

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 by the ATLAS Collaboration at $\sqrt{s} = 13$ TeV, corresponding to $3.2 \pm 0.2 \text{ fb}^{-1}$ of 2015 and $32.9 \pm 1.1 \text{ fb}^{-1}$ 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 GeV and 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}_{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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ATLAS members for their contributions.

0

Introduction

Why do we look for $bb \rightarrow 4b$?

There are two types of analysis in particle physics. The first one is measurement, which yields a observable with an uncertainty. This could either improve our current knowledge, or show some inconsistency. The other type is search, which generally assumes some new physics model and try to justify in data whether 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 improve signal acceptance of high mass resonances.

The discovery of the Standard Model (SM) Higgs boson (h)^{2,3} 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^{1,2}, 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^{3,4}, 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 scalars⁵ or direct $t\bar{t}hh$ vertices^{6,7}.

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 3.2fb^{-1} of 13 TeV data⁸ collected during 2015. CMS searched for the production of resonances

with masses of 750–3000 GeV² using 13 TeV data and with masses 270–1100 GeV with 8 TeV data². Using 8 TeV data, ATLAS has examined the $b\bar{b}b\bar{b}$ ⁹, $b\bar{b}\gamma\gamma$ ¹⁰, $b\bar{b}\tau^+\tau^-$ and $W^+W^-\gamma\gamma$ channels, all of which were combined in Ref.². CMS has performed searches using 13 TeV data for the $b\bar{b}\tau^+\tau^-$ ² and $b\bar{b}\ell\nu\ell\nu$ ² final states, and used 8 TeV data to search for $b\bar{b}\gamma\gamma$ ² in addition to a search in multilepton and multilepton+photons final states².

The analyses presented in this paper exploit the dominant $h \rightarrow b\bar{b}$ 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 publication⁸; 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 $HH \rightarrow b\bar{b}b\bar{b}$ 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 techniques 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 summarized a conclusion and brief outlook of future Higgs physics with ATLAS.

Knowledge knows no bounds.

Creator

1

Motivation and Theory

1.1 THE STANDARD MODEL AND THE HIGGS BOSON

The Standard Model(SM) ^{[11,12,13,14](#)} is a quantum field theory describing the interactions of fundamental particles. The particles are shown in Figure 1.1. So far, the SM predictions agree extremely well with experimental observations.

In the SM, the Higgs mechanism introduces a complex scalar Higgs field, ϕ , with nonzero vacuum expectation values. Through spontaneous symmetry breaking of the Higgs potential $V(\phi) = -\nu^2\lambda_\nu\phi^\dagger\phi + \lambda_\nu(\phi^\dagger\phi)^2$, W^\pm and Z bosons acquire their masses. This process also predicts an extra

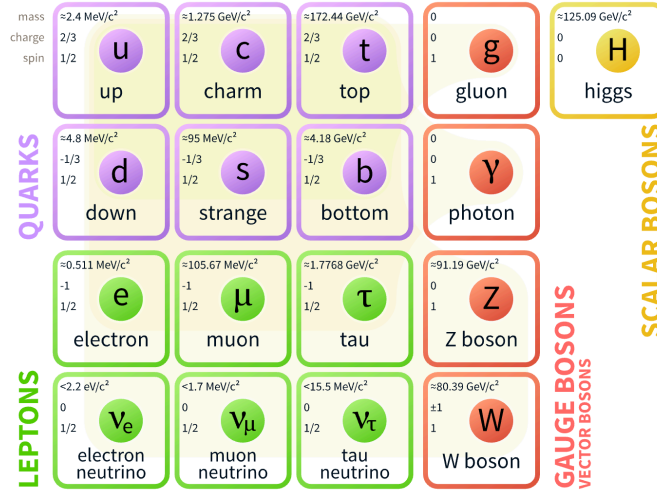


Figure 1.1: Fermions and bosons of the Standard Model and their properties¹¹, where all the values are measured experimentally.

scalar, the Higgs boson. The SM Lagrangian containing Higgs couplings, $\mathcal{L}_{\text{Higgs}}$, is shown in Eq 1.1.

