PROCEEDINGS OF SCIENCE

Search for a resonance in the di-Higgs channel decaying into $\gamma\gamma\bar{b}b$ with the ATLAS detector

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In 2012, the ATLAS and CMS experiments jointly discovered the Higgs boson, a key particle of the Standard Model of particle physics. This discovery raised new questions, in particular about the mass hierarchy. The existence of new particles could help answering this problem, a Higgs-like resonance being one of them. Various theories beyond the Standard Model predict the existence of such new scalar particles that can decay into two Higgs bosons. Among the different decay channels, the decay of the first Higgs boson into a pair of photons and the second Higgs boson into a pair of b-quarks is one of the most promising since it benefits from the good di-photon resolution for the first one and the high branching ratio of the second one. This proceeding presents this search with 139 $fb^{-1}$of data collected by the ATLAS detector at the LHC in 2015-2018. Limits on the production cross-section for a new particle over the mass range 251-1000 GeV are set, improving by up to a factor three the expected limit of the 36 fb^{-1}result.

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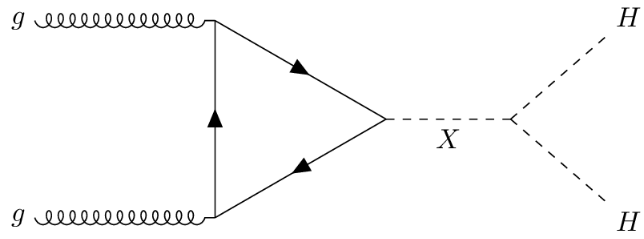

Figure 1: Gluon-gluon fusion production of a heavy resonance decaying into a Higgs boson pair. [2]

1. Introduction

A resonant enhancement of the Higgs pair production through the presence of a spin 0 particle, presented in Figure 1, is well motivated. Theories such as models with two Higgs doublets, the minimal supersymmetric extension of the Standard Model (SM), twin Higgs models and composite Higgs models predict the existence of such scalar particles. The Randall-Sundrum model of warped extra dimensions predicts spin-2 radions that could also couple to a Higgs boson pair. The two photons plus two b-jets final state gain from the high branching ratio of the Higgs decay into a b-jet pair and gain from the excellent di-photon invariant mass as well as the good photon isolation and reconstruction that lead to a competitive triggering efficiency and a high signal over background ratio. This paper will present the strategy used to search for a resonance decaying into a Higgs pair in the two photons plus two b-jet final states at 13 TeV with 139 fb^{-1}of data collected during the Run 2 by the ATLAS detector [1] at the LHC.

2. Analysis strategy

The two main sources of background are the continuum $\gamma\gamma$+jets events and the single-Higgs-boson events. The analysis strategy aims to reduce the number of background events compared to the number of signal events.

Events are required to pass the di-photon trigger threshold and to contain two photon identified with a tight efficiency. To further improve the rejection of mis-identified photons, isolation criteria are requested. $E_{\mathrm{t}}^{\mathrm{calo-iso}}$ is defined as the sum of the transverse energy of the photon cluster in a cone of ΔR=0.2 and $P_{\mathrm{t}}^{\mathrm{track-iso}}$ is defined as the scalar sum of the transverse momenta of all tracks that originate from the primary vertex within a cone of ΔR=0.2. The isolated photon must have $E_{\mathrm{t}}^{\mathrm{calo-iso}} < 0.065E_{\mathrm{t}}$ and $P_{\mathrm{t}}^{\mathrm{track-iso}} < 0.065E_{\mathrm{t}}$. The transverse energy of the leading (subleading) photons must be higher that 35% (25%) of the di-photon invariant mass. The di-photon invariant mass must be included in the 105-160 GeV mass window. The events should contain less than 6 central jets (with $|\eta|$<2.5) with their transverse impulsion higher than 25 GeV. The two b-jets used in the analysis must be tagged with at least the 77% efficiency criteria. This criterion is not only set to reduce the background but is also defined to avoid double counting with analysis looking for other decay channels of Higgs pairs. Avoiding the double counting allows to combine the result from the different final states of the di-Higgs production.
In order to improve the resolution, the four-object invariant mass is changed to $m^*_{\bar{\mathrm{b}}\mathrm{b}\gamma\gamma}$ defined by :

$$m^*_{\bar{\mathrm{b}}\mathrm{b}\gamma\gamma} = m_{\bar{\mathrm{b}}\mathrm{b}\gamma\gamma} - m_{\mathrm{b}\bar{\mathrm{b}}} - m_{\gamma\gamma} + 250[\mathrm{GeV}].$$

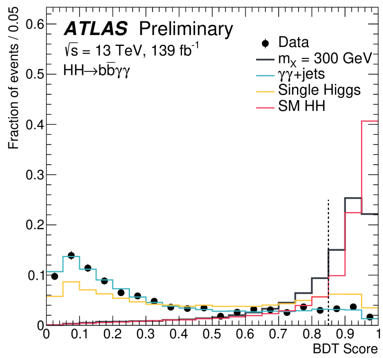

Figure 2: The BDT score for the benchmark signals (m_X = 300 GeV) and for the main backgrounds. Distributions are normalized to unit area. The dotted line denotes the event selection threshold. Events with a BDT score below 0.85 for m_X = 300 GeV are discarded. [2]

For each mass hypothesis, a requirement is set on the $m^*_{\mathrm{bb}\gamma\gamma}$ value to select events within $\pm 2\sigma$ (4σ) window around the mean value for signal events (for the 900 and 1000 GeV resonances). σ is the standard deviation parameter of a fit of the $m^*_{\mathrm{bb}\gamma\gamma}$ distribution with a Crystal Ball function.

