ATLAS Paper Draft
HIGG-2017-09
Version 3.0

Comments are due by: 19 March 2018

Supporting internal notes

Supporting note: https://cds.cern.ch/record/2259309

Search for Higgs boson decays into pairs of light (pseudo)scalar particles in the $\gamma\gamma jj$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

This Letter presents a search for exotic decays of the Higgs boson to a pair of new (pseudo)scalar particles, $H \to aa$, with a mass in the range 20–60 GeV, and where one of the a bosons decays into a pair of photons and the other to a pair of gluons. The search is performed in event samples enhanced in vector-boson fusion Higgs boson production by requiring two jets with large invariant mass in addition to the Higgs boson candidate decay products. The analysis is based on the full dataset of pp collisions at $\sqrt{s} = 13$ TeV recorded in 2015 and 2016 with the ATLAS detector at the CERN Large Hadron Collider, corresponding to an integrated luminosity of 36.7 fb^{-1}. The data are in agreement with the Standard Model predictions and an upper limit at the 95% confidence level is placed on the production cross section times the branching ratio for the decay $H \to aa \to \gamma\gamma gg$. This limit ranges from 3.1 pb to 9.0 pb depending on the mass of the a boson.

To be submitted to: Phys. Lett. B.

Document created on 15th March 2018 using ATLAS LaTeX Version 05-03-00.

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Search for Higgs boson decays into pairs of light (pseudo)scalar particles in the $\gamma\gamma jj$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

This Letter presents a search for exotic decays of the Higgs boson to a pair of new (pseudo)scalar particles, $H \to aa$, with a mass in the range 20–60 GeV, and where one of the a bosons decays into a pair of photons and the other to a pair of gluons. The search is performed in event samples enhanced in vector-boson fusion Higgs boson production by requiring two jets with large invariant mass in addition to the Higgs boson candidate decay products. The analysis is based on the full dataset of pp collisions at $\sqrt{s} = 13$ TeV recorded in 2015 and 2016 with the ATLAS detector at the CERN Large Hadron Collider, corresponding to an integrated luminosity of 36.7 fb^{-1}. The data are in agreement with the Standard Model predictions and an upper limit at the 95% confidence level is placed on the production cross section times the branching ratio for the decay $H \to aa \to \gamma\gamma gg$. This limit ranges from 3.1 pb to 9.0 pb depending on the mass of the a boson.

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1 Introduction

The search for the Standard Model (SM) Higgs boson has been one of the main goals of the Large Hadron Collider (LHC) physics programme. A Higgs boson with mass of 125 GeV, and with properties compatible with those expected for the SM Higgs boson (H), was discovered by the ATLAS [**HIGG-2012-27**] and CMS [**CMS-HIG-12-028**] collaborations. Since its discovery, a comprehensive programme of measurements of the properties of this particle has been underway. These measurements could uncover deviations from expected SM branching ratios or set a limit on the possible branching ratio for decays into new particles beyond the SM (BSM). Existing measurements constrain the branching ratio for such decays (B_{BSM}) to less than 34% at 95% confidence level (CL) [**HIGG-2015-07**], assuming that the absolute couplings to vector bosons are smaller than or equal to the SM ones.

Many BSM models predict exotic decays of the Higgs boson [**Curtin:2013fra**]. One possibility is that the Higgs boson decays into a pair of new (pseudo)scalar particles, a, which in turn decay to a pair of SM particles. Several searches have been performed for $H \to aa$ in various final states [**Abazov:2009yi**, **CMS-HIG-13-010**, **CMS-HIG-16-015**, **EXOT-2013-15**, **HIGG-2014-02**].

The results presented in this Letter cover the unexplored $\gamma\gamma jj$ final state in searches for $H \to aa$, where one of the a bosons decays into a pair of photons and the other decays into a pair of gluons. This final state becomes relevant in models where the fermionic decays are suppressed and the a boson decays only into photons or gluons [**Curtin:2013fra**, **hep-ph/0703247**]. The ATLAS Run 1 search for $H \to aa \to \gamma\gamma\gamma\gamma$ [**EXOT-2013-24**] set a 95% CL limit $\sigma_H \times B(H \to aa \to \gamma\gamma\gamma\gamma) < 10^{-3}\ \sigma_{\mathrm{SM}}$ for $10 < m_a < 62$ GeV, where σ_{SM} is the production cross-section for the SM Higgs boson. There is currently no direct limit set on $B(H \to aa \to \gamma\gamma gg)$; however, in combination with $B_{\mathrm{BSM}} < 34\%$, the $H \to aa \to \gamma\gamma\gamma\gamma$ result sets an indirect limit on $B(H \to aa \to \gamma\gamma gg)$ to less than $\sim 4\%$. Assuming the same ratio of photon and gluon couplings to the a boson as to the SM Higgs boson, the $H \to \gamma\gamma\gamma\gamma$ decay occurs very rarely relative to the $H \to \gamma\gamma gg$ decay (a typical value for the ratio $B(H \to \gamma\gamma\gamma\gamma)/B(H \to \gamma\gamma gg)$ is 3.8×10^{-3} [**hep-ph/0703247**]) making $H \to \gamma\gamma jj$ an excellent unexplored final state for probing these fermion-suppressed coupling models. The branching ratio for $a \to \gamma\gamma$ can be enhanced in some scenarios. The two searches are therefore complementary, where the $H \to \gamma\gamma jj$ final state is more sensitive to photon couplings with the new physics sector similar to the photon coupling to the SM Higgs boson, while the $H \to \gamma\gamma\gamma\gamma$ final state is more sensitive to scenarios with enhanced photon couplings.