$$\mathcal{L}_{\text{Higgs}} = -\lambda_{h\bar{f}f}h\bar{f}f + \delta_V V_\mu V^\mu (\lambda_{hVV}h + \lambda_{hhVV}h^2) + \lambda_{hh}h^2 + \lambda_{hhh}h^3 + \lambda_{hhhh}h^4 \quad (\text{I.1})$$

where

- $v \sim 246 \text{ GeV}$, is the non-zero expectation value of the Higgs field;
- $m_h = \sqrt{2\lambda_v}v \sim 125 \text{ GeV}$, is the Higgs mass; this is discovered in 2012^{15,16};
- λ_v , coefficient for the quartic potential term, is constrained from Higgs mass, to be ~ 0.13 ;
- $V = W^\pm$ or Z , $\delta_W = 1$, $\delta_Z = \frac{1}{2}$;
- $\lambda_{h\bar{f}f} = \frac{m_f}{v}$, is the Higgs to fermion coupling; m_f is the mass of the fermion;
- $\lambda_{hVV} = \frac{2m_V^2}{v}$, is the Higgs to boson coupling; m_V is the mass of the boson;
- $\lambda_{hhVV} = \frac{m_V^2}{v^2}$, is the Higgs-Higgs to boson-boson coupling;
- $\lambda_{hh} = \frac{m_h^2}{2}$, is the Higgs mass term;

- $\lambda_{h\bar{h}h} = \frac{m_h^2}{2v} = \lambda_{\nu} \nu$, or $\lambda_{h\bar{h}h}$, is the Higgs self-coupling;
- $\lambda_{hhhh} = \frac{m_h^2}{8v^2}$, is the Higgs quartic-coupling.

What's particularly interesting and has not been measured experimentally in Eq 1.1 is λ_{hhhh} . SM predicts $\lambda_{hhhh} = \frac{m_h^2}{2v}$, which is referred as λ_{SM} in this thesis. This term directly probes the Higgs potential. Also, $\lambda_{h\bar{h}h} h^3$ term shows one way for double Higgs production within the SM. Double Higgs production is also known as di-Higgs or Higgs pair production.

1.2 STANDARD MODEL DI-HIGGS PRODUCTION

There are two main production diagrams of di-Higgs at the LHC, shown in Figure 1.2. In the gluon-gluon fusion process, di-Higgs are produced through a box or a triangle loop. Only the triangle loop 1.2b probes the λ_{hhhh} . In the triangle diagram, the middle Higgs boson acts as a propagator (off-shell), and the two Higgs boson in the final state are on-shell. An on-shell middle Higgs, with two off-shell Higgs bosons in the final state, is strongly disfavored^[1]. The box and triangle diagrams interfere destructively, which makes the overall production rate smaller than what would be expected in the absence of a λ_{hhhh} term.

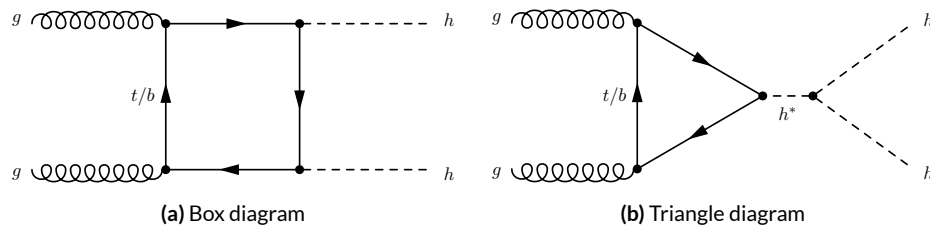


Figure 1.2: Leading order Feynman diagrams contributing to di-Higgs production via gluon-gluon fusion, through the Higgs-fermion Yukawa interactions 1.2a and the Higgs boson self-coupling 1.2b. Only Figure 1.2b probes λ_{hhhh} .

Many other different production modes of di-Higgs exist, but gluon-gluon fusion is the dominant one. Figure 1.3¹⁷ compares the cross sections of gluon-gluon fusion, Vector Boson Fusion (VBF), and top-pair, W^\pm , Z and single-top associated di-Higgs production.

