Measurement of exclusive $\gamma\gamma \to W^+W^-$ production and search for exclusive Higgs boson production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector

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Searches for exclusively produced W boson pairs in the process $pp(\gamma\gamma) \to pW^+W^-p$ and an exclusively produced Higgs boson in the process $pp(gg) \to pHp$ have been performed using $e^\pm\mu^\mp$ final states. These measurements use 20.2 fb^{-1} of pp collisions collected by the ATLAS experiment at a center-of-mass energy $\sqrt{s} = 8$ TeV at the LHC. Exclusive production of W^+W^- consistent with the Standard Model prediction is found with 3.0σ significance. The exclusive W^+W^- production cross section is determined to be $\sigma(\gamma\gamma \to W^+W^- \to e^\pm\mu^\mp X) = 6.9 \pm 2.2(\text{stat}) \pm 1.4(\text{sys})$ fb, in agreement with the Standard Model prediction. Limits on anomalous quartic gauge couplings are set at 95% confidence level as $-1.7 \times 10^{-6} < a_0^W/\Lambda^2 < 1.7 \times 10^{-6}$ GeV^{-2} and $-6.4 \times 10^{-6} < a_C^W/\Lambda^2 < 6.3 \times 10^{-6}$ GeV^{-2}. A 95% confidence-level upper limit on the total production cross section for an exclusive Higgs boson is set to 1.2 pb.

I. INTRODUCTION

In the Standard Model (SM) of particle physics, the interactions between electroweak gauge bosons are described by the non-Abelian $SU(2) \times U(1)$ structure of the electroweak sector. Measurement of the strengths of the trilinear (VVV, where $V = \gamma$, W, or Z) and quartic ($VVVV$) gauge couplings represent an important test of the SM, as deviations from SM predictions would indicate new physics. The discovery of a Higgs boson [1,2] at the Large Hadron Collider (LHC) has taken a major step toward confirming the mechanism of electroweak symmetry breaking. Anomalous quartic gauge couplings (aQGCs) provide a window to further probe possible new physics extensions of electroweak theory. Exclusive production of W boson pairs, $pp(\gamma\gamma) \to pW^+W^-p$, provides an opportunity to study $\gamma\gamma \to W^+W^-$ aQGC couplings [3,4].

In pp collisions, exclusive W^+W^- events are produced when each proton emits a photon and the two photons annihilate, either via t- and u-channel W-exchange diagrams involving trilinear gauge couplings or via a quartic gauge coupling diagram, to create a W^+W^- pair. Figure 1 shows the exclusive production of a W^+W^- pair, where the blobs represent the t-channel, u-channel, and quartic diagrams. After the collisions, either both protons remain intact as shown in Fig. 1(a) (referred to as elastic hereafter), only one proton remains intact as in Fig. 1(b) (single

dissociation, SD), or both protons dissociate as in Fig. 1(c) (double dissociation, DD). In all three cases the trajectories of the protons or their remnants deviate only slightly from their initial directions so that they never enter the acceptance of the ATLAS detector. On the other hand, inclusive processes are produced with accompanying activity such as initial- and final-state radiation and additional scattering in the same pp collision. The accompanying activity is collectively called the underlying event and emits particles into the acceptance of the ATLAS detector.

Photon scattering in hadron colliders can be described in quantum electrodynamics (QED) by the equivalent-photon approximation (EPA) [5,6]. In this framework the exclusive W^+W^- cross section can be written as

$$\sigma_{pp(\gamma\gamma)\to ppW^+W^-}^{\text{EPA}} = \iint f(x_1)f(x_2)\sigma_{\gamma\gamma\to W^+W^-}(m_{\gamma\gamma}^2)dx_1dx_2,$$

(1)

where $f(x_i)$, for $i \in \{1, 2\}$, is the number of equivalent photons carrying a fraction of the proton's energy, x_i, that are emitted, while $m_{\gamma\gamma}$ is the two-photon center-of-mass energy. This approach has been used to describe similar exclusive processes in the CDF [7], STAR [8], and CMS [9,10] experiments.

Exclusive W^+W^- pair production is particularly sensitive to new physics that may be described by aQGC of the form $WW\gamma\gamma$ [4,11]. The dimension-6 operators in Ref. [3] are the lowest-dimension operators that give rise to anomalous $WW\gamma\gamma$ couplings, a_0^W/Λ^2 and a_C^W/Λ^2, where Λ is the scale of new physics. A procedure adopted by previous measurements [12–14] uses a dipole form factor to preserve unitarity at high $m_{\gamma\gamma}$. The couplings a_0^W/Λ^2 and a_C^W/Λ^2 then become

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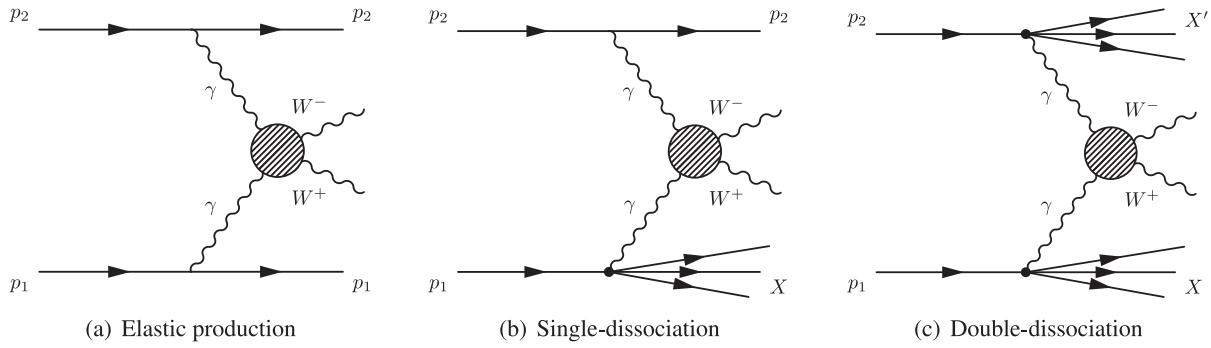(a) Elastic production   (b) Single-dissociation   (c) Double-dissociation

FIG. 1.   Diagrams for the exclusive $\gamma\gamma \to W^+W^-$ production representing the (a) elastic process, (b) single-dissociation where one initial proton dissociates (SD) and (c) double dissociation where both protons fragment (DD). The symbols X and X' denote any additional final state created.

$$a_{0,C}^W/\Lambda^2 \to \frac{a_{0,C}^W}{\Lambda^2} \frac{1}{(1+\frac{m_{\gamma\gamma}^2}{\Lambda_{\text{cutoff}}^2})^2}, \tag{2}$$

where Λ_{cutoff} defines the scale of possible new physics, and the term containing it ensures that unitarity is preserved.

Anomalous triple gauge couplings (aTGCs) could also produce similar effects, but the sensitivity of this study to aTGC is not competitive compared with other processes [4], so these are taken to be zero.

More recent parametrizations of aQGC are of dimension 8. The parametrizations of the dimension-8 couplings, $f_{M,0,1,2,3}/\Lambda^4$, in Ref. [15] are linearly related to the $a_{0,C}^W/\Lambda^2$ as follows:

$$\frac{f_{M,0}}{\Lambda^4} = \frac{a_0^W}{\Lambda^2}\frac{1}{g^2\nu^2}, \qquad \frac{f_{M,1}}{\Lambda^4} = -\frac{a_C^W}{\Lambda^2}\frac{1}{g^2\nu^2}, \tag{3}$$

where $g = e/\sin(\theta_W)$ and ν is the Higgs boson vacuum expectation value. Also, with this parametrization, $f_{M,2} = 2 \times f_{M,0}$ and $f_{M,3} = 2 \times f_{M,1}$.

In addition to the discovery of the Higgs boson, several of its properties—such as mass, coupling strengths to various final-state particles, and branching ratios of its decay—have been determined [1,16] using Higgs boson candidates from inclusive production. Higgs boson candidates from the exclusive production ($pp \to pggp \to pHp$) would have lower systematic uncertainties due to their cleaner production environment [17–20]. Since measurements using these Higgs boson candidates would have better precision, they could be used to improve knowledge of the Higgs boson sector. It is therefore interesting to determine the cross section for exclusive Higgs boson production and examine the feasibility of using exclusive Higgs boson candidates for Higgs boson property measurements. This interest is reflected in the inclusion of the exclusive Higgs boson process studies as part of the physics program of forward proton-tagging detectors [21–23] that extend the ATLAS and CMS coverage for LHC runs at 13 TeV.

Unlike exclusive W^+W^- production, exclusive Higgs boson production proceeds through a quantum chromodynamics (QCD) process involving at least three gluons, as shown in Fig. 2. Two gluons from the colliding protons interact through a top-quark loop to produce a Higgs boson, while additional gluon exchange between the colliding protons keeps the protons color-neutral and allows the protons to remain intact after the collision. The proton trajectories deviate slightly after the collision. One W boson from Higgs boson decays must be off shell so the event selection for that study needs to be different than the exclusive W^+W^- event selection, and the samples are largely orthogonal.

The exclusive Higgs boson production cross section can be written as [24]

$$\sigma_{pp(gg)\to ppH} \propto \hat{\sigma}(gg \to H)$$
$$\times \left(\int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', Q_t^2) f_g(x_2, x_2', Q_t^2) \right)^2 \tag{4}$$

where $\hat{\sigma}(gg \to H)$ is the cross section for the gluon fusion process that produces the Higgs boson. The functions f_g [25] are the generalized gluon densities for the finite proton
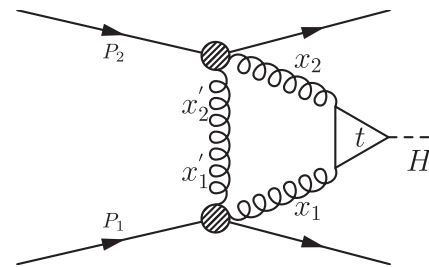

FIG. 2.   The lowest-order Feynman diagram for the exclusive Higgs boson production. The variables x_1 and x_2 are the fractions of the momenta carried by the gluons that contribute to the production of the Higgs boson, with respect to the momenta of the protons P_1 and P_2. The variables x_1' and x_2', on the other hand, are the fractions of the momentum carried by the exchanged third gluon with respect to the momenta of the protons P_1 and P_2.

size, which take into account the impact parameter. The variables x_1 and x_2 are the fractions of the momenta carried by the gluons that contribute to the production of the Higgs boson, with respect to the momenta of the protons P_1 and P_2. The variables x'_1 and x'_2 are the fractions of the momentum carried by the exchanged third gluon with respect to the momenta of the protons P_1 and P_2 as shown in Fig. 2. These gluon densities are integrated over the exchanged (third) gluon transverse momentum Q_t. This formalism, used in several theoretical calculations, predicts cross sections that vary by over an order of magnitude [24,26]. This wide disparity in predictions is an additional motivation for this measurement. While either proton could dissociate, the predictions presented here are for elastic production only and could underestimate the cross section by an order of magnitude [24].

