Search for the Dimuon Decay of the Higgs Boson in $pp$ Collisions at $\sqrt{s}=13$ TeV with the ATLAS Detector

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A search for the dimuon decay of the Higgs boson was performed using data corresponding to an integrated luminosity of 36.1 fb$^{-1}$ collected with the ATLAS detector in $pp$ collisions at $\sqrt{s}=13$ TeV at the Large Hadron Collider. No significant excess is observed above the expected background. The observed (expected) upper limit on the cross section times branching ratio is 3.0 (3.1) times the Standard Model prediction at the 95% confidence level for a Higgs boson mass of 125 GeV. When combined with the $pp$ collision data at $\sqrt{s}=7$ TeV and $\sqrt{s}=8$ TeV, the observed (expected) upper limit is 2.8 (2.9) times the Standard Model prediction.

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In July 2012, the ATLAS and CMS Collaborations discovered a new particle with a mass of approximately 125 GeV [1–3] at the CERN Large Hadron Collider (LHC). Subsequent measurements have indicated that this particle is consistent with the Standard Model (SM) Higgs boson [4–10], denoted by $H$. The $H \rightarrow \mu\mu$ decay is a sensitive channel in which the Higgs coupling to second-generation fermions can be measured with a clean final-state signature at the LHC. The SM branching ratio for the Higgs boson to dimuon decay is $2.18 \times 10^{-4}$ [11] for $m_H = 125$ GeV. Several scenarios beyond the SM [12–14] predict a higher branching ratio. Any deviation from the SM prediction could be a sign of new physics. The ATLAS experiment carried out a search for the $H \rightarrow \mu\mu$ process using data collected in 2011 and 2012 (LHC Run 1), corresponding to integrated luminosities of 4.5 fb$^{-1}$ at a center-of-mass energy $\sqrt{s} = 7$ TeV and 20 fb$^{-1}$ at $\sqrt{s} = 8$ TeV [15]. For a Higgs boson with a mass of 125 GeV, an observed (expected) upper limit of 7.1 (7.2) was set at the 95% confidence level (C.L.) on the signal strength, defined as the production rate of the $H \rightarrow \mu\mu$ process normalized to the SM prediction. The CMS experiment also performed searches for the $H \rightarrow \mu\mu$ process with data collected in LHC Run 1 [16]. The observed (expected) upper limit from CMS on the signal strength was 7.4 (6.5) at the 95% C.L. for a Higgs boson with $m_H = 125$ GeV.

In this Letter, a search for the dimuon decay of the Higgs boson is presented. The Higgs boson mass is assumed to be $m_H = 125$ GeV for all the results presented in this Letter. The search is performed using $pp$ collision data recorded with the ATLAS detector in 2015 and 2016 at $\sqrt{s} = 13$ TeV. The data set corresponds to an integrated luminosity of 36.1 fb$^{-1}$. This analysis selects events with exactly two opposite-charge muons and classifies them into eight orthogonal categories. Two categories are defined using a multivariable discriminant and provide good sensitivity to the vector-boson fusion (VBF) process. Signal events produced in the VBF process tend to have two high-$p_T$ forward jets in opposite detector hemispheres and little hadronic activity between them. The other six categories are sensitive to signal events produced in the gluon–gluon fusion ($ggF$) process and are defined with different requirements on muon pseudorapidity ($\eta$) and the transverse momentum of the dimuon system ($p_T^{\mu\mu}$).

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the $ggF$ and VBF processes were generated with POWHEG-BOX v2 [19] at next-to-leading order (NLO) in quantum chromodynamics (QCD) using the CT10 [20] parton distribution function (PDF) set and PYTHIA8 [21] for parton showering and hadronization. PYTHIA8 was also used to model \(H \rightarrow \mu\mu\) events produced in association with a W or Z boson (VH). The hadronization and underlying-event parameters were set according to the A2ZLNO tune based on the Z boson \(p_T\) distribution measurement in 7 TeV \(pp\) collisions [22]. The simulated Higgs boson \(p_T\) spectrum for the $ggF$ process is tuned to match the HRES prediction [23,24].

The signal samples are normalized to the predicted cross sections times branching ratio. The production cross sections of the Higgs boson at $\sqrt{s} = 13$ TeV are reported in Refs. [11,25,26]. The cross section for the $ggF$ process is calculated at next-to-next-to-next-to-leading-order QCD [27] and NLO electroweak accuracies [28,29]. Both the VBF and VH cross sections are computed with next-to-next-to-leading-order QCD [30] and NLO electroweak precision [31–33]. The branching ratio for the $H \rightarrow \mu\mu$ decay is calculated using HDECAY [34] at NLO in QCD.

Drell-Yan background events were generated with MADGRAPH5 [35] with the NNPDF23LO [36] PDF set interfaced to PYTHIA8. The $t\bar{t}$ and single-top quark samples were generated with POWHEG-BOX v2 using the CT10 PDF set interfaced to PYTHIA6 [37] for parton showering and hadronization. The diboson processes (WW, WZ, and ZZ) were generated with SHERPA v2.1 [38] with the CT10 PDF set.