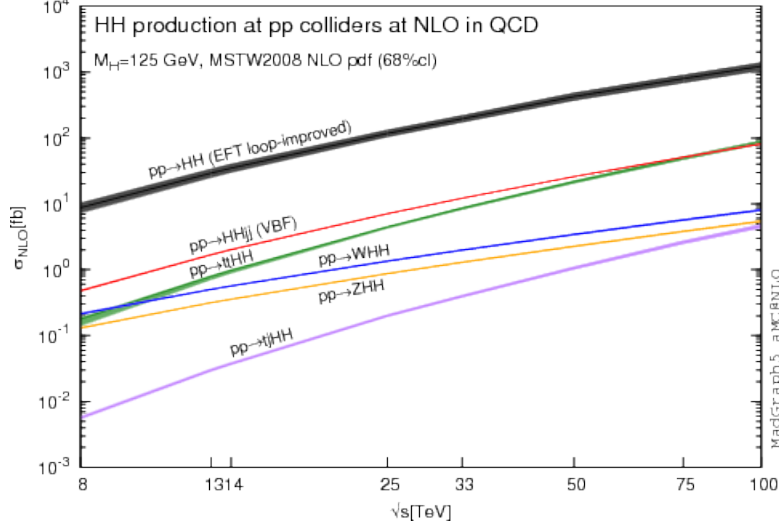


Figure 1.3: Total cross sections (y-axis) at the NLO in QCD for the six largest di-Higgs production channels at p-p colliders at different energy (x-axis). The thickness of the lines corresponds to the scale and PDF uncertainties added linearly. H refers to the SM Higgs.

For p-p collisions at $\sqrt{s} = 13$ TeV, the total cross section for SM gluon fusion di-Higgs production¹⁸, at the Next to Next Leading Order (NNLO) with top quark mass effects, is $33.49^{+4.3\%}_{-6.0\%} \pm 2.1\% \pm 2.3\%$ fb. The cross section for the next dominant production, VBF, is $1.62^{+2.3\%}_{-2.7\%} \pm 2.3\%$ fb. The estimated cross section for triple-Higgs production is $0.06332^{+16.1\%}_{-14.1\%} \pm 3.4\%$ fb, which is negligible with current dataset. The uncertainties are Scale uncertainty, PDF uncertainty and α_s uncertainty. This means inside 2015 and 2016 $\sqrt{s} = 13$ TeV ATLAS 36 fb^{-1} data, there are only around one thousand SM di-Higgs events.

1.3 BEYOND THE STANDARD MODEL PHYSICS DI-HIGGS PRODUCTION

BSM physics could significantly enhance the production of di-Higgs at the LHC. This is separated into two categories: non-resonant and resonant productions. The non-resonant production generally refers to modifications of the Higgs couplings, either the Higgs self-coupling or the Higgs-top couplings. Resonant production refers to a particle with invariant mass greater than twice the Higgs mass decays directly into two Higgs bosons. The difference also comes from the distribution of the di-Higgs invariant mass at the truth level. In the non-resonant case, the distribution has no clear peak, whereas in the resonant case, the invariant mass distribution usually forms a peak with model dependent width.

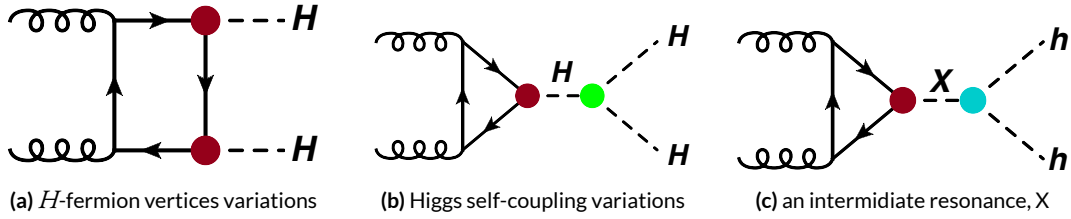


Figure 1.4: BSM Higgs boson pair production: non-resonant production proceeds through changes in the SM Higgs couplings in 1.4a and 1.4b, resonant production proceeds through 1.4c an intermediate resonance, X . H and h both refers to the SM Higgs.

1.3.1 BSM NON-RESONANT DI-HIGGS

Enhanced non-resonant Higgs boson pair production is predicted by many models. Models featuring direct $t\bar{t}hh$ vertices^{6,7} or new light colored scalars⁵ could change vertices shown as the red dots in Figure 1.4. A direct modification of Higgs self-coupling term in Eq 1.1 to $\lambda b\bar{b}hh$, where λ is different from λ_{SM} , is also possible. This is shown as the green dot in Figure 1.4b.

The non-resonant di-Higgs enhancement is usually described by $\frac{\lambda}{\lambda_{\text{SM}}}$, which is the cross section ratio between λ and λ_{SM} . From the SM electroweak measurements, the self coupling term could be

constrained to $-14 \leq \frac{\lambda}{\lambda_{\text{SM}}} \leq 17.4$ ¹⁹. Variations of λ have a non-trivial effect on di-Higgs production cross section, shown in Figure 1.5¹⁷. In the regime of relatively high trilinear coupling, the observation will be an excess of di-Higgs events with respect to the expected background. A simple limit can be set in this case.