This paper describes searches for exclusive W^+W^- and $H \to W^+W^-$ production using $e^\pm\mu^\mp$ final states. Events where a W boson decays to a τ lepton that subsequently decays to an electron or muon are also included. This final state is denoted $e\mu X$, where X represents the neutrinos. Section II describes the experimental setup. Section III describes the data set and simulation tools used to model signal and background processes. Initial selection of electron, muon, jet and track candidates is discussed in Sec. IV. Section V introduces a new approach to separate exclusive from inclusive production processes. Section VI describes the event selections including signal regions for both the exclusive W^+W^- and Higgs boson processes. Section VII outlines studies of the exclusive event selection and underlying-event models using samples of same-flavor opposite-sign lepton pairs in $p\gamma\gamma p \to p\ell^+\ell^- p$ candidates ($\ell = \mu$ or e) to validate modeling and selection criteria. In Sec. VIII, data control regions designed to test and correct physics and detector modeling are described. Systematic uncertainties are summarized in Sec. IX, and the results of the study are described in detail in Sec. X. Section XI summarizes the findings.

II. THE ATLAS DETECTOR

ATLAS [27] is a multipurpose cylindrical detector[1] that consists of an inner detector surrounded by a superconducting solenoid, a calorimeter system, and a muon spectrometer that includes superconducting toroidal magnets. The inner detector system consists of three subsystems: a pixel detector, a silicon microstrip detector, and a transition

radiation tracker. Immersed in a 2 T magnetic field provided by the superconducting solenoid, these three subsystems enable the inner detector to accurately reconstruct the trajectories of charged particles in a pseudorapidity range $|\eta| < 2.5$ and measure their momenta and charges. The inner detector is surrounded by high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeters covering the pseudorapidity range $|\eta| < 3.2$. A steel/scintillator tile calorimeter provides hadronic energy measurements in the pseudorapidity region $|\eta| < 1.7$. In the regions $1.5 < |\eta| < 4.9$ the hadronic energy measurements are provided by two end-cap LAr calorimeters using copper or tungsten as absorbers. The calorimeters are surrounded by a muon spectrometer that provides muon tracking beyond the calorimeters in the range $|\eta| < 2.7$, and improves muon momentum resolution, charge measurements, and identification including triggering.

Events are selected using a three-level trigger system [28]. A hardware-based level-1 trigger uses a subset of detector information to reduce the event rate to 75 kHz or less. The rate of accepted events is then reduced to about 400 Hz by two software-based trigger levels, level-2 and the event filter. These events are then stored for later offline reconstruction and analysis.

III. DATA AND SIMULATED EVENT SAMPLES

This analysis uses a data set of pp collisions collected at a center-of-mass energy $\sqrt{s} = 8$ TeV during 2012 under stable beam conditions. After applying data quality requirements, the data set has a total integrated luminosity of 20.2 ± 0.4 fb^{-1} [29].

The exclusive SM $\gamma\gamma \to W^+W^-$ signal sample is generated using the HERWIG++[30] Monte Carlo (MC) generator, while $\gamma\gamma \to W^+W^-$ signal samples with both the SM and non-SM aQGC predictions are generated by FPMC [31]. These two generators use the EPA formalism with a standard dipole parametrization [32] of the proton electromagnetic form factors to produce an equivalent photon flux in pp collisions. FPMC is used in these studies to generate $pp \to pggp \to pHp$ events. None of these exclusive W^+W^- and Higgs boson generators supports the case where one or both of the initial protons dissociate.

Produced via a mechanism similar to that for the exclusive W^+W^- signal, exclusive $\tau^+\tau^-$ production is an irreducible background when the two τ leptons decay to an $e^\pm\mu^\mp$ final state. Elastic $\gamma\gamma \to \tau^+\tau^-$, $\gamma\gamma \to \mu^+\mu^-$ and $\gamma\gamma \to e^+e^-$ backgrounds are generated using HERWIG++. Single- and double-dissociative $\gamma\gamma \to \mu^+\mu^-$ and $\gamma\gamma \to e^+e^-$ backgrounds are produced using LPAIR 4.0 [33], while PYTHIA8 [34] is used to produce single-dissociative $\gamma\gamma \to \tau^+\tau^-$ candidates. Double-dissociative $\gamma\gamma \to \tau^+\tau^-$ samples are not available, but their contribution is small. This paper refers to the τ processes described in this paragraph as the

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[1]The ATLAS experiment 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 direction. The x axis points from the IP to the center of the LHC ring and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse (x, y) plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. The angular distance ΔR in the $\eta - \phi$ space is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

TABLE I. A list of the simulated samples used for estimating the expected contributions to the exclusive W^+W^- signal region and exclusive Higgs boson signal region. The exclusive W^+W^- production is treated as background in the exclusive Higgs boson channel. Similarly, the exclusive Higgs boson production is a background to exclusive W^+W^- signal.

Process	MC generator
Exclusive W^+W^- signal	
$\quad \gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$ $(\ell, \ell' = e, \mu, \tau)$	HERWIG++
aQGC signal	
$\quad \gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$ with $a_{0,C}^W/\Lambda^2 \neq 0$	FPMC
Exclusive Higgs boson signal	
$\quad$ Exclusive $gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$	FPMC
Exclusive dilepton	
$\quad \gamma\gamma \rightarrow \ell^+\ell^-$ $(\ell = e, \mu, \tau)$	HERWIG++, LPAIR, PYTHIA8
Inclusive W^+W^-	
$\quad W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$ $(\ell, \ell' = e, \mu, \tau)$	POWHEG+PYTHIA8, GG2WW+HERWIG
$\quad$ Inclusive $gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$	POWHEG+PYTHIA8
$\quad$ Vector-boson fusion $W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$	SHERPA
Non-W^+W^- diboson (Other-VV diboson)	
$\quad WZ, ZZ$	POWHEG+PYTHIA8
Other background	
$\quad W + \text{jets}$	ALPGEN+PYTHIA6
$\quad Z + \text{jets}$	ALPGEN+PYTHIA6, ALPGEN+HERWIG
$\quad t\bar{t}$, single top-quark, Wt	POWHEG+PYTHIA6, ACERMC+PYTHIA6, MC@NLO+HERWIG

exclusive background. In the exclusive Higgs boson search, exclusive W^+W^- production is an additional background.

Inclusive W^+W^- production is a dominant background and has similar final states to the signal process, except that it is usually accompanied by additional charged particles from the underlying event. The inclusive W^+W^- background is the sum of nonresonant $q\bar{q} \rightarrow W^+W^-$ events, $gg \rightarrow W^+W^-$ events from nonresonant direct production, and resonant production and decay of the 125 GeV Higgs boson. The $q\bar{q} \rightarrow W^+W^-$ and $H \rightarrow W^+W^-$ samples are generated using the POWHEG-BOX [35–39] generator (hereafter referred to as POWHEG) interfaced to PYTHIA8 (POWHEG+PYTHIA8) for parton showering, hadronization, and underlying-event simulation. The AU2 [40] parameter set ("tune") is used for the underlying event. For the nonresonant $gg \rightarrow W^+W^-$ sample, the GG2WW [41] program is used and the showering, hadronization, and underlying event are simulated using HERWIG [42] and JIMMY [43], with the AUET2 [44] tune. The CT10 PDF set [45] is employed for all of these samples. The contribution from vector-boson fusion production of W^+W^- events, generated with SHERPA [46] with CT10 PDFs, is also included. In all regions of phase space, a normalization factor of 1.2 is applied to inclusive W^+W^- background as a correction to the cross section as described in Sec. VIII C.

Other backgrounds such as $W/Z + \text{jets}$ are easier to reject than inclusive W^+W^- production, because, in addition to being produced with extra charged particles, their final-state topologies are also different. However, their contribution is non-negligible due to their several orders of magnitude higher cross section. Both $W/Z + \text{jets}$ processes are modeled with ALPGEN [47] interfaced to

PYTHIA6 [48] (ALPGEN+PYTHIA6) using the CTEQ6L1 PDF set [49] and Perugia 2011C [50] tune. Diboson processes such as WZ and ZZ^2 are also sources of background if exactly two charged lepton candidates are reconstructed and identified. The WZ and ZZ samples are generated using POWHEG+PYTHIA8 [51] with the AU2 tune and the CT10 PDF set. Other diboson processes ($W\gamma$ and $Z\gamma$) are also considered, but their contributions are found to be negligible. The POWHEG generator interfaced to PYTHIA6 with the CT10 PDF set is used to simulate $t\bar{t}$ background. Single-top-quark production through the t-channel is modeled with ACERMC [52] interfaced to PYTHIA6 with the CTEQ6L1 PDF set, while s-channel and Wt single-top-quark backgrounds are simulated using MC@NLO [53] interfaced to HERWIG and JIMMY with the CT10 PDF set and AUET2 tune. The underlying event AUET2B [44] tune is employed for the $t\bar{t}$ and t-channel single-top-quark backgrounds. A summary of the processes and simulation tools used in this paper are given in Table I.

The same background samples are used for the exclusive Higgs boson search, except for $Z + \text{jets}$, which is modeled with ALPGEN interfaced to HERWIG and JIMMY (ALPGEN +HERWIG) and top-quark background whose contribution to the exclusive Higgs boson signal region is negligible. The CTEQ6L1 PDF set is employed for the ALPGEN+HERWIG $Z + \text{jets}$ samples. Two more sets of $Z + \text{jets}$ samples, generated using POWHEG+PYTHIA8 and SHERPA with CT10 PDF set, are used for additional background studies.

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[2] The symbol Z in WZ and ZZ is used here for both Z and γ^* production decaying to a lepton pair.

