed for the following benchmark signals: a spin-2 graviton decaying into Higgs bosons, a scalar resonance decaying into a Higgs boson pair, and SM non-resonant Higgs boson pair production.

This dissertation begins by discussing the status of di-Higgs. Chapter 1 gives an overview of double Higgs production in the Standard Model and beyond. Chapter 2 and 3 present details regarding the Large Hadron Collider and the ATLAS experiment. Chapter 4 provides an overview of object reconstruction in ATLAS, with a focus on Muon Segment Seeding. A brief interlude in Chapter 5 on the ATLAS Muon Data Quality, as this has been a focus of my graduate work.

The rest of the dissertation presents a search for Higgs pair production in the $HH \to b\bar{b}b\bar{b}$ channel. Chapter 6 presents an overview of physics object selection, where the Higgs pairs are the result of the decay of a heavy resonance. Chapter 7 discusses the background estimation techinics in detail, followed by Chapter 8, Systematics. Chapter 9 presents the results, and Chapter 10 shows the limits between the boosted regime and the resolved regime, which is sensitive to lower mass resonances and non-resonant Higgs pair production. Finally, the work is summaried a conclusion and brief outlook of future Higgs physics with ATLAS.

Ugliness is in a way superior to beauty because it lasts.

Serge Gainsbourg

1 Detector

The ATLAS experiment[1] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage insolid angle. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) 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 towards the sky. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle ϑ as $\eta = -\ln\tan(\vartheta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$. The ATLAS detector consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS).

1.1 Inner Detector

The ID covers the pseudorapidity range $|\eta| < 2.5$. It has three parts: silicon pixel, silicon microstrip, and straw-tube transition-radiation tracking detectors. An additional pixel detector layer[2], inserted at a mean radius of 3.3 cm, is used in the Run-2 data-taking and improves the identification of b-jets[3].

Material of ATLAS Inner Detector for Run 2 of the LHC. note.

1.2 Calorimeter

Lead/liquid-argon (LAr) sampling calorimeters provide EM energy measurements. A steel/scintillator-tile hadronic 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 $|\eta| = 4.9$.

1.3 MuonSpectrometer

The muon spectrometer surrounds the calorimeters and includes three large superconducting air-core toroids. The field integral of the toroids ranges between 2 and 6 T/m for most of the detector. The MS includes a system of precision tracking chambers and triggering chambers.

1.4 Trigger and Data Aquasition

A dedicated trigger system is used to select events[4]. The first-level trigger is implemented in hardware and uses the calorimeter and muon detectors to reduce the accepted event rate to 100 kHZ. This is followed by a software-based high-level trigger that reduces the accepted event rate to 1 kHZ on average.

To avoid too high accept rates for certain triggers, the triggers are often prescaled, which means the accepted events get rejected at the prescale. For example, a prescale of two means only every second event passing all trigger conditions gets accepted.

For further trigger information, see 2015 note and 2016 updates.

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Conclusion

Di-Higgs search has a short history, but will have a long future. This thesis presents a search for both resonant and non-resonant production of pairs of Standard Model Higgs bosons has been carried out in the dominant $b\bar{b}b\bar{b}$ channel, using 27.5–36.1 fb^{-1} of LHC pp collision data at $\sqrt{s} = 13$ TeV collected by ATLAS in 2015 and 2016. The search sensitivity of this analysis exceeds that of the previous analysis of the $\sqrt{s} = 13$ TeV 2015 dataset[2] for non-resonant signal and also across the entire mass range of 260-3000 GeV for the resonance search, with significantly improvement in the high mass resonance sensitivities. The resolved analysis has each $h \to b\bar{b}$ reconstructed as two separate b-tagged jets, and the boosted analysis has each $h \to b\bar{b}$ reconstructed as a single large-radius jet associated with at least one small-radius b-tagged track-jet. The estimated background consists mainly of multi-jet and $t\bar{t}$ events.

No significant excess is observed in the data. The largest deviation from the background-only hypothesis is observed for narrow signal models at a mass of 280 GeV in the resolved analysis, with a global significance of 2.3σ. This excess could be a trigger-turn on combined with kinematic selection effect and might not last with more data. Upper limits on the production cross section times branching ratio to the $b\bar{b}b\bar{b}$ final state are set for a narrow-width scalar and for spin-2 resonances. The 95% CL upper limit on the non-resonant production is 147 fb, which corresponds to 13.0 times the SM expectation.

Future improvement with the rest of $\sqrt{s} = 13$ TeV Run II could come from b-tagging, especially in the high p_{T}region. Advanced trigger technologies and selections will increase the data rate, and better jet energy and mass resolution will increase the purity in selection. With the larger dataset and improvements in physics performance, it is possible to reach twice as the current sensitivity of resonance searches. For non-resonance searches, an order of 10 times the SM expectation is more sensible at the end of Run II.

For longer term perspectives, di-Higgs measurements will continue to be one of the most important analysis that help constraining our understanding of physics beyond the Standard Model. Given the current status, it is possible that in fifteen to twenty years there will be no new discovery, and the experiments at the LHC will be able to constrain the Higgs self-coupling within unity.

As humans, we have a limited life. However, physics, as well as the understanding of the universe, is an endless journey. I sincerely hope that my biased prediction of the future of Higgs physics will be wrong, but nevertheless I am deeply honored to be a small part of this odyssey towards Veritas.

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