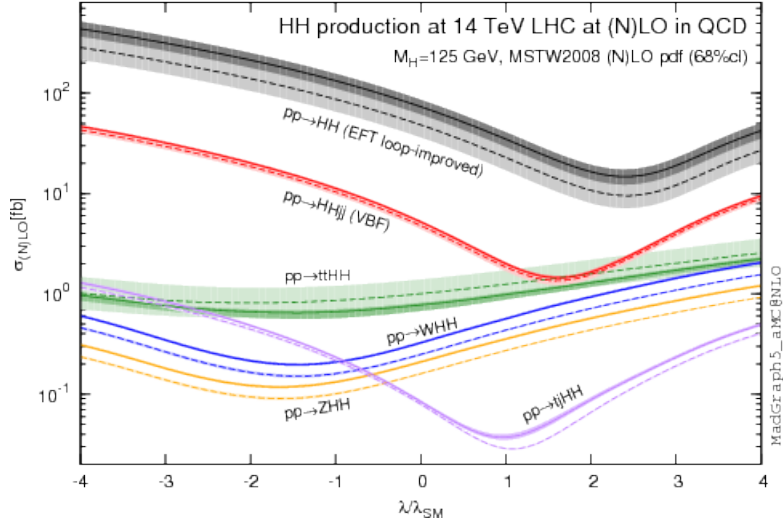


Figure 1.5: Total cross sections (y-axis) at the LO and NLO in QCD for di-Higgs production channels, at the $\sqrt{s} = 14$ TeV LHC as a function of the self-interaction coupling λ (x-axis). The dashed (solid) lines and light- (dark-) color bands correspond to the LO (NLO) results and to the scale and PDF uncertainties added linearly. The SM values of the cross sections are obtained at $\frac{\lambda}{\lambda_{\text{SM}}} = 1$. H refers to the SM Higgs.

1.3.2 BSM RESONANT DI-HIGGS

Resonant Higgs boson pair production is also predicted by many models. Extensions of the Higgs sector, such as two-Higgs-doublet models (2HDM)^{3,4}, propose the existence of a heavy spin-0 scalar H that can decay into di-Higgs. The bulk Randall-Sundrum model^{1,2}, which features spin-2 Kaluza-Klein gravitons, G_{KK}^* , could also subsequently decay to pairs of Higgs bosons. These proposed heavy particles, heavy CP-even scalar H and G_{KK}^* , are represented as X in Figure 1.4c.

The 2HDM is a simple extension of the SM which can exhibit large resonance effects¹⁸. The 2HDM has 5 physical Higgs bosons: h (light scalar Higgs), H (heavy scalar Higgs), A (heavy pseudoscalar Higgs), and H^\pm (two charged Higgs). The 2HDM can introduce tree level flavor changing neutral currents. To avoid this, models impose discrete symmetries in which the charged fermions only couple to one of the Higgs doublets. One version is type II 2HDM, in which all positively charged quarks couple to one doublet and the negatively charged quarks and leptons couple to the other. The type II model is the Minimal Supersymmetric Standard Model (MSSM)'s Higgs sector.

Resonant di-Higgs production in 2HDM models can proceed through decays of the heavy CP-even Higgs $H \rightarrow hh$. The branching ratio for $H \rightarrow hh$ depends on the model type as well as the values of $\tan \beta$ and $\cos(\beta - \alpha)$. $\tan \beta = \frac{v_{\text{doublet}_2}}{v_{\text{SM}}}$ is the ratio of the vacuum expectation values of the two Higgs doublets. α is the mixing angle between the heavy H and light h fields. The limit where $\cos(\beta - \alpha) = 0$ is called the alignment limit, and in this limit the light Higgs h has the same couplings as a SM Higgs. Near the alignment limit there is some unprobed phase space depending on the exact models and values of $\tan \beta$ being considered, and they are particularly interesting to be searched for at the LHC.

The Randall-Sundrum model proposes a five-dimensional warped spacetime that contains two manifolds: one where the force of gravity is very strong and a second manifold at the TeV scale corresponding to the known SM sector. The experimental consequence of this theory is a series of widely spaced (in mass) Kaluza-Klein graviton resonances, G_{KK}^* . In theories where the fermions are localized to the SM brane, production of gravitons from fermion pairs is suppressed and the primary mode of production is gluon fusion. These gravitons have a substantial branching fraction to di-Higgs, ranging from 6.43% for gravitons with a mass of 500 GeV to 7.66% at 3 TeV. Randall-Sundrum models have two free parameters - the mass of the graviton and $c = k/\bar{M}_{\text{Pl}}$, where \bar{M}_{Pl} is the reduced Planck mass and k is the curvature parameter. The width of the graviton increases with both mass and c .