All the background samples mentioned above are processed through a simulation of the ATLAS detector [54] based on GEANT4 [55]. The signal samples are processed through the fast detector simulation program ATLFAST2 [56]. The effect of the multiple pp collisions, which is referred to as pileup throughout this paper, is also simulated by overlaying minimum-bias events generated using PYTHIA8 and corrected to agree with data.

IV. SELECTION OF LEPTONS, JETS, AND CHARGED PARTICLES

Selection criteria are applied to the data and simulated samples to identify events that have good quality electron and muon candidates. Electron candidates are reconstructed from clusters of energy deposited in the electromagnetic calorimeter that are matched to tracks in the inner detector. They are required to have transverse momentum $p_T > 10$ GeV and be within a pseudorapidity range $|\eta| < 2.47$, excluding the region $1.37 \leq |\eta| \leq 1.52$. Also, they satisfy shower shape and track selection criteria that make up the "very tight" likelihood criteria [57] defined by a multivariate likelihood algorithm. Electrons are required to be isolated based on tracking and calorimeter information. Efficiencies for very tight electron identification range from 60% to 70%. Muon candidates with $p_T > 10$ GeV are reconstructed from tracks in the inner detector matched to tracks in the muon spectrometer. Muon candidates are required to be within a pseudorapidity range $|\eta| < 2.5$ and must satisfy the criteria outlined in Ref. [58], providing muon identification efficiencies of up to 95%. The tracking and calorimeter isolation criteria for muon and electron candidates are the same as those used in Ref. [59].

Jets with $|\eta| < 4.5$ are reconstructed from energy clusters in the calorimeter using the anti-k_t algorithm [60] with a radius parameter of 0.4. To suppress jets from pileup, only jets with $p_T > 25$ GeV are considered. Missing transverse momentum $p_T^{\mathbf{miss}}$ with magnitude E_T^{miss} is reconstructed as the magnitude of the negative vector sum of the momentum of reconstructed physics objects—e, μ, photons, and jets—and remaining calorimeter clusters that are not associated with any hard objects are also included with the proper calibration [61].

Charged particle tracks having $p_T > 0.4$ GeV and $|\eta| < 2.5$ reconstructed by the inner detector are used in this paper to reject nonexclusive production. They are required to leave at least one hit in the pixel detector and at least four hits in the silicon microstrip detector.

V. EXCLUSIVITY SELECTION

Exclusive candidates are characterized by large rapidity gaps [62,63] between the protons and the system of interest —a W^+W^- pair or Higgs boson. A signature for this, in the ATLAS detector, is an absence of tracks, other than tracks from the W^+W^- pair or Higgs boson decay products. Inclusive candidates, in contrast, are produced with extra particles that originate from the emission and hadronization of additional gluons, and the underlying event. These extra particles usually produce tracks in the inner detector. This analysis takes advantage of the absence of additional charged particle tracks to separate exclusive from inclusive (color processes) production.

In exclusive Higgs boson and W^+W^- production, no further charged particles are produced apart from the two final-state leptons. So in order to select exclusive events, the distance between the z_0 of the leptons is required to be less than 1 mm, where z_0 is the z coordinate at the point of closest approach of a lepton (or track) to the beam line in the r-ϕ plane. Then the average z_0 of the two leptons, z_0^{av}, is taken as the event vertex and is referred to as the lepton vertex. In this paper, an exclusivity selection is applied, which requires zero additional tracks with $p_T > 0.4$ GeV near z_0^{av} with $|z_0^{\mathrm{track}} - z_0^{\mathrm{av}}| < \Delta z_0^{\mathrm{iso}}$. To improve the efficiency for exclusive events whose leptons have more than one associated track (due to bremsstrahlung for example), candidate tracks considered for this selection are required to be unmatched to either of the final-state leptons. Therefore, a candidate track within an angular distance $\Delta R < 0.01$ and within 1 mm in z_0 of either of the final-state leptons is considered matched and is ignored. The value $\Delta z_0^{\mathrm{iso}}$ is optimized using exclusive Higgs boson and exclusive W^+W^- simulated samples. A value of $\Delta z_0^{\mathrm{iso}} = 1$ mm is chosen for all results in this paper. The exclusivity selection efficiency is found to be 58% and is largely process independent as is discussed in Sec. VIII A. In Fig. 3 the exclusivity efficiency is extracted from exclusive Higgs boson signal simulated by FPMC, plotted against the average number of interactions per beam crossing μ. For the data set used in this study, $\langle \mu \rangle$ is 20.7.
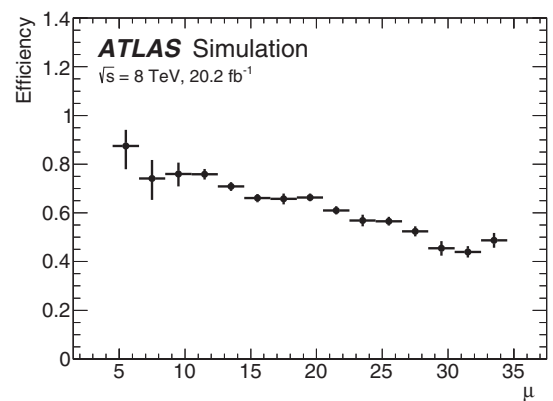

FIG. 3. Efficiency of the exclusivity selection, extracted from the exclusive Higgs boson signal simulation, is plotted against the average number of interactions per beam crossing μ. The average is 20.7 for the current data set.

TABLE II. Single-lepton and dilepton triggers are used to select event candidates. Single-lepton triggers require either of the leptons to satisfy the specified p_T criterion, while dilepton triggers have two specific p_T criteria.

Trigger	Lepton p_T criteria [GeV]
Single electron	$p_T^e > 24$
Single muon	$p_T^\mu > 24$
Symmetric dielectron	$p_T^{e_1} > 12$, $p_T^{e_2} > 12$
Asymmetric dimuon	$p_T^{\mu_1} > 18$, $p_T^{\mu_2} > 8$
Electron-muon	$p_T^e > 12$, $p_T^\mu > 8$

VI. EVENT SELECTION

Events are required to satisfy at least one of the single-lepton and dilepton triggers in Table II. They are further categorized into ee, $\mu\mu$, and $e\mu$ final states. A combination of single-lepton and different-flavor dilepton triggers is used to select the signal events, while the same-flavor dilepton triggers are used to select ee and $\mu\mu$ events for validation and control regions.

For both the exclusive W^+W^- and Higgs boson channels, this analysis selects candidates consistent with leptonic decays of W-boson pairs into oppositely charged different-flavor leptons. Additional kinematic requirements reject background while retaining as much of the signal as possible. Exclusive W^+W^- production is a large background in the exclusive Higgs boson search, while the exclusive Higgs boson contribution to the exclusive W^+W^- signal is negligible. So the kinematic requirements for the two channels differ slightly. Table III summarizes the selection criteria for both channels.

A. Exclusive W^+W^- candidate selection

For the exclusive W^+W^- channel, requiring oppositely charged $e^\pm\mu^\mp$ leptons rejects same-flavor lepton events from Drell-Yan and exclusive dilepton processes. The invariant mass of the dilepton system is required to be greater than 20 GeV. This rejects a significant fraction of the remaining background in which jets have nonprompt or fake electron and/or muon signatures. The lepton with the higher p_T is referred to as the leading lepton ($\ell 1$), and the other, the subleading lepton ($\ell 2$). The p_T requirement on the leading lepton is chosen to be higher than the single-lepton trigger threshold, resulting in different leading and subleading leptons requirements: $p_T^{\ell 1} > 25$ GeV and $p_T^{\ell 2} > 20$ GeV, respectively. These selection criteria define preselection.

To reduce $\gamma\gamma \to \tau^+\tau^-$ and $Z/\gamma^* \to \tau^+\tau^-$ contamination, the magnitude of the transverse momentum of the dilepton system ($p_T^{e\mu}$) is required to be greater than 30 GeV. The exclusivity requirement rejects most of the remaining inclusive background. After applying these selection criteria, 70% of the predicted background is due to inclusive W^+W^- production, while $\gamma\gamma \to \tau^+\tau^-$ contributes 15% and the contributions from other categories are negligible.

The limits on aQGCs are extracted from the region with $p_T^{e\mu} > 120$ GeV. This requirement considerably reduces the SM contribution.

B. Exclusive Higgs boson candidate selection

The Higgs boson decays to W^+W^- give one on-shell and one off-shell W boson. Thus, the subleading lepton minimum p_T is lowered to 15 GeV. For the same reason, the $m_{e\mu}$ threshold is lowered to 10 GeV. The other requirements in the preselection are the same as for the exclusive W^+W^- sample. In contrast to the W^+W^- topology, the zero spin of the Higgs boson implies that the final-state leptons have small angular separation. Therefore, the angular separation of the leptons in the transverse plane ($\Delta\phi_{e\mu}$) and the dilepton mass ($m_{e\mu}$) are two good discriminating variables against the remaining exclusive W^+W^- background, which has a wider angular separation and relatively higher dilepton mass. Thus, $m_{e\mu}$ and $\Delta\phi_{e\mu}$ selection criteria are further imposed in the Higgs boson search. The transverse mass of the Higgs boson system, m_T, is defined as

$$m_T = \sqrt{(E_T^{e\mu} + E_T^{miss})^2 - |\boldsymbol{p}_T^{e\mu} + \boldsymbol{p}_T^{miss}|^2}, \qquad (5)$$

where $E_T^{e\mu} = \sqrt{|\boldsymbol{p}_T^{e\mu}|^2 + m_{e\mu}^2}$ and $|\boldsymbol{p}_T^{miss}| = E_T^{miss}$. Requiring $m_T < 140$ GeV further reduces both the inclusive and

TABLE III. Selection criteria for the two analysis channels.

	W^+W^- selection	Higgs boson selection
	Oppositely charged $e\mu$ final states	
Preselection	$p_T^{\ell 1} > 25$ GeV and $p_T^{\ell 2} > 20$ GeV	$p_T^{\ell 1} > 25$ GeV and $p_T^{\ell 2} > 15$ GeV
	$m_{e\mu} > 20$ GeV	$m_{e\mu} > 10$ GeV
	$p_T^{e\mu} > 30$ GeV	
	Exclusivity selection, Δz_0^{iso}	
aQGC signal	$p_T^{e\mu} > 120$ GeV	$\cdots$
Spin-0 Higgs boson	$\cdots$	$m_{e\mu} < 55$ GeV
	$\cdots$	$\Delta\phi_{e\mu} < 1.8$
	$\cdots$	$m_T < 140$ GeV

exclusive W^+W^- backgrounds and improves the signal significance by 20% (see Fig. 15). The exclusivity selection uses $\Delta z_0^{\text{iso}} = 1$ mm here as well.

