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Search for resonant and enhanced non-resonant di-Higgs production in the $\gamma\gamma b\bar{b}$ channel with data at 13 TeV with the ATLAS detector

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Leonor Cerda Alberich[*†]
Instituto de Fisica Corpuscular, Univ. of Valencia and CSIC (ES)
E-mail: leonor.cerda.alberich@cern.ch

This document presents the Run 2 search for di-Higgs production in the $\gamma\gamma b\bar{b}$ channel. In the Standard Model (SM), this process provides a lens on the Higgs self-coupling and it is enhanced, resonantly or non-resonantly, in many extensions of the SM. It is appealing thanks to a clean diphoton trigger, relatively small backgrounds, and excellent diphoton mass resolution. It is also particularly important in the range from 260 to 400 GeV, where QCD backgrounds and combinatorics make other channels ($b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$) challenging. The dataset used corresponds to an integrated luminosity of 3.2 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider.

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[*]Speaker, on behalf of the ATLAS Collaboration.

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1. Introduction

Since the discovery of the Higgs boson, the ATLAS and CMS collaborations have completed a program of measurements demonstrating that its spin and couplings are consistent with the predictions of the Standard Model (SM) [1]. Moreover the Higgs boson constitutes an important window for new physics searches.

This document presents a Run 2 search for di-Higgs production in the $hh \to \gamma\gamma b\bar{b}$ channel with 2015 ATLAS [2] data. This process is appealing thanks to a clean diphoton trigger, relatively small backgrounds, and excellent diphoton mass resolution and provides a handle on the Higgs self-coupling. The enhancements to the SM rate can be of resonant and non-resonant forms [3].

2. Object and event selection

Resonant and non-resonant analyses present a common selection:

- Photons are required to pass tight photon identification criteria, based on the lateral and longitudinal energy profiles of EM showers in the calorimeter. Photon candidates are also required to pass a set of calorimeter- and track-based isolation criteria. The two with the highest-p_T are required to have $E_T/m_{\gamma\gamma} > 0.35$ (0.25) respectively, where $m_{\gamma\gamma}$ is the invariant mass of the diphoton system, which is initially required to fall within a broad mass window of 105 GeV $< m_{\gamma\gamma} <$ 160 GeV.
- Jets are required to have $p_T > 25$ GeV and $|\eta| < 2.5$.
- b-jets are required to have $p_T > 55$ (35) GeV for the leading (sub-leading) selected b-tagged jets and have to fall within a mass window of 95 GeV $< m_{bb} <$ 135 GeV.

Events are selected if there are at least two photons and exactly two b-jets satisfying the criteria outlined above. They are called 2-tag events (signal region) and are used to test the presence of signal. Events with no jets b-tagged but passing all the other requirements are called 0-tag events (control region) and are used to provide a data-driven estimate of the continuum background.

3. Optimisation studies

The four-momentum of the $b\bar{b}$ system is scaled by $m_h/m_{b\bar{b}}$. This improves the $m_{\gamma\gamma b\bar{b}}$ resolution on average by 60% across the resonance mass range, as illustrated in Figure 1 (left), without significantly impacting the shape of the background, as shown in Figure 1 (middle).

Two additional criteria are applied in the search for resonant di-Higgs production. A parametrised double-sided Crystal Ball function is fit to the $m_{\gamma\gamma}$ distribution in simulated single-Higgs events. The width of this fit, $\sigma_{m_{\gamma\gamma}}$, is found to be 1.55 GeV. The diphoton mass restriction is tightened to $2\sigma_{m_{\gamma\gamma}}$ on each side of the central mass value of m_h. The final signal region is then selected using the smallest window in the $m_{\gamma\gamma b\bar{b}}$ distribution containing 95% of the simulated di-Higgs events for each mass hypothesis, m_X. The size of the window increases from 20 to 50 GeV with the mass of the resonance. A linear parametrisation is adopted to calculate the $m_{\gamma\gamma b\bar{b}}$ windows for the resonances which are not simulated. This parametrisation is shown in Figure 1 (right).

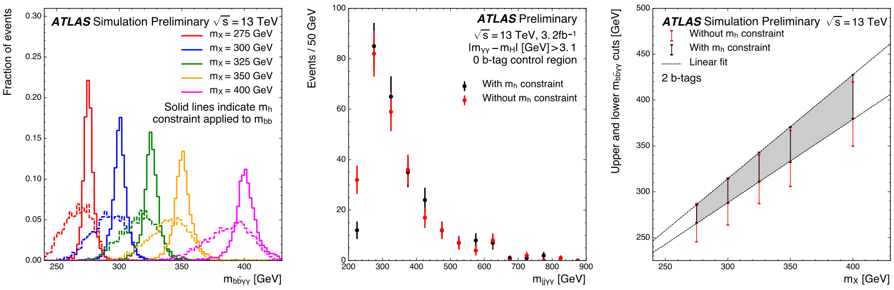

Figure 1: The effect of the $m_h/m_{b\bar{b}}$ scaling on the $m_{\gamma\gamma b\bar{b}}$ resolution is shown (left) for di-Higgs signal samples in the resonant production mode and (middle) for data in the 0-tag $m_{\gamma\gamma}$ sidebands control region. In (right) the 95% efficient mass windows (grey shaded area) are presented as a function of the mass of the resonance [4].