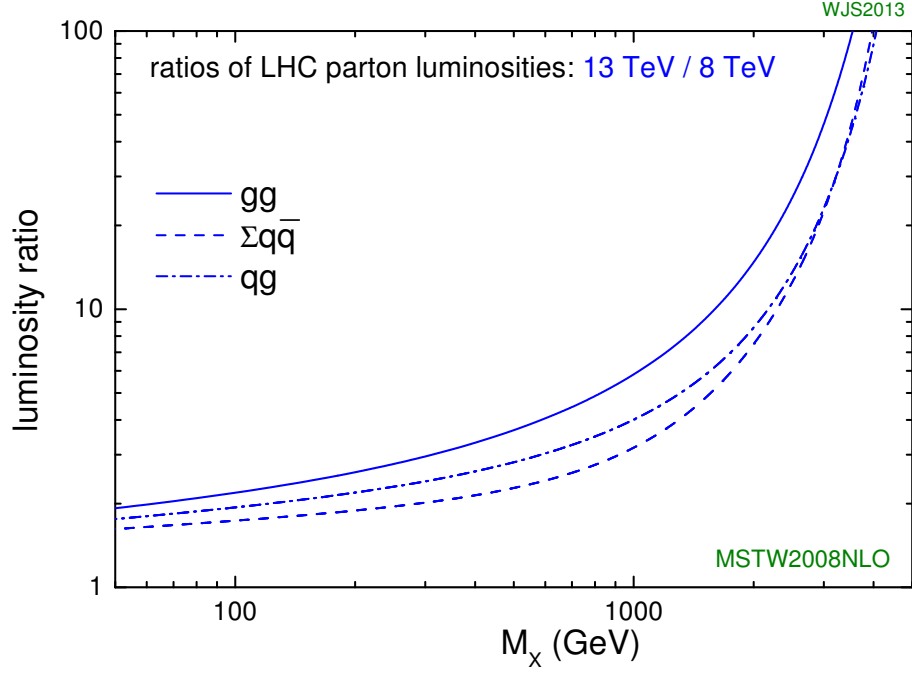


Figure 1.6: Parton luminosity ratios as a function of resonance mass M_X for 13/8 TeV²⁰. For a 2 TeV X , the luminosity ratio is almost 10.

Generally, it is easy theoretically for new heavy resonance particles to interact with the SM through the Higgs as a portal, resulting in resonance di-Higgs production. With the increased center of mass collision energy from 8 TeV to 13 TeV, the production cross section through gluon-gluon fusion for heavy particles above TeV grows in LHC Run 2, as shown in Figure 1.6. Therefore, it is particularly important to focus on resonant searches above TeV region.

1.4 DI-HIGGS DECAY AND LHC PREVIOUS SEARCH RESULTS

Di-Higgs decay is a combination of single Higgs decays. The coupling terms to fermions and bosons are shown in Eq 1.1. The branching ratio of the di-Higgs final state is shown in Figure 1.7.

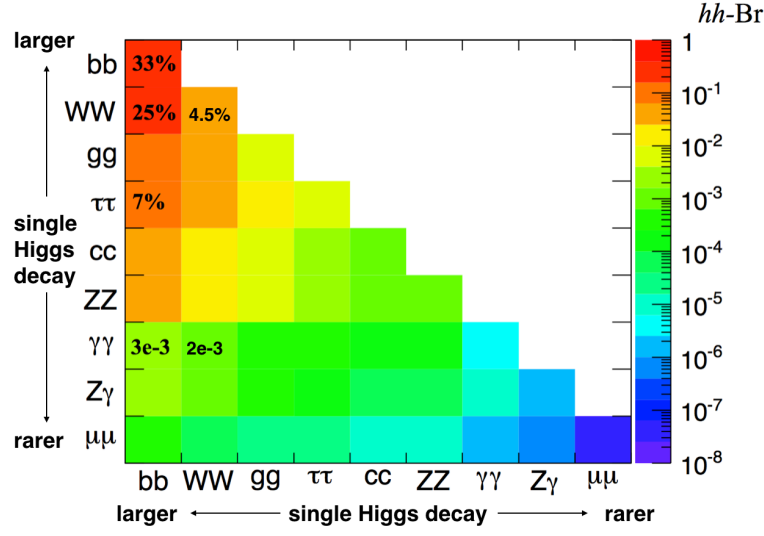


Figure 1.7: Summary of di-Higgs final states and their ratios. Top left, $b\bar{b}b\bar{b}$, has the largest branching ratio.