VII. PILEUP AND EXCLUSIVITY VALIDATION WITH $\gamma\gamma \to \ell^+\ell^-$ EVENTS

The selection strategy described in Sec. V represents a new approach to extract exclusive processes without using the usual vertex reconstruction [64]. This section describes two studies designed to validate this technique. The first one demonstrates how the Δz_0^{iso} selection gives results comparable to those of previous strategies employed by the ATLAS Collaboration in a related measurement at $\sqrt{s} = 7$ TeV [65], and the second one shows how simulation of pileup and modeling of underlying event activity are verified. Except for possible nonstandard couplings, the exclusive production of W^+W^- and that of $\ell^+\ell^-$ are similar. Exclusive dilepton candidates are therefore used in both studies because elastic $\gamma\gamma \to \ell^+\ell^-$ production can be separated from SD and DD production using dilepton transverse momentum $p_T^{\ell\ell}$ and acoplanarity $(1 - |\Delta\phi_{\ell\ell}|/\pi)$ of the dilepton system, where $\Delta\phi_{\ell\ell}$ is the dilepton azimuthal separation. The $\gamma\gamma \to \mu^+\mu^-$ candidates are used for these studies, while $\gamma\gamma \to e^+e^-$ candidates are used for cross-checks.

First, a measurement is made of the correction factor, f_{EL}, defined as the ratio of observed elastic $\gamma\gamma \to \mu^+\mu^-$ candidates to the HERWIG++ prediction based on the EPA formalism. This factor is expected to be lower than 1.0 due to the finite size effects of the proton [66]. Alternative formulations give similar results [67]. Candidates are required to have two muons with $p_T^\mu > 20$ GeV, invariant mass $45 < m_{\mu\mu} < 75$ GeV or $m_{\mu\mu} > 105$ GeV and pass the exclusivity selection $(\Delta z_0^{\text{iso}} = 1$ mm). The Drell-Yan $Z/\gamma^* \to \mu^+\mu^-$ process is the dominant background, while contributions from other backgrounds are negligible. The elastic $\gamma\gamma \to \mu^+\mu^-$ signal is enhanced by selecting the low-$p_T^{\ell\ell}$ region with an upper limit on $p_T^{\ell\ell}$ varied between 3 GeV and 5 GeV to study systematic uncertainties.

The value of f_{EL} is extracted from template fits in acoplanarity. Some of the contributing processes have similar acoplanarity shapes; in particular, the Drell-Yan and DD backgrounds are not distinguishable. Two fitting strategies are pursued. The first template strategy attempts to distinguish three shapes: elastic, SD, and combined DD plus background. The relative weighting of DD and background is varied to estimate the associated systematic uncertainty. The second template strategy uses the elastic and combined SD and DD shapes, with the background yield constrained to the simulation's prediction. These two fitting strategies give consistent results and are stable at the level of 10% under the variation of $p_T^{\mu\mu}$ and Δz_0^{iso} selections, the four different Drell-Yan generators, bin width, and fit range. These variations reflect mismodeling of $p_T^{\mu\mu}$ and systematic uncertainties related to shape correlations and
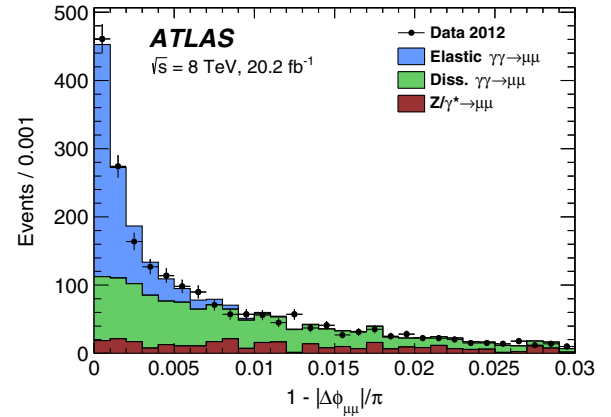

FIG. 4.   Dimuon acoplanarity distributions after applying the exclusivity selection and requiring $p_T^{\mu\mu} < 3$ GeV. The expected Drell-Yan shape and the elastic and combined SD and DD (dissociative) shapes normalized from the fit are stacked. This fit determines the factor f_{EL}.

signal strength. The effect of these variations is much larger than the 3% combined effect of the systematic uncertainties discussed in Ref. [65], which can then be ignored. The best-fit value is $f_{\text{EL}} = 0.76 \pm 0.04(\text{stat}) \pm 0.07(\text{sys})$, where the systematic uncertainty covers the spread of fit values, and Fig. 4 shows the acoplanarity distribution compared to SM expectation normalized by the factors determined in this fit. An additional uncertainty of 10% related to pileup is discussed in the following paragraph. A similar study using $\gamma\gamma \to e^+e^-$ candidates yields a consistent correction factor but with lower precision; thus, the final value for f_{EL} is taken from the $\gamma\gamma \to \mu^+\mu^-$ sample. This correction factor is used to correct the number of $\gamma\gamma \to \tau^+\tau^-$ candidates predicted by simulation in both the exclusive W^+W^- and the exclusive Higgs boson signal regions. Similar suppression is expected [66] and observed [65] in dissociative events, so the f_{EL} factor is applied to dissociative events as well.

In the second study, the impact of pileup on the signal efficiency and accuracy of the modeling in the simulation is evaluated. A kinematic selection is defined to enhance the fraction of elastic events. Events with $p_T^{\mu\mu} < 3$ GeV and acoplanarity < 0.0015 are studied with both the nominal exclusivity selection criteria and by demanding exactly one extra track within $\Delta z_0^{\text{iso}} = 3$ mm. In the case of exclusive signal, when there is one extra track, the extra track is from pileup and its $\Delta z_0 = |z_0^{\text{track}} - z_0^{\text{av}}|$ has a locally constant distribution, while for any inclusive background, the track originates from the same vertex and the Δz_0 distribution peaks at zero, as can be seen in Fig. 5. A normalization factor, the background-subtracted ratio of observed exclusive events to the predicted sum of elastic, SD, and DD, is determined for both selections. For nominal (zero track) exclusivity this normalization factor is $0.73 \pm 0.03(\text{stat}) \pm 0.01(\text{sys})$. The one-track selection, illustrated in Fig. 5, gives a factor of $0.70 \pm 0.06(\text{stat}) \pm 0.03(\text{sys})$ where the systematic uncertainties result from the uncertainty in the
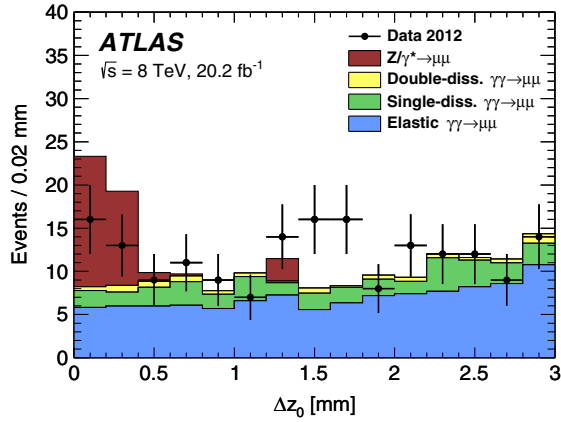
FIG. 5.   Absolute Δz_0 of the extra track to the lepton vertex in the region defined by acoplanarity < 0.0015. The exclusivity requirement was changed to select exactly one extra track within 3 mm. The exclusive predictions are scaled by a factor of 0.70.

background normalization factor. The zero-track and one-track normalization factors are consistent at the level of 10%, which is taken to be a measure of the accuracy of the pileup simulation in predicting signal efficiency.

The value of f_{EL} with the additional $\pm 10\%$ relative systematic uncertainty for signal efficiency added in quadrature with the previous systematic uncertainty

$$f_{EL} = 0.76 \pm 0.04 \text{(stat)} \pm 0.10 \text{(sys)} \tag{6}$$

is consistent with the value of $0.791 \pm 0.041 \text{(stat)} \pm 0.026 \text{(sys)} \pm 0.013 \text{(theory)}$ obtained in an earlier analysis using data from pp collisions at $\sqrt{s} = 7$ TeV [65]. This value is also consistent with the theoretical estimate of $f_{EL} \sim 0.73$–0.75, related to the proton size effects in the probed region of dimuon mass [66].

VIII. SIGNAL AND BACKGROUND CONTROL REGIONS

Several control regions are established to use data events to cross-check simulations in areas where they are known to be less reliable. The ratio of elastic to dissociative contributions is extracted from one control region, since a simulation for $\gamma\gamma \to W^+W^-$ dissociative events is not available. Another set of control regions is used to study the proximity of small numbers of extra tracks to the lepton vertex. This is another regime where the underlying-event models have not been thoroughly tested, so relying on the data is preferred. Finally a control region is established for inclusive W^+W^- production, a predominant background. This control region has a different exclusivity requirement, one to four extra tracks, in order to increase the fraction of inclusive W^+W^- events. The inclusive W^+W^- contribution to the exclusive W^+W^- signal region is estimated using a data-driven method. Based on the number of events observed in this control region, this method makes some

assumptions about the rejection of background when going from the control (one to four tracks) to the nominal (zero tracks) exclusivity requirement, and derives an estimate for the background from inclusive W^+W^-, Drell-Yan, $W + $ jets, and top-quark production. The latter three processes collectively have a smaller contribution and are referred to as other background. Other contributions to the background are derived from Monte Carlo simulation and are found to be negligible.