A multivariate analysis based on a Boosted Decision Tree (BDT) technique is applied to further discriminate the signal events from the background events. Two BDTs are used for this purpose. The first one $\mathrm{BDT}_{\gamma\gamma}$ is trained in order to discriminate the signal from the continuum background and from the $\bar{\mathrm{t}}\mathrm{t}\gamma\gamma$ events. The second one $\mathrm{BDT}_{\mathrm{SingleH}}$ is train to separate the signal from the single Higgs boson background where the ZH and $\bar{\mathrm{t}}\mathrm{tH}$ are the dominant ones. The two BDTs are combined with the formula :

$$\mathrm{BDT}_{\mathrm{tot}} = \frac{1}{\sqrt{C_1^2 + (1 - C_1)^2}} \sqrt{C_1^2 (\frac{\mathrm{BDT}_{\gamma\gamma} + 1}{2})^2 + (1 - C_1)^2 (\frac{\mathrm{BDT}_{\mathrm{SingleH}} + 1}{2})^2},$$

where C_1 is a coefficient that is set trough the optimization. The multivariate analysis method is common for all mass point but the selection criterion is mass dependent. The distribution and the selection criterion of the final BDT score for the mass hypothesis of 300 GeV is presented in Figure 2. The selection value is chosen in two steps. The first step is done by maximizing the significance allowing the selection value and the coefficient to be different for each mass hypothesis. The second optimization is performed in order to find a common value of the coefficient C_1 allowing up to a 5% variation from the maximum significance value of each resonance mass value. From the possible value, the coefficient $C_1 = 0.65$ is chosen.

For each mass hypothesis, a fitting procedure with analytic functions on the data di-photon invariant mass is done to extract the signal and the background. The parameterized form of the signal and the single Higgs boson events is chosen to be a Double Sided Crystal Ball function fitted to the Monte Carlo signal sample. The continuum background is modelled from a data side-band fit. The function is chosen via the spurious signal method. The signal bias is estimated by fitting the background-only Monte Carlo sample using a signal plus background function. The exponential function is chosen due to small number of bias and the small number of free parameters.

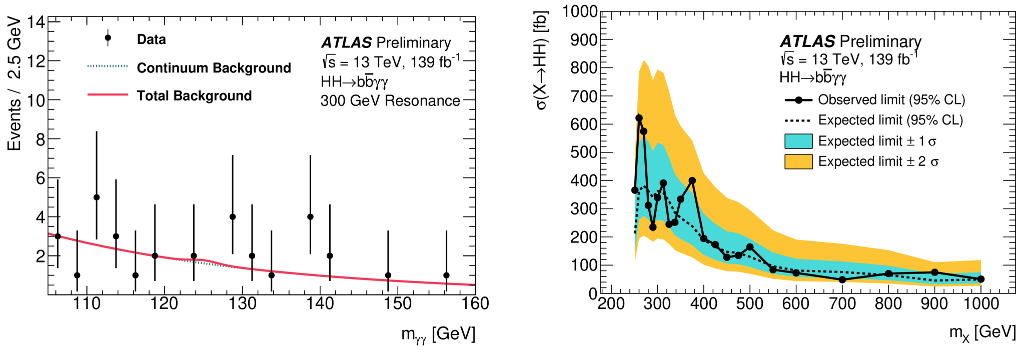

Figure 3: Data are compared to the background-only fit for the resonant search for the m_X= 300 GeV mass hypothesis (on the left side). The continuum background, as well as the background from single Higgs boson production and from the SM HH production are considered. Observed and expected limits at 95% CL on the production cross section of a narrow width scalar resonance X as a function of the mass m_X of the hypothetical scalar particle (on the right side). The black solid line represents the observed upper limits. The dashed line represents the expected upper limits. The $\pm 1\sigma$ and $\pm 2\sigma$ variations about the expected limit due to statistical and systematic uncertainties are also shown. [2]

3. Results

The final fit on the data events are presented for the 300 GeV mass hypothesis in Figure 3. No sign of new physics is observed on the data; the exclusion limits are set using the CLs method with the asymptotic approximation. The distribution of the observed and the expected upper limits on the cross section is presented as function of the mass of the resonance in Figure 3.

A search for a resonant di-Higgs pair production was presented in the final state with two photons and two b-jets using 139 fb^{-1}of pp collision data at a center-of-mass energy of 13 TeV with the ATLAS detector at LHC. No sign of new physics is observed. A 95% CL observed (expected) upper limits are set on the cross section for a scalar particle in the range 610-47 (360-43) fb for a mass hypotheses between 251 and 1000 GeV. A gain of a factor two to three, depending on the mass hypothesis, is obtained compared to the previous analysis done at 36 fb^{-1}[3]. This improvement is attributed to the increase of the luminosity and to the use of the multivariate technique.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, 2008 Journal of Instrumentation 3 S08003.

[2] ATLAS Collaboration, *Search for Higgs boson pair production in the final state with two bottom quarks and two photons in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, ATLAS-CONF-2021-016

[3] ATLAS Collaboration, *Search for Higgs boson pair production in the $\gamma\gamma b\bar{b}$ final state with 13 TeV pp collision data collected by the ATLAS experiment*, Journal of High Energy Physics 11 (2018) 040