Previous searches for Higgs boson pair production have all yielded null results. Using 8 TeV data, ATLAS has examined the $b\bar{b}b\bar{b}$ ⁹, $b\bar{b}\gamma\gamma$ ¹⁰, $b\bar{b}\tau^+\tau^-$ and $W^+W^-\gamma\gamma$ channels, all of which were combined in Ref²¹. The resonant search combination result is shown in Figure 1.8. The best non-resonant $\sigma(pp \rightarrow hh)$ cross section limit in Run 1 is the ATLAS combination, at 0.69 pb. This corresponds to $\frac{\lambda}{\lambda_{SM}} < 70$. Different di-Higgs search challenges and perspectives are summarized below:

- $b\bar{b}b\bar{b}$: Trigger limits the low mass resonance searches, but for high mass resonances above 500 GeV, the branching ratio of this channel provides a decisive advantage. Great for non-resonant searches.
- $b\bar{b}W^+W^-$: Despite the second largest branching ratio, large background from $t\bar{t}$ limits this search sensitivity.
- $b\bar{b}\gamma\gamma$: Benefit from a good double photon trigger efficiency, a good photon reconstruction efficiency and a low SM background. Most sensitive at low mass $m_X \leq 350$ GeV. At higher masses, the smaller branching ratio and the merging of photons hurt the search sensitivity. Great for non-resonant searches.

- $b\bar{b}\tau^+\tau^-$: An intermediate choice between $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$ for resonance searches. Yet this channel contributes to the non-resonant result significantly.
- $W^+W^-\gamma\gamma$: Suffers from much lower branching ratio and lower reconstruction efficiency of the W^+W^- compared to $b\bar{b}$.
- $W^+W^-\tau\tau$, $W^+W^-W^+W^-$, $b\bar{b}ZZ$: There are no search results on these channels yet. But because of the relatively large branching ratio, it is likely that they would be explored in the future.

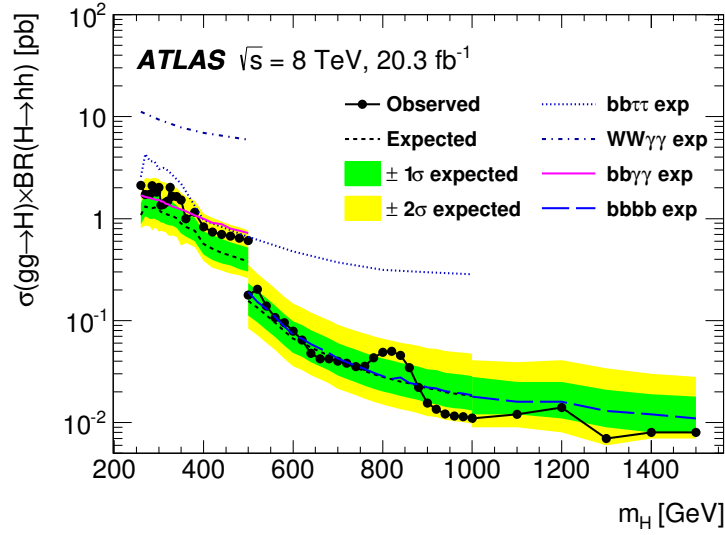


Figure 1.8: The observed and expected 95% CL upper limits of $\sigma(gg \rightarrow H) \times BR(H \rightarrow hh)$ at $\sqrt{s} = 8$ TeV as functions of the heavy Higgs boson mass m_H , combining resonant searches in Higgs boson pair to $b\bar{b}\tau^+\tau^-$, $W^+W^-\gamma\gamma$, $b\bar{b}\gamma\gamma$, and $b\bar{b}b\bar{b}$ final states. The expected limits from individual searches are also shown. The green and yellow bands represent $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty ranges of the expected combined limits. The improvement above $m_H = 500$ GeV reflects the sensitivity of the $b\bar{b}b\bar{b}$ analysis. The results beyond 1 TeV are only from the $b\bar{b}b\bar{b}$ final state alone.

In summary, di-Higgs has a small production rate in the SM, but could be significantly enhanced in BSM scenarios. In particular, a heavy resonance spin-0 or spin-2 particle could decay into Higgs boson pair directly. The search sensitivity for resonance mass above TeV increases as the center of mass energy of the collision increases. For resonance signals above 1 TeV decaying into di-Higgs,

$b\bar{b}b\bar{b}$ channel has the best discovery potential in Run 2. Therefore, searching for TeV scale resonance production of di-Higgs $\rightarrow b\bar{b}b\bar{b}$ is the goal of thesis.