A. Single-dissociative and double-dissociative contributions

Without detecting the outgoing protons, the elastic $\gamma\gamma \to W^+W^-$ events are indistinguishable from SD and DD candidates. However, simulations are only available for the elastic $\gamma\gamma \to W^+W^-$ process; predictions for dissociative production of W^+W^- are not available. Following the strategy in Ref. [68], a normalization factor f_γ is determined. This factor is used to correct the prediction for elastic $\gamma\gamma \to W^+W^-$ to account for dissociative events. It is computed from data using $\gamma\gamma \to \mu^+\mu^-$ candidates that satisfy the exclusivity selection with $\Delta z_0^{iso} = 1$ mm, $p_T^\mu > 20$ GeV and $m_{\mu\mu} > 160$ GeV ($\sim 2m_W$). The factor f_γ is defined as the ratio of observed dimuons in data to the HERWIG++ prediction for elastic dimuon production:

$$f_\gamma = \left. \frac{N_{\text{Data}} - N_{\text{Background}}^{\text{POWHEG}}}{N_{\text{Elastic}}^{\text{HERWIG++}}} \right|_{m_{\mu\mu} > 160 \text{ GeV}}$$
$$= 3.30 \pm 0.22 \text{(stat)} \pm 0.06 \text{(sys)}, \tag{7}$$

where N_{Data} is the number of candidates in the data, $N_{\text{Background}}^{\text{POWHEG}}$ is the expected number of background events, and $N_{\text{Elastic}}^{\text{HERWIG++}}$ is the expected number of elastic $\gamma\gamma \to \mu^+\mu^-$ candidates directly from HERWIG++, i.e, the unscaled EPA prediction. Drell-Yan processes are the main sources of background, whereas inclusive and exclusive W^+W^- processes contribute less than 10%. The uncertainty is predominantly statistical but also contains a systematic component estimated by varying the POWHEG+PYTHIA8 Drell-Yan correction factor by $\pm 20\%$, as is discussed in Sec. VIII B. Predictions for this ratio are becoming available [69].

The dilepton invariant mass distributions for the $\mu^+\mu^-$ and e^+e^- final states are shown in Fig. 6. The elastic contribution is scaled by $f_{EL} = 0.76$, and the SD contribution is normalized so that the sum of the elastic and SD contributions corresponds to $f_\gamma \times N_{\text{Elastic}}^{\text{HERWIG++}}$. The shapes of the SD and DD samples are quite similar, so the SD shape is used to describe both the SD and DD processes. The data are well described by the simulation over the full mass range. While the range of $m_{\ell\ell} > 160$ GeV was chosen to correspond to the threshold $m_{WW} > 2m_W$, the value of f_γ is in fact rather insensitive to the choice of this threshold. The W^+W^- sample tends to have higher m_{WW}
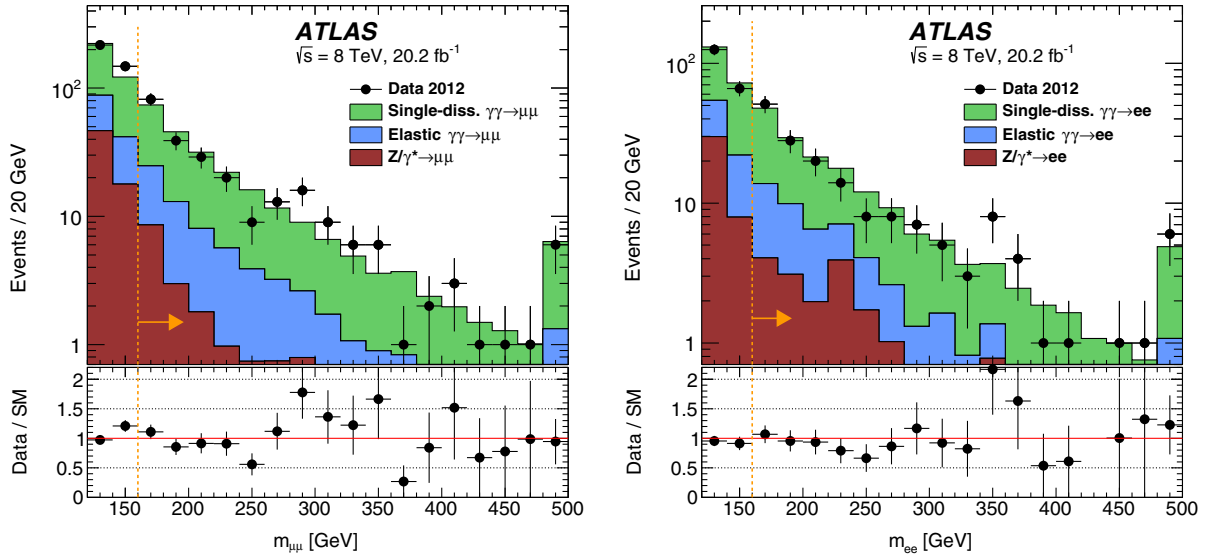
FIG. 6.   The dilepton invariant mass distribution for muon candidates (left) and electron candidates (right). The elastic yield is scaled by $f_{EL} = 0.76$, and the SD distribution is scaled to bring the sum of the elastic and SD contributions to the HERWIG++ prediction for the elastic process multiplied by the f_γ factor in the mass region above 160 GeV. The last bin includes overflow.

than these dilepton control samples $m_{\ell\ell}$. The m_{ee} distribution in Fig. 6 shows that f_γ is also valid for the electron channel. Therefore, the total expected $\gamma\gamma \to W^+W^-$ event yield in both the exclusive W^+W^- and the exclusive Higgs boson channels is taken to be the product of f_γ times the HERWIG++ prediction for elastic $\gamma\gamma \to W^+W^-$ production.

The dimuon signal sample with mass above 160 GeV is also used to determine the signal efficiency for exclusivity, which is 0.58 ± 0.06, where the 10% uncertainty arises from pileup modeling as described in Sec. VII. Other signal samples give compatible results.

B. Track multiplicity modeling

In pp collisions, inclusive Drell-Yan, W^+W^-, $t\bar{t}$, and many other events are initiated by quarks or gluons. Through hard radiation and the accompanying underlying event, such events are produced with several additional charged particles. The exclusivity selection is designed to reject such inclusive candidates that have additional tracks near the dilepton vertex. To estimate inclusive backgrounds from Drell-Yan production of $\tau^+\tau^-$ and inclusive W^+W^- production, the track multiplicity modeling of low-multiplicity candidates is studied with a high-purity Z boson sample and scaled with appropriate correction factors.

Drell-Yan candidates are selected by requiring exactly two muons with $p_T^\mu > 20$ GeV and $|\eta| < 2.4$, and satisfying $m_{\mu\mu} > 45$ GeV. The Z-resonance region, $80 < m_{\mu\mu} < 100$ GeV, is used to measure the efficiency of the exclusivity selection in both the data and simulation. The contributions from non-Z processes are subtracted before and after the exclusivity selection for both the data and simulated samples. This non-Z contribution is

estimated from the sideband regions $70 < m_{\mu\mu} < 80$ GeV and $100 < m_{\mu\mu} < 110$ GeV. The efficiency of the exclusivity selection for inclusive Z events in data is found to be 0.004. This was compared to efficiencies for simulated Drell-Yan samples from four generators: ALPGEN+PYTHIA6, ALPGEN+HERWIG, POWHEG+PYTHIA8, and SHERPA. In general, the exclusivity criterion rejects more $Z/\gamma \to \mu^+\mu^-$ candidates in the data than in the simulation. The study was repeated for events with one to four additional tracks.

Correction factors are defined as the ratio of the exclusivity selection efficiency in data to the one in the simulation. They are reported in Table IV and denoted by $f_{nTracks}^{sim}$, where sim is P for POWHEG+PYTHIA8, AH for ALPGEN+HERWIG, and AP for ALPGEN+PYTHIA6, and nTracks is the number of additional tracks. These correction factors are used to scale the Monte Carlo prediction for the inclusive processes considered in the paper. The background event tuning for simulation of low multiplicity in 8 TeV data is seen to vary widely.

TABLE IV.   Ratio of exclusivity efficiencies for $Z \to \mu\mu$ production in data and simulation for different generators after sideband subtraction of nonresonant contributions. The efficiency ratios $f_{nTracks}^{sim}$ are shown for exclusive selection ($n = 0$) as well as for a relaxed selection with one to four additional tracks ($n = 1$–4).

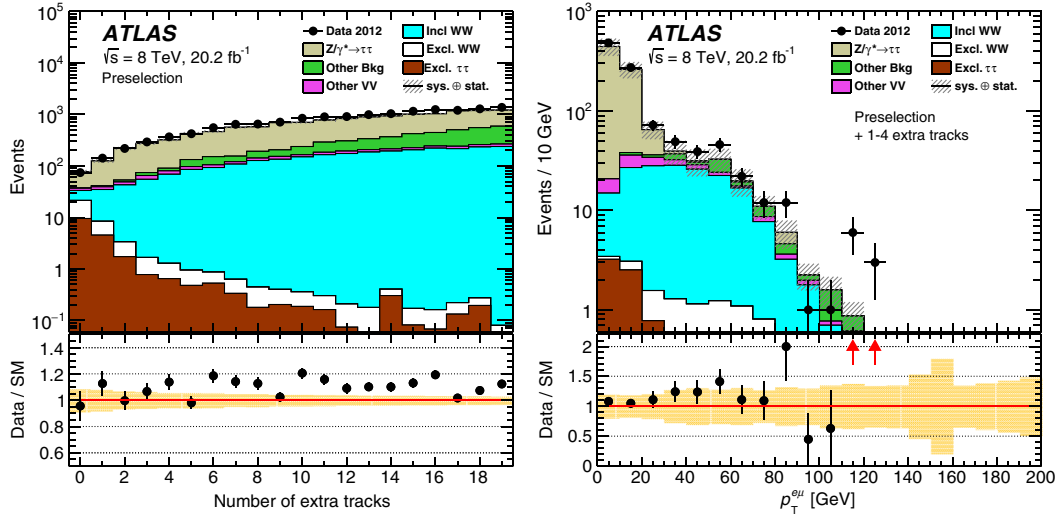| Number of extra tracks	POWHEG +PYTHIA8 f_n^P	ALPGEN +HERWIG f_n^{AH}	ALPGEN +PYTHIA6 f_n^{AP}
$n = 0$	0.58	0.21	0.69
$n = 1$–4	0.88	0.39	0.85

FIG. 7. Distribution of track multiplicities after requiring the exclusive W^+W^- preselection (left) with no number of track-dependent correction, and the $p_T^{e\mu}$ distribution of candidates that have 1–4 extra tracks (right), with the simulation including all appropriate correction factors such as $f_{\text{nTracks}}^{\text{sim}}$ (Table IV) for Drell-Yan and inclusive W^+W^- production. The enriched inclusive W^+W^- control region is the 1–4 extra-track region above $p_T^{e\mu} > 30$ GeV. The band around the Data/SM ratio of one illustrates the systemic uncertainties. The upward red arrows indicate ratios outside the plotting range.