All simulated samples were processed through the full ATLAS detector simulation [39] based on GEANT4 [40]. The effects arising from multiple $pp$ collisions in the same or neighboring bunch crossings (pileup) were included in the MC simulation. Events are reweighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data. Simulated events are corrected to reflect the muon momentum scale and resolution and the muon trigger and identification efficiencies measured in data.

Events are required to contain at least one reconstructed $pp$ collision vertex candidate with at least two associated ID tracks, each with $p_T > 0.4$ GeV. The vertex with the largest sum of $p_T^2$ of tracks is considered to be the primary vertex. Dimuon events are selected by requiring two opposite-charge muons. Muons are reconstructed by combining tracks in the ID with tracks in the MS. Candidate muons are required to satisfy the “medium” criteria defined in Ref. [41] and required to have $p_T > 15$ GeV and $|\eta| < 2.5$. Muons are matched to the primary vertex by requiring the longitudinal impact parameter $z_0$ to satisfy $|z_0 \sin(\theta)| < 0.5$ mm, where $\theta$ is the polar angle of the track. The significance of the transverse impact parameter $d_0$ calculated with respect to the measured beam line position is required to satisfy $|d_0|/\sigma(d_0) < 3$, where $\sigma(d_0)$ is the uncertainty in $d_0$. Furthermore, the “loose” isolation criteria described in Ref. [41] are applied to suppress muons from b-hadron decays. Jets are reconstructed using the anti-$k_t$ algorithm [42] with a radius parameter of $R = 0.4$. Candidate jets must have $|\eta| < 4.5$, and the jet $p_T$ must be larger than 25 (30) GeV for $|\eta| < 2.5$ (2.5 < $|\eta| < 4.5$). To suppress pileup contributions, an additional requirement using the track and vertex information inside a jet [43] is imposed on jets with $|\eta| < 2.4$ and $p_T < 60$ GeV. Top quark production is the second largest background with neutrinos and b-hadrons in the final states. Jets containing b hadrons with $|\eta| < 2.5$ are identified as b-tagged jets using a multivariate b-tagging algorithm that provides a 60% efficiency and a rejection factor of more than 1000 for light-flavor jets [44]. Neutrinos escape from the detector and lead to missing transverse momentum $E_T^{\text{miss}}$. The $E_T^{\text{miss}}$ is defined as the magnitude of the negative vectorial sum of the transverse momenta of the selected and calibrated physics objects (including muons and jets) and the ID tracks not associated with any physics object (soft term) [45]. To reduce the top quark contribution, events are required to have $E_T^{\text{miss}} < 80$ GeV and no b-tagged jets.

To ensure a high trigger efficiency, the leading muon must have $p_T > 27$ GeV. These criteria form the preselection, and events passing the preselection with 110 GeV < $m_{\mu\mu}$ < 160 GeV constitute the inclusive signal region. The signal efficiency is 57% (59%) for the $ggF$ (VBF) process. The $m_{\mu\mu}$ distributions for data and MC events in the inclusive signal region are shown in Fig. 1.

The VBF categories are only considered for events containing at least two jets. To optimize the selections, several kinematic variables that are sensitive to the

![FIG. 1. Observed and simulated $m_{\mu\mu}$ distributions in the inclusive signal region. The expected signals are scaled by a factor of 100. The total background prediction is normalized to the observed data yield, while the relative fractions between the different processes are fixed to the SM predictions. The error band only reflects the statistical and experimental uncertainties in the MC background prediction, while the theoretical uncertainties are not included.](image-url)
The background model should be able to describe the steeply falling $m_{\mu\mu}$ distributions from the dominant Drell-Yan process. At the same time, it should have sufficient flexibility to absorb potential differences between data and MC simulation, and allow variations in the $m_{\mu\mu}$ spectra due to different selections and additional contributions from minor background processes. The adopted model is the sum of a Breit-Wigner function (BW)
convolved with a GS, and an exponential function divided by a cubic function,

\[
P_B(m_{\mu\mu}) = f \times \left[ B(m_{BW}, \Gamma_{BW}) \otimes GS(\sigma_{GS}^B)(m_{\mu\mu}) \right] + (1 - f) \times e^{\lambda m_{\mu\mu}} / m_{\mu\mu}^3,
\]

where \( f \) is the fraction of the BW component when each component is normalized to unity. The \( \sigma_{GS}^B \) parameter in each category is fixed to the corresponding average \( m_{\mu\mu} \) resolution as determined from MC Drell-Yan events. For all the categories, the BW parameters are fixed to \( m_{BW} = 91.2 \text{ GeV} \) and \( \Gamma_{BW} = 2.49 \text{ GeV} \) [50]. The parameters \( f \) and \( A \) are unconstrained and uncorrelated between different categories.

A binned maximum-likelihood fit to the observed \( m_{\mu\mu} \) distributions in the range 110–160 GeV is performed using the sum of the signal and background models (“S + B model”). The fit is done simultaneously in all the categories. In addition to the background model parameters (\( f \) and \( A \)) described earlier, the background normalization in each category is a free parameter in the fit. The product of the \( H \rightarrow \mu\mu \) signal strength \( \mu_S \) and the expected signal yield gives the signal normalization in each category.