*A man who procrastinates in his choosing will inevitably
have his choice made for him by circumstance.*

Hunter S. Thompson

2

The Large Hadron Collider

The Large Hadron Collider (LHC) is a proton-proton collider at the European Organization for Nuclear Research (CERN) laboratory in Geneva, Switzerland²². In order to discover the Higgs boson, the two most important design parameters for a collider are beam energy and luminosity. This chapter will cover how these two parameters are reached by the LHC, and the final design and layout.

2.1 BEAM ENERGY

In order to probe the quarks and gluons inside, protons need to be accelerated to high energies. For a charged particle, charge Z (for protons, $Z = 1$) and momentum p , its trajectory within a mag-

netic field $B(s)$ is described by the deflection angle $d\vartheta$, with radius ϱ .

$$d\vartheta = \frac{ds}{\varrho} = \frac{ZB(s)ds}{p} \quad (2.1)$$

Integrate this angle over the circumference:

$$\oint_C d\vartheta = 2\pi = \frac{1}{p} \oint_C B(s)ds \quad (2.2)$$

Thus the momentum (\sim energy) of the charged particle is:

$$p = \frac{1}{2\pi} \oint_C B(s)ds = 1 \times 47.7 \left[\frac{MeV}{cTm} \right] \oint_C B(s)ds \quad (2.3)$$

In order to achieve a designed center of mass energy of $\sqrt{s} = 14$ TeV, the momentum of the proton is 7 TeV. The Niobium Titanium magnetic dipole is 14.3 meters in length, and while cooled by superfluid helium to a temperature of 1.9 Kelvin, can generate 8.33 Tesla magnetic field. Therefore, according to Eq2.3, the LHC needs 1232 such magnets for steering. Additionally, 6800 superconducting magnets are used to focus the beam, squeeze the beam, correct the trajectory, and damp oscillation in beam position.

2.2 LUMINOSITY

In order to study certain physics processes, the production rate affects the length of the experiment. The rate of a specified physics process $R_{\text{phy}} = L\sigma$, where L is the instantaneous luminosity ($m^{-2}s^{-1}$) the collider, and $\sigma(m^2)$ the physics process' cross section. The instantaneous luminosity is could be controlled and affects the experiment data taking length. For a Gaussian beam profile, it is defined in Eq2.4 ²³:

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (2.4)$$

In the above Eq2.4:

- N_b is the number of protons per bunch;
- n_b is the number of bunches per beam; n_b cannot be too large due to potential beam loss damages on the accelerator and detector;
- f_{rev} is the proton revolution frequency; or the ratio of the circumference of LHC, 26.7 km, and the speed of light.
- γ_r is the relativistic Lorentz factor for the protons;
- ε_n is the average beam spread in the transverse plane;
- β^* is a measure of the beam spread in the longitudinal direction; affected by focusing magnets;
- F is a reduction factor for the angle beams are colliding; smaller crossing angles could cause larger spread in the longitudinal direction.

The instantaneous luminosity can also be written as the ratio of the rate of inelastic collisions to the inelastic cross section σ_{inel} ²⁴.

$$L = \frac{R_{\text{inel}}}{\sigma_{\text{inel}}} = \frac{\mu n_b f_{\text{rev}}}{\sigma_{\text{inel}}} \quad (2.5)$$

where, μ is the number of interactions per bunch crossing. At each bunch crossing, multiple proton-proton collide, and the collisions without the highest center of mass energy are called “pileup” interactions. The averaged collision activities over all bunch crossings, $\langle \mu \rangle$, is a measurement of the level of pileup in the detector. For High Luminosity LHC, the expected $\langle \mu \rangle$ is 200. The higher number of pileup, the higher total collision events are produced, but is harder for the detectors to distinguish each collision separately.

| Parameter [unit] | Nominal design value | 2015 Operating value | 2016 Operating value |
|--|----------------------|----------------------|-----------------------|
| Beam Energy [TeV] | 7 | 6.5 | 6.5 |
| Peak L [$\text{cm}^2 \text{s}^{-1}$] | 10^{34} | 5×10^{33} | 1.25×10^{34} |
| Bunch spacing [ns] | 25 | 25 | 25 |
| n_b [10^{11} p/bunch] | 1.15 | 1.15 | 1.12 |
| N_b [bunch] | 2808 | 1825 | 2220 |
| f_{rev} [kHz] | 11245 | 11245 | 11245 |
| ε_n [mm mrad] | 3.5 | 3.5 | 2 |
| β^* [cm] | 55 | 80-40 | 40 |
| F | 0.84 | 0.84 | 0.59 |
| $\langle \mu \rangle$ | 19 | 13 | 41 |

Table 2.1: LHC nominal²² and operational parameters in 2015²⁵ and 2016²⁶.