The uncertainties in these correction factors are estimated from the variation of the exclusive efficiency as a function of $m_{\mu\mu}$ of the various generators. To check the consistency of the predictions of evolution of underlying event multiplicity as a function of mass, ratios of the predictions of the three generators to the one by SHERPA are listed in Table V. These are normalized such that the average over the full mass range is 1. The variations are typically within 20%, which is taken as the systematic uncertainty in extrapolating the $f_{\text{nTracks}}^{\text{sim}}$ correction factors.

To validate the correction factors $f_{\text{nTracks}}^{\text{sim}}$, an $e^\pm\mu^\mp$ sample was defined. Figure 7 (left) shows the distribution of the number of additional tracks after applying the W^+W^- preselection as defined in Table III. Applying a relaxed exclusivity selection to select $e^\pm\mu^\mp$ candidates with one to four extra tracks yields a sample that has low enough statistical uncertainties and is dominated by Drell-Yan events for $p_T^{e\mu} < 30$ GeV as illustrated in Fig. 7 (right). Selecting $m_{e\mu} < 90$ GeV further rejects non-Drell-Yan contamination as shown in Fig. 8. The correction factor for ALPGEN+PYTHIA6 Drell-Yan, computed in the region defined by $p_T^{e\mu} < 30$ GeV and $m_{e\mu} < 90$ GeV, is found to be 0.90 ± 0.11, in good agreement with $f_{1-4}^{\text{AP}} = 0.85$ found above for $Z \to \mu^+\mu^-$.

C. Inclusive W^+W^- normalization

Inclusive W^+W^- production is a significant background in both the exclusive Higgs boson and exclusive W^+W^- channels. From previous measurements [59,70], it known that the NLO prediction for the $q\bar{q} \to W^+W^-$ process as provided by POWHEG+PYTHIA8 underestimates the observed W^+W^- event yield. It is therefore necessary to understand

the simulation of this background before requiring the exclusivity selection. A region close in phase space to the exclusive Higgs boson signal region is chosen, referred to here as the Higgs-specific inclusive W^+W^- control region. It has the same definition except for the following: $55 < m_{e\mu} < 110$ GeV, $\Delta\phi_{e\mu} < 2.6$ to reduce Drell-Yan
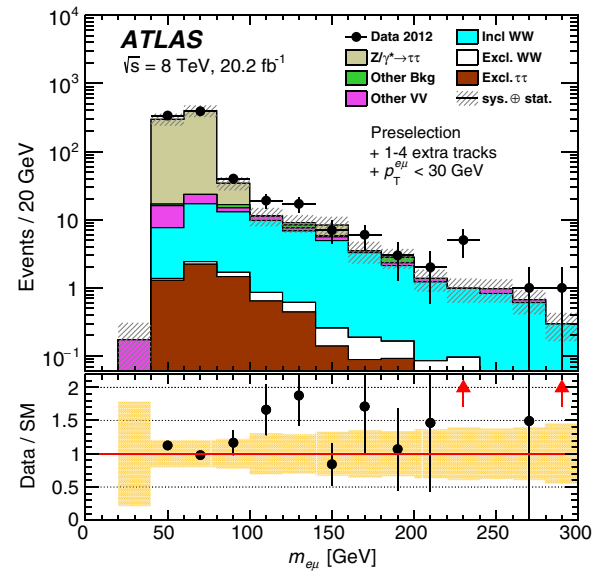
FIG. 8. The $m_{e\mu}$ distribution after requiring 1–4 extra tracks within $\Delta z_0^{\text{iso}} = 1.0$ mm and $p_T^{e\mu} < 30$ GeV. The Drell-Yan and inclusive W^+W^- samples are scaled by the factors f_{1-4}^{AP} and f_{1-4}^{P}, respectively. The other samples are normalized as mentioned in the text. In the Data/SM ratio plot, the color band illustrates the systematic uncertainties, and the red upward arrows indicate ratios outside the plotting range.

TABLE V.   Ratio of the exclusivity selection efficiency in Drell-Yan $\mu^+\mu^-$ production as a function of dimuon mass of different generators to SHERPA. A common normalization factor is applied to each column to obtain an average ratio of 1. Only statistical uncertainties are shown. The statistical uncertainty from SHERPA is included and contributes 2.9%, 0.8%, 0.7% and 5.7% in the four mass regions.

Mass [GeV]	ALPGEN +HERWIG	ALPGEN +PYTHIA6	POWHEG +PYTHIA8
44–60	0.81 ± 0.02	0.84 ± 0.03	0.99 ± 0.09
60–90	1.04 ± 0.02	0.98 ± 0.03	1.01 ± 0.02
90–116	1.00 ± 0.01	1.02 ± 0.02	1.00 ± 0.02
116–200	0.89 ± 0.10	1.04 ± 0.19	0.76 ± 0.10

background, no jets to reduce $t\bar{t}$ background, and no requirement on exclusivity. This region is dominated by inclusive W^+W^- production and has a purity of 60%. After subtracting the predicted backgrounds from data, $(20 \pm 5)\%$ more data is observed than is predicted by POWHEG +PYTHIA8. A normalization factor of $1.20 \pm 0.05\text{(stat)}$ is therefore taken as a correction to the cross section and applied to the inclusive W^+W^- prediction in all regions of phase space studied here, as done in Ref. [59]. The transverse mass m_T distributions in the Higgs-specific inclusive W^+W^- control region after applying the normalization factor to the POWHEG+PYTHIA8 prediction is shown in Fig. 9.

D. Sum of inclusive W^+W^- and other background

An estimate of the sum of inclusive W^+W^- background and smaller contributions from Drell-Yan, $W +$ jets, and

top-quark production (collectively referred to as other background) is performed using an inclusive W^+W^--enriched control region defined with the same criteria as the exclusive W^+W^- signal region, except the exclusivity selection requires 1–4 extra tracks within $\Delta z_0^{\text{iso}} = 1$ mm. This control region is shown in Fig. 7 (right) in the region above $p_T^{e\mu} > 30$ GeV. It is dominated by the inclusive W^+W^- process and also has small contributions of exclusive events, non-W^+W^- (other-VV) dibosons, and other background.

Figure 10 shows the leading lepton $p_T^{\ell 1}$ distribution in this control region. The prediction is systematically lower than the data. The processes contributing to this control region can be found in Table VI, and the total SM expectation is compared to the data. The data exceed the simulation by 2σ. This discrepancy is attributed to a component from jets faking leptons that is unreliably simulated. Events produced with jets such as $W +$ jets, $Z +$ jets, and top-quark production, particularly jets faking leptons, are more easily rejected by the exclusivity selection, while other-VV and Drell-Yan (without accompanying jets) processes are likely to extrapolate from the 1–4 extra-track control region to the zero-track region with a scale factor similar to that for inclusive W^+W^- background. Therefore, this control region is used to constrain the inclusive W^+W^- plus other background involving fake leptons.

For the purpose of estimating the contribution of inclusive W^+W^- events and other background in the zero-track region, the number of these events in the 1–4 extra-track control region is bracketed by the number of observed events in the data, after subtracting the exclusive and other-VV contributions, as an upper bound and by the predicted number of inclusive W^+W^- obtained from POWHEG+PYTHIA8 as a lower bound. To obtain the contribution for the exclusive W^+W^- signal region, the two
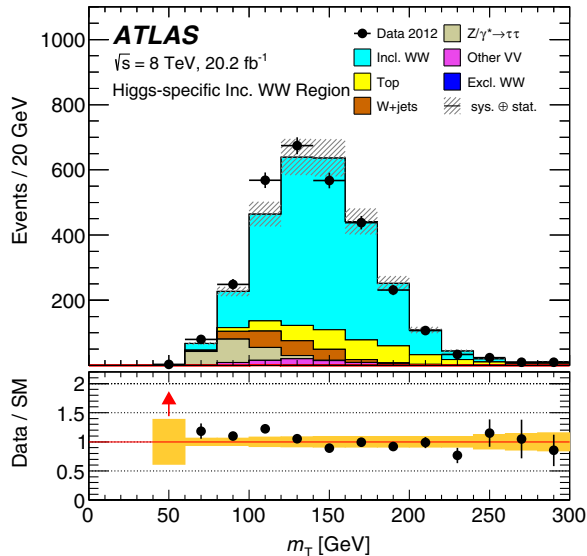

FIG. 9.   The m_T distributions in the Higgs-specific inclusive W^+W^- control region that is used to determine the scaling for the POWHEG+PYTHIA8 inclusive W^+W^- prediction. In the Data/SM ratio plot, the color band illustrates systematic uncertainties, and the red upward arrow indicates a ratio outside the plotting range.
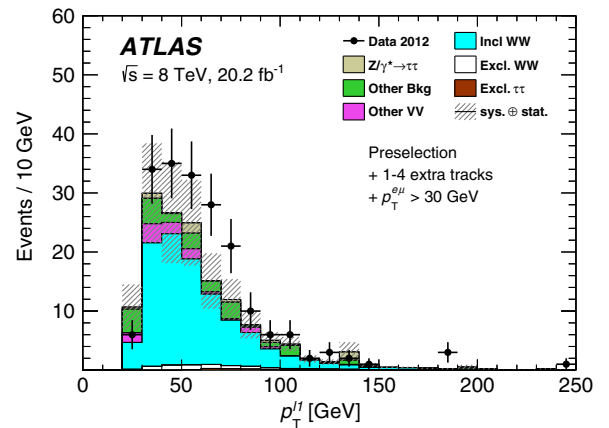

FIG. 10.   The leading-lepton $p_T^{\ell 1}$ distribution in the inclusive W^+W^- control region. The simulation includes all appropriate correction factors such as f_{1-4}^{sim} for Drell-Yan and f_{1-4}^{P} for inclusive W^+W^- production.

TABLE VI.   Event yields in the inclusive W^+W^- control region. The uncertainties quoted are statistical and systematic.

Processes	Inclusive W^+W^-
Inclusive W^+W^-	102 ± 20
Exclusive W^+W^-	5.5 ± 0.4
Exclusive $\tau^+\tau^-$	1.2 ± 0.2
Other diboson	10.9 ± 2.2
Other background	27.4 ± 6.2
Total SM	147 ± 21
Data	191

TABLE VII.   Sources of uncertainty for the measured exclusive W^+W^- cross section. "All other" includes other efficiencies, acceptance, luminosity, and lepton scales and resolution.