The expected signal yields used in the fit are subject to experimental and theoretical uncertainties. The systematic uncertainties in the expected signal are correlated between all the categories.

The uncertainty in the combined 2015 and 2016 integrated luminosity is 3.2%, derived, following a methodology similar to that detailed in Ref. [51], from a preliminary calibration of the luminosity scale using \( x \)-\( y \) beam-separation scans performed in August 2015 and May 2016. Other sources of experimental uncertainty include the muon reconstruction and identification efficiencies, the efficiencies due to the trigger, isolation, and impact parameter requirements, the muon momentum scale and resolution, the determination of the \( E_T^{miss} \) soft term, the \( b \)-tagging efficiency, the pileup modeling, as well as the jet energy scale and resolution. The total experimental uncertainty in the predicted signal yield in each \( ggF \) category is between 4% and 6%, dominated by the luminosity, muon, jet, and pileup contributions. The experimental uncertainty increases to 15% in the VBF categories, due to larger contributions from the jet energy scale and resolution uncertainties. The effects of the experimental uncertainties in the predicted signal \( m_{\mu\mu} \) shapes are found to be minor and are therefore neglected in this search.

The theoretical uncertainties in the production cross section of the Higgs boson and the \( H \rightarrow \mu\mu \) decay branching ratio are set according to Refs. [25,26]. The uncertainty in the signal acceptance in the \( ggF \) categories, due to the modeling of the Higgs boson \( p_T \) spectrum, is estimated by varying the QCD scales used in the HRES program. The acceptance uncertainties of \( ggF \) signal events in the VBF categories are estimated using the method described in Ref. [15]. The uncertainties associated with the modeling of multiparton interactions are estimated by turning them off in the event generation, according to the recommendations in Ref. [11]. The uncertainty in the \( ggF \) signal prediction ranges from 15% to 25%, dominated by the uncertainties due to omitted high-order effects. The total theoretical uncertainty in the VBF signal yield in each category is typically around 5%.

Any systematic bias in the background model when describing the underlying \( m_{\mu\mu} \) spectrum might result in spurious signal events in the measurement. In each category, the number of spurious signal events (\( N_{\text{spur}} \)) is estimated by fitting the parameterized S + B model to the simulated background \( m_{\mu\mu} \) distribution in the range 110–160 GeV. The \( m_{\mu\mu} \) spectra are obtained from large Drell-Yan MC samples, which were produced with POWHEG-BOX v2[19] and MADGRAPH5 [35] for the \( ggF \) and VBF categories, respectively, and correspond to an equivalent integrated luminosity of about 5 ab\(^{-1}\). Values of \( N_{\text{spur}} \) are derived for three nearby Higgs boson masses (120, 125, and 130 GeV), and from these the largest value between the yields and their statistical uncertainties is taken as the \( N_{\text{spur}} \) value for a certain category. A detailed discussion about how \( N_{\text{spur}} \) is used in the fitting procedure is given in Ref. [52]. The background modeling uncertainty is treated as uncorrelated among all the categories. This uncertainty varies from 8% to 50% of the statistical uncertainties of the background, depending on the selection category. The impact of the background mismodeling on the expected upper limit on the signal strength is about 2%.

The observed \( m_{\mu\mu} \) spectrum is compared to the background-only fit in Fig. 2 for the VBF tight category. The S + B model is fitted to the observed \( m_{\mu\mu} \) spectra in eight signal categories simultaneously, and the measured overall

![FIG. 2. Background-only fit to the observed \( m_{\mu\mu} \) distribution in the VBF tight category. Only the statistical uncertainties are shown for the data points. The expected signal is scaled by a factor of 20.](image-url)
signal strength is \( \mu_S = -0.1 \pm 1.5 \). An upper limit on \( \mu_S \) is computed using a modified frequentist \( \text{CL}_{s} \) method \([53,54]\) with the profile-likelihood-ratio test statistic \([53]\). The observed (expected) upper limit on \( \mu_S \) at the 95\% C.L. is found to be \( 3.0 (3.1) \). This limit is driven by the data statistical uncertainty, while the impact of the systematic uncertainties is found to be 2.2\%. When combined with the ATLAS Run 1 data, the observed (expected) upper limit is \( 2.8 (2.9) \) at the 95\% C.L. The corresponding measured signal strength is \( \mu_S = -0.1 \pm 1.4 \). The theoretical and experimental uncertainties in the expected signal and the background modeling uncertainty are correlated in the combination.

To conclude, a search for the dimuon decay of the Higgs boson is performed using 36.1 fb\(^{-1} \) of data collected with the ATLAS detector in pp collisions at \( \sqrt{s} = 13 \) TeV at the LHC. No significant excess is observed in data, and an upper limit is set on the signal strength.

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Seventh Framework Programme


ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the $z$ axis along the beam pipe. The $x$ axis points from the IP to the center of the LHC ring, and the $y$ axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$ axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.


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