The target peak instantaneous luminosity for both the ATLAS and CMS experiments is $L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ ²², which is already exceeded in 2016. The main parameters of the LHC beam and performance are shown in Table 2.1. At the nominal LHC conditions, the beam energy is about 360 MJ, and the LHC in total consumes 115 MW of energy.

2.3 LAYOUT

Protons accelerated in the LHC originate from a red bottle of hydrogen gas. The whole series take around 4 + 20 (LHC only) minutes:

- An electric field strips the electrons from the hydrogen to create protons;
- A linear particle accelerator, Linac 2, accelerates the protons to 50 MeV;
- The Proton Synchrotron Booster (PSB) accelerates the protons to 1.4 GeV;
- The Proton Synchrotron (PS) accelerates the protons to 25 GeV;
- The Super Proton Synchrotron (SPS) accelerates the protons to 450 GeV; it sends the protons in bunch trains;
- The LHC accelerates the protons in a series of Radio Frequency cavities to the final TeV energies.

Interaction points (IP) are where the two proton beams focused and collided. Only a part of the protons in the bunch collide, and the rest remains in LHC and travels to the next interaction point.

ATLAS (A Toroidal LHC ApparatuS), CMS (the Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment), and LHCb^{27,28,29,30} are the four main experiments. They are located at the IPs of the accelerator. Figure 2.1 shows a schematic of the LHC ring and its experiments.

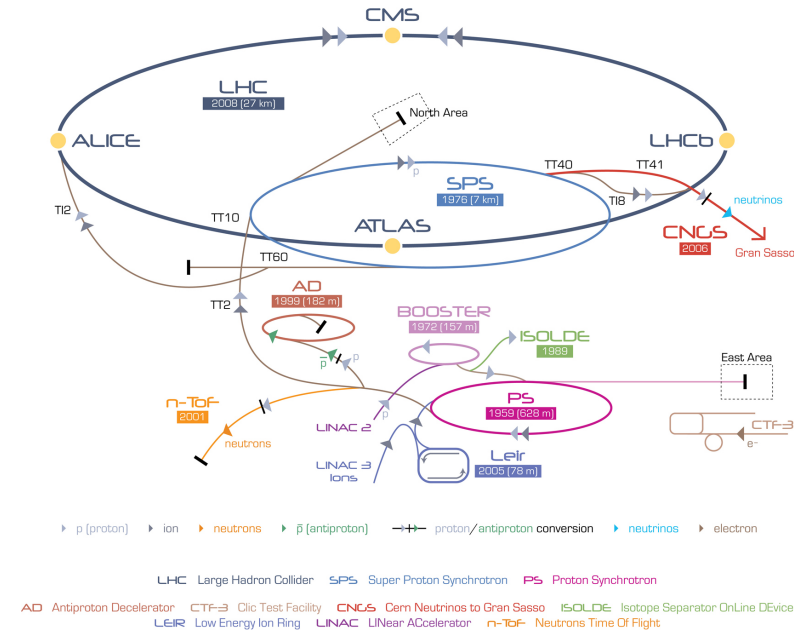


Figure 2.1: A schematic view of the LHC ring²³. LINAC2, Booster, PS, SPS, and LHC accelerate the protons in order. Four main experiments are located at interaction points along the ring. ATLAS and CMS are general purpose experiments, while ALICE focuses on heavy ion collisions and LHCb is dedicated to B physics.

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

Serge Gainsbourg

3

Detector

The ATLAS experiment³¹ 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. 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).

3.1 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 layer³², inserted at a mean radius of 3.3 cm, is used in the Run-2 data-taking and improves the identification of b -jets³³.

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

3.2 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 $|\eta| = 4.9$.

3.3 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.

3.4 TRIGGER AND DATA ACQUISITION

A dedicated trigger system is used to select events³⁴. 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](#).

4

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 $27.5\text{--}36.1\text{ fb}^{-1}$ of LHC pp collision data at $\sqrt{s} = 13\text{ TeV}$ collected by ATLAS in 2015 and 2016. The search sensitivity of this analysis exceeds that of the previous analysis of the $\sqrt{s} = 13\text{ TeV}$ 2015 dataset² 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 $b \rightarrow b\bar{b}$ reconstructed as two separate b -tagged jets, and the boosted analysis has each $b \rightarrow b\bar{b}$ 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 improving 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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