Source of uncertainty	Uncertainty [%]
Statistics	33%
Background determination	18%
Exclusivity signal efficiency	10%
All other	< 5%
Total	39%

estimates are extrapolated from the 1–4 extra-track control region to the zero-track signal region. In this framework, the lower bound corresponds to the optimistic case where the other background contribution is completely rejected by the zero-track exclusivity requirement, while the upper bound corresponds to the case where all observed candidates in the control region are suppressed by the same factor as the inclusive W^+W^- process. Finally, the average of the two estimates (after extrapolation) is taken as the contribution for the signal region.

The extrapolation is achieved by multiplying the estimates by the ratio of the predicted numbers of inclusive W^+W^- events:

$$N_0^{\text{Estimated}} = N_{1-4}^{\text{Estimated}} \times \frac{N_{WW,0}^{\text{Predicted}}}{N_{WW,1-4}^{\text{Predicted}}}, \tag{8}$$

where $N_0^{\text{Estimated}}$ and $N_{1-4}^{\text{Estimated}}$ are the estimates for the lower bound or upper bound mentioned above, and $N_{WW,0}^{\text{Predicted}}$ and $N_{WW,1-4}^{\text{Predicted}}$ are, respectively, the number of inclusive W^+W^- events predicted by POWHEG+PYTHIA8 for the zero-track and 1–4 extra-track regions. This ratio is found to be 0.048 ± 0.014, where the uncertainty is dominated by the 20% systematic uncertainties taken to be uncorrelated between the f_0^{P} and f_{1-4}^{P} factors that are included in the predicted numbers of events. As mentioned above, the small exclusive and other-VV contributions are subtracted before the extrapolation. So for inclusive W^+W^- and Drell-Yan processes, the expected number of events in the zero-track region is 20 times less than the prediction for the 1–4 extra-track control region.

As mentioned above, the inclusive W^+W^- and other background contributions to the signal region are taken as the average of the two estimates. Half the difference is included as an additional contribution to the uncertainty in this determination. This results in a final estimate of 6.6 ± 2.5 background candidates for the exclusive W^+W^- signal region.

This background estimate, 6.6 ± 2.5 events in the exclusive W^+W^- signal region, corresponds to scaling the POWHEG+PYTHIA8 W^+W^- prediction by a normalization factor of 0.79. This factor is used to estimate the inclusive W^+W^- and other background contamination in the Higgs boson and aQGC signal regions.

IX. SYSTEMATIC UNCERTAINTIES

The main sources of systematic uncertainty are related to the exclusivity selection and the background determination. The uncertainty in the efficiency of the exclusive signal selection contributes 10% to the exclusive W^+W^- and Higgs boson signal yields, as estimated in Sec. VII from the ratios of dimuon event yields without extra tracks and those with exactly one extra track. The prediction of the exclusive W^+W^- process uses the f_γ factor as described in Sec. VIII A and thus carries the 7% uncertainty in f_γ. The $\gamma\gamma \to \tau^+\tau^-$ background has an uncertainty of 14% that is propagated from the f_{EL} factor. As described in Sec. VII, the f_{EL} uncertainty includes 10% related to the exclusive signal selection and another 10% that results from acoplanarity fits. There is a 38% uncertainty in the inclusive W^+W^- background, as discussed in Sec. VIII D. This 38% uncertainty contains a component from the $\pm 20\%$ uncertainty in Drell-Yan background described in Sec. VIII B.

The contributions from these systematic uncertainties to the measured exclusive W^+W^- cross section can be found
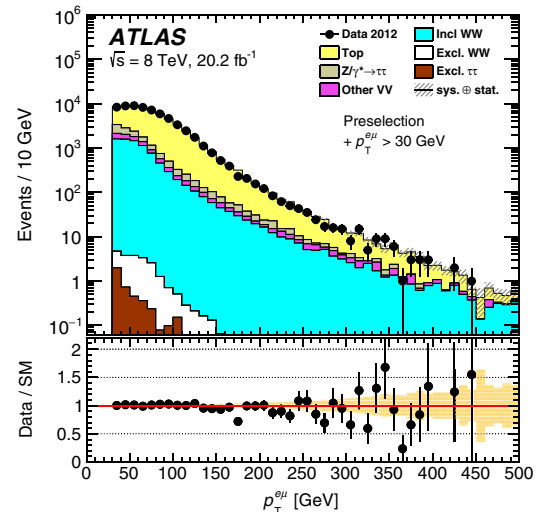

FIG. 11.   The $p_{\text{T}}^{e\mu}$ distribution before exclusivity, i.e., after requiring $p_{\text{T}}^{e\mu} > 30$ GeV. The main backgrounds at this stage are top-quark production, inclusive W^+W^- and Drell-Yan. In the Data/SM ratio plot, the color band illustrates systematic uncertainties.

TABLE VIII. The event yield at different stages of the selection. The expected signal ($\gamma\gamma \to W^+W^-$) is compared to the data and total background. The SM-to-data ratio (SM/Data) gives the level of agreement between prediction and data. The product of efficiency and acceptance (ϵA) for the signal is computed from the $\gamma\gamma \to W^+W^- \to e^\pm\mu^\mp$ MC generator. The statistical and systematic uncertainties are added in quadrature. For the background, the uncertainties are only shown for the yields after exclusivity selection, where they are relevant for the measurement.

	Expected signal	Data	Total bkg.	Incl. W^+W^-	Excl. $\tau\tau$	Other-VV	Other bkg.	SM/Data	ϵA (signal)
Preselection	22.6 ± 1.9	99424	97877	11443	21.4	1385	85029	0.98	0.254
$p_T^{\ell\ell} > 30$ GeV	17.6 ± 1.5	63329	63023	8072	4.30	896.3	54051	1.00	0.198
$\Delta z_0^{\rm iso}$ requirement	9.3 ± 1.2	23	8.3 ± 2.6	6.6 ± 2.5	1.4 ± 0.3	0.3 ± 0.2	$\cdots$	0.77	0.105 ± 0.012
aQGC signal region									
$p_T^{\ell\ell} > 120$ GeV	0.37 ± 0.04	1	0.37 ± 0.13	0.32 ± 0.12	0.05 ± 0.03	0	$\cdots$	0.74	0.0042 ± 0.0005

in Table VII. The overall background contribution is 18%, predominantly from uncertainty in the extrapolation from the 1–4 track control region. In addition to the systematic uncertainty from the exclusivity selection (10%), other systematic uncertainties (lepton selection efficiencies and acceptance, luminosity and lepton scales and resolution) contribute less than 5%. The statistical uncertainty dominates the uncertainties in the cross section.

X. RESULTS

This paper presents three main results: the exclusive W^+W^- production cross section, limits on possible aQGCs, and a limit from a search for exclusive Higgs boson production. Each is summarized in the following. The exclusive W^+W^- signal is the sum of elastic and single- and double-dissociative events through the f_γ factor discussed in Sec. VIII A.

A. Standard Model exclusive W^+W^- production

Before the exclusivity selection, good agreement between data and background prediction is observed. In the $e\mu$ final state, the overall event yield agrees to within 2%, and after requiring $p_T^{e\mu} > 30$ GeV, it agrees to within

0.5%. The $p_T^{e\mu}$ distribution before the exclusivity requirement is shown in Fig. 11.

The numbers of candidates at various stages of the analysis are listed in Table VIII, and the uncertainties quoted include both the statistical and systematic uncertainties. Top-quark and Drell-Yan $Z/\gamma^* \to \tau^+\tau^-$ processes are the dominant backgrounds before exclusivity, while after requiring exclusivity their contributions are less than 0.5 events. These two backgrounds, along with $W +$ jets, are grouped together as other background (Table VIII). The inclusive W^+W^- estimate (described in Sec. VIII D) already includes these three processes; thus, the other background contribution after requiring exclusivity is not added to the total background. Non-W^+W^- (other-VV) diboson processes are also highly suppressed by the exclusivity selection: They contribute 0.3 ± 0.2 events. Diffractive W^+W^- production was considered as a background and found to be insignificant. The expected signal yield is 9.3 ± 1.2 events, including the dissociative contributions (f_γ factor) discussed in Sec. VIII A. The total predicted background is 8.3 ± 2.6, while 23 candidates are observed in the data.

Figure 12 shows the $p_T^{e\mu}$ and $\Delta\phi_{e\mu}$ distributions after applying all selection criteria. The shapes of the signal and the inclusive W^+W^- distributions are similar. The
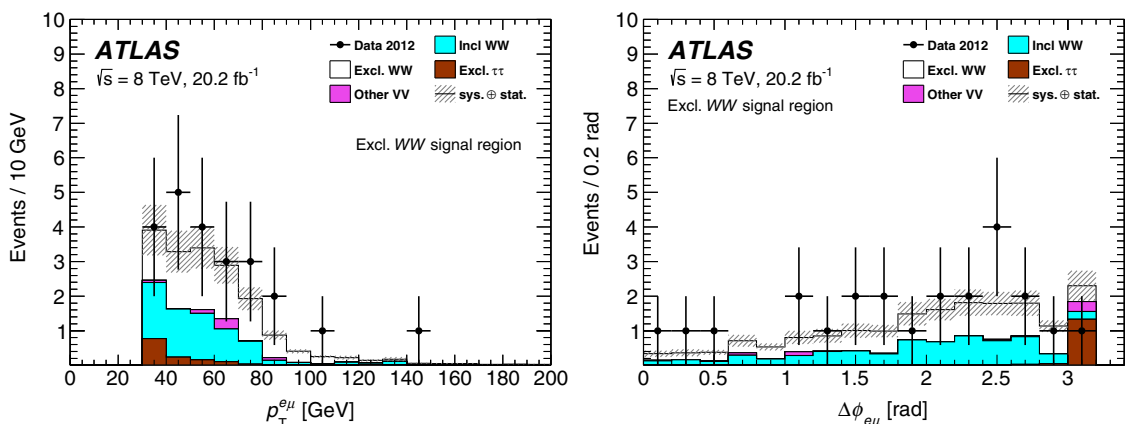