Reference [**hep-ph/0703247**] shows that the search for $H \to \gamma\gamma gg$, where the Higgs boson is produced in association with a vector boson which decays leptonically, would require approximately 300 fb^{-1} of LHC data in order to be sensitive to branching ratios less than 4%. The gluon–gluon fusion (ggF) production has a larger cross-section, but is overwhelmed by the $\gamma\gamma$+multi-jet background. The strategy described in this Letter consists in selecting events where vector-boson fusion (VBF) is the dominant Higgs boson production mode. Even though the production rate is lower than that for the ggF mode, the characteristic topology of the jets produced in association with the Higgs boson enables more effective suppression of the background.

2 Data and simulation

The search presented in this Letter is based on the 36.7 fb^{-1} dataset of proton–proton collisions recorded by the ATLAS experiment at the LHC at $\sqrt{s} = 13$ TeV during 2015 and 2016. The ATLAS detector [**PERF-2007-01**] comprises an inner detector in a 2 T axial magnetic field, for tracking charged particles and a precise localisation of the interaction vertex, a finely segmented calorimeter, a muon spectrometer and a two-level trigger [**TRIG-2016-01**] that accepts about 1 kHz rate for data storage.

Monte Carlo (MC) event generators were used to simulate the $H \to aa \to \gamma\gamma gg$ signal. Signal samples for the ggF and VBF processes were generated at next-to-leading order using Powheg-Box [**Nason:2004rx**, **Frixione:2007vw**, **Alioli:2010xd**] interfaced with Pythia [**Sjostrand:2014zea**] for parton showering and hadronisation using the AZNLO set of tuned parameters set [**STDM-2012-23**] and the CT10 parton distribution function (PDF) set [**Lai:2010vv**]. Samples were generated in the m_a range[1] 20 GeV $< m_a <$ 60 GeV, assuming the a boson to be a (pseudo)scalar. All MC event samples were processed through a detailed simulation [**SOFT-2010-01**] of the ATLAS detector based on geant4 [**Agostinelli:2002hh**], and contributions from additional pp interactions (pile-up), simulated using Pythia and the MSTW2008LO PDF set [**Martin:2009iq**], were overlaid onto the hard-scatter events.

3 Selection criteria

Events are selected by two diphoton triggers. One trigger path requires the presence in the electromagnetic (EM) calorimeter of two clusters of energy deposits with transverse energy[2] above 35 GeV and 25 GeV for the leading (highest transverse energy) and sub-leading (second-highest transverse energy) clusters, respectively. In the high-level trigger the shape of the energy deposit in both clusters is required to be loosely consistent with that expected from an EM shower initiated by a photon. The other trigger path requires the presence of two clusters with transverse energy above 22 GeV. In order to suppress the additional rate due to the lower transverse energy threshold, the shape requirements for the energy deposits are more stringent.

The photon candidates are reconstructed from the clusters of energy deposits in the EM calorimeter within the range $|\eta| < 2.37$. The energies of the clusters are calibrated to account for energy losses upstream of the calorimeter and for energy leakage outside the cluster, as well as other effects due to the detector geometry and response. The calibration is refined by applying η-dependent correction factors of the order of $\pm 1\%$, derived from $Z \to ee$ events [**PERF-2013-05**]. As in the trigger selection, photon candidates are required to satisfy a set of identification criteria based on the shape of the EM cluster [**PERF-2013-04**]. Two working points are defined: a *Loose* working point, used for the preselection and the data-driven background estimation, and a *Tight* working point, with requirements that further reduce the misidentification of neutral hadrons decaying to two photons. In order to reject the hadronic jet background, photon candidates are required to be isolated from any other activity in the calorimeter. The calorimeter isolation is defined as the sum of the transverse energy in the calorimeter within a cone of

[1] The diphoton triggers considered for this search do not have acceptance for the lower mass range ($m_a < 20$ GeV), where the two photons are collimated.

[2] 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 upward. 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 $\eta = -\ln \tan(\theta/2)$.