4. Analysis Strategy and Results

4.1 Non-resonant analysis

An unbinned likelihood fit is performed simultaneously in the signal and control regions in the search for non-resonant di-Higgs production. Figure 2 shows the $m_{\gamma\gamma}$ distributions in the 0-tag (left) and 2-tag (middle) categories. Within a $\pm 2\sigma_{m_{\gamma\gamma}}$ window around m_h, 1.8 events are expected and none are observed. The profile likelihood-ratio test statistic is used to test the background-only or signal-plus-background hypotheses. A modified frequentist method known as CL_S [5] is used to compute the 95% confidence level (CL) exclusion limits. Assuming SM branching fractions, the expected upper limit on the non-resonant hh production cross-section is $5.4^{+2.8}_{-1.0}$ pb. As a result of the deficit observed in the signal region, the observed limit is 3.9 pb, as shown in Figure 2 (right).

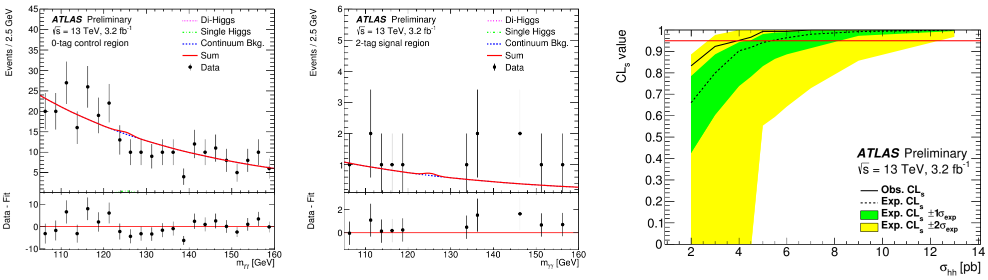

Figure 2: Observed diphoton invariant mass spectrum in the search for the non-resonant di-Higgs production, together with the corresponding signal-plus-background fit in the (left) 0-tag and (middle) 2-tag regions. Scan of the observed (solid line) and expected (dashed line) CL_S values as a function of the production cross-section σ_{hh} in the search for the non-resonant di-Higgs production (left). The green (yellow) band represents the 1σ (2σ) intervals on the expected CL_S value [4].

4.2 Resonant analysis

The search for the resonant di-Higgs production requires additional selection on the $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$ distributions. Two counting categories are defined - a background-dominated category from the $m_{\gamma\gamma}$ sidebands, and a signal region, inside the $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$ windows. One factor is required

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in each dimension to extrapolate the background rate from the sideband to the signal region. Here, N_{SB} refers to the observed number of sideband events from the continuum background, and N^B_{SR} refers to the expected number of continuum background events in the signal region. The two ε values are the efficiencies to pass the cuts on $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$. Figure 3 (left) shows a schematic view of the strategy followed in the resonant analysis.

SM branching fractions for the light Higgs bosons are assumed in the search for the resonantly produced di-Higgs states. The expected exclusion limits at 95% CL vary from 7.5 pb at m_X = 275 GeV to 4.4 pb at m_X = 400 GeV. They improve at higher resonance masses because of the higher acceptance and selection efficiency. The observed limits vary from 7.0 pb to 4.0 pb in the same mass range. Figure 3 (right) shows the 95% CL upper limits on the cross-section times branching fraction for a narrow resonance with mass m_X.

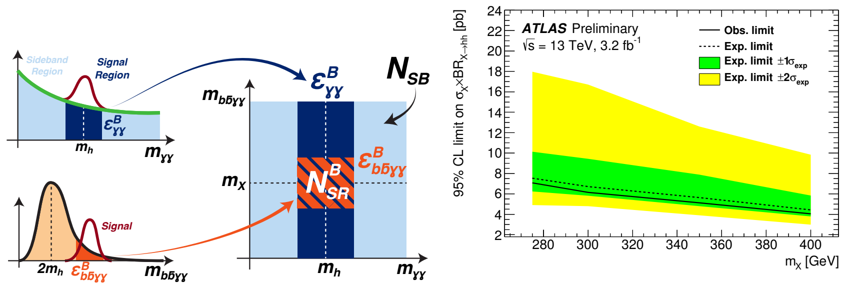

Figure 3: A diagram representing the analysis strategy in the resonant search (left). Using the CL_S method, 95% CL expected (dashed line) and observed (solid line) limits on the production cross-section times $X \to hh$ branching fraction in the search for a narrow resonance with a mass m_X (right) [4].

5. Conclusions

Searches for both resonant and non-resonant production of pairs of Higgs bosons are performed in the $\gamma\gamma b\bar{b}$ final state using 3.2 fb^{-1} of pp collision data collected at 13 TeV and recorded with the ATLAS detector at the LHC. No excess was found with respect to the background-only hypothesis.

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