FIG. 12. The $p_T^{e\mu}$ (left) and $\Delta\phi_{e\mu}$ (right) distributions in the exclusive W^+W^- signal region. The inclusive W^+W^- estimate includes small contributions from other backgrounds (Drell-Yan, $W +$ jets, and top-quark production).
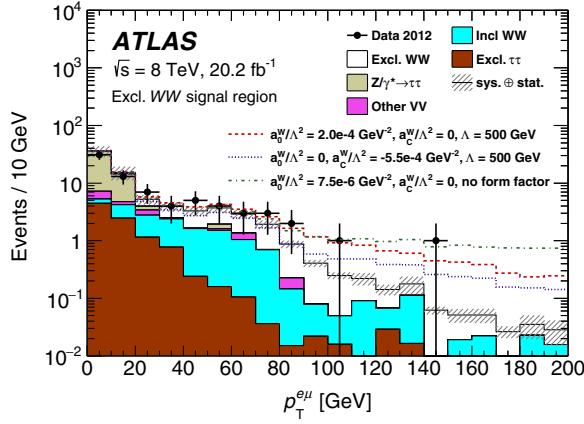
FIG. 13. The $p_T^{e\mu}$ distribution for data compared to the SM prediction for events satisfying all the exclusive W^+W^- selection requirements apart from the one on $p_T^{e\mu}$ itself. Also shown are various predictions for aQGC parameters $a_{0,C}^W$.
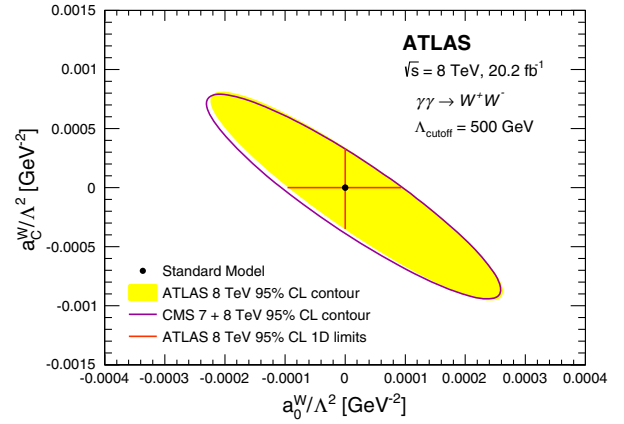

FIG. 14. The observed log-likelihood 95% confidence-level contour and 1D limits for the case with a dipole form factor with $\Lambda_{\text{cutoff}} = 500$ GeV. The CMS combined 7 and 8 TeV result [14] is shown for comparison.

remaining $\tau^+\tau^-$ background has an azimuthal opening angle close to $\Delta\phi_{e\mu} \sim \pi$; i.e., the leptons are back-to-back. No further requirement is applied to $\Delta\phi_{e\mu}$ to reject this background, as the aQGC signal also has an enhancement for $\Delta\phi_{e\mu} \sim \pi$.

1. $\gamma\gamma \to W^+W^-$ cross section

The full phase-space cross section predicted by HERWIG++ is $\sigma_{\gamma\gamma\to W^+W^-}^{\text{HERWIG}++} = 41.6$ fb. This number is well defined, but $\sim 20\%$ corrections similar to those for the EPA dilepton prediction are expected, as discussed with Eq. (6) above. The branching ratio of the W^+W^- pair decaying to $e^\pm\mu^\mp X$ is $\text{BR}(W^+W^- \to e^\pm\mu^\mp X) = 3.23\%$ [71] (including the leptonic decays of τ leptons). Therefore, the predicted cross section corrected for $\text{BR}(W^+W^- \to e^\pm\mu^\mp X)$ and including the dissociative contributions through the normalization $f_\gamma = 3.30 \pm 0.23$ becomes

$$\sigma_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\mp X}^{\text{Predicted}} = f_\gamma \cdot \sigma_{\gamma\gamma\to W^+W^-}^{\text{HERWIG}++} \cdot \text{BR}(W^+W^- \to e^\pm\mu^\mp X)$$
$$= 4.4 \pm 0.3 \text{ fb}, \qquad (9)$$

which corresponds to the prediction of $N_{\text{Predicted}} = 9.3 \pm 1.2$ signal events, quoted in Table VIII. The number of candidates observed in the data is $N_{\text{Data}} = 23$, while the predicted background is $N_{\text{Background}} = 8.3 \pm 2.6$ events. So the observation exceeds the prediction by a ratio:

$$R = (N_{\text{Data}} - N_{\text{Background}})/N_{\text{Predicted}} = 1.57 \pm 0.62. \qquad (10)$$

The uncertainty in R results from propagation of the uncertainties of each of the numbers that go into the calculation. The uncertainty in the factor f_γ contributes 7%.

The measured cross section is determined in the exclusive W^+W^- region and extrapolated to the full $W^+W^- \to e^\pm\mu^\mp + X$ phase space:

TABLE IX. The observed allowed ranges for a_0^W/Λ^2 and a_C^W/Λ^2, for a dipole form factor with $\Lambda_{\text{cutoff}} = 500$ GeV and without a form factor ($\Lambda_{\text{cutoff}} \to \infty$). The regions outside the quoted ranges are excluded at 95% confidence level.

Coupling	Λ_{cutoff}	Observed allowed range [GeV^{-2}]	Expected allowed range [GeV^{-2}]
a_0^W/Λ^2	500 GeV	$[-0.96 \times 10^{-4},$ $0.93 \times 10^{-4}]$	$[-0.90 \times 10^{-4},$ $0.87 \times 10^{-4}]$
a_C^W/Λ^2	500 GeV	$[-3.5 \times 10^{-4},$ $3.3 \times 10^{-4}]$	$[-3.3 \times 10^{-4},$ $3.1 \times 10^{-4}]$
a_0^W/Λ^2	∞	$[-1.7 \times 10^{-6},$ $1.7 \times 10^{-6}]$	$[-1.5 \times 10^{-6},$ $1.6 \times 10^{-6}]$
a_C^W/Λ^2	∞	$[-6.4 \times 10^{-6},$ $6.3 \times 10^{-6}]$	$[-5.9 \times 10^{-6},$ $5.8 \times 10^{-6}]$

TABLE X. The allowed ranges for dimension-8 coupling values derived from the a_0^W and a_C^W parameters, for a dipole form factor with $\Lambda_{\text{cutoff}} = 500$ GeV and without a form factor. The regions outside the quoted ranges are excluded at 95% confidence level. The limits on $f_{M,2,3}/\Lambda^4$ can be determined using the relations $f_{M,2} = 2 \times f_{M,0}$ and $f_{M,3} = 2 \times f_{M,1}$.

Coupling	Λ_{cutoff}	Observed allowed range [GeV^{-4}]	Expected allowed range [GeV^{-4}]
$f_{M,0}/\Lambda^4$	500 GeV	$[-3.7 \times 10^{-9},$ $3.6 \times 10^{-9}]$	$[-3.5 \times 10^{-9},$ $3.4 \times 10^{-9}]$
$f_{M,1}/\Lambda^4$	500 GeV	$[-13 \times 10^{-9},$ $14 \times 10^{-9}]$	$[-12 \times 10^{-9},$ $13 \times 10^{-9}]$
$f_{M,0}/\Lambda^4$	∞	$[-6.6 \times 10^{-11},$ $6.6 \times 10^{-11}]$	$[-5.8 \times 10^{-11},$ $6.2 \times 10^{-11}]$
$f_{M,1}/\Lambda^4$	∞	$[-24 \times 10^{-11},$ $25 \times 10^{-11}]$	$[-23 \times 10^{-11},$ $23 \times 10^{-11}]$

TABLE XI. Summary of signal and background yields at different stages of the Higgs boson event selection. Only major background sources are listed explicitly. All the other background sources are summed up in the "Other" category. For the background, the uncertainties are only shown for the yields after exclusivity selection, where they are relevant for the measurement. They include the systematic and statistical components, added in quadrature.

	Excl. H signal	Data	Total bkg.	Incl. W^+W^-	Excl. W^+W^-	Other bkg.
Preselection	0.065 ± 0.005	129018	120090	12844	43	107200
$p_T^{e\mu} > 30$ GeV, $m_{e\mu} < 55$ GeV, $\Delta\phi_{e\mu} < 1.8$	0.043 ± 0.004	18568	17060	2026	5.7	15030
Δz_0^{iso} requirement	0.023 ± 0.003	8	4.7 ± 1.3	1.4 ± 0.5	3.1 ± 1.3	0.2 ± 0.1
$m_T < 140$ GeV [signal region]	0.023 ± 0.003	6	3.0 ± 0.8	1.0 ± 0.4	1.8 ± 0.8	0.2 ± 0.1

$$\sigma_{\gamma\gamma \to W^+W^- \to e^\pm\mu^\mp X}^{\text{Measured}} = (N_{\text{Data}} - N_{\text{Background}})/(\mathcal{L}\epsilon A)$$

$$= 6.9 \pm 2.2(\text{stat}) \pm 1.4(\text{sys}) \text{ fb}, \qquad (11)$$

where $\mathcal{L} = 20.2 \pm 0.4$ fb^{-1}. The acceptance (A) is the ratio of the number of simulated events passing the kinematic requirements in Table III to the total number of events generated. The efficiencies (ϵ) account for the detector efficiencies due to lepton identification and reconstruction, triggering, and pileup. Both A and ϵ are computed using the HERWIG++ prediction for the elastic $\gamma\gamma \to W^+W^-$ process. At the end of the event selection, the acceptance is $A = 0.280 \pm 0.001$ and the efficiency, which includes the exclusivity selection efficiency, is $\epsilon = 0.37 \pm 0.04$.

The efficiency of the exclusivity selection is 0.58 ± 0.06. The elastic, SD, and DD predicted acceptances can be compared using $\gamma\gamma \to \mu^+\mu^-$ events with $m_{\mu\mu} > 160$ GeV, and they are found to be the same within 3%. Therefore, the measurement of the cross section can be performed with the acceptances for elastic $\gamma\gamma \to W^+W^-$ events. The products of acceptance and efficiencies (ϵA) at different stages of the event selection are given in Table VIII.

The sources of uncertainty are given in Table VII. The statistical uncertainty dominates. The contribution from intermediate τ leptons to the accepted signal MC is determined using the HERWIG++ generator to be 9.1%.

The background-only hypothesis has a p-value of about 0.0012, corresponding to a significance of 3.0σ.

2. Limits on anomalous quartic gauge couplings

The aQGC limit setting was performed using the region $p_T^{e\mu} > 120$ GeV where the aQGC contributions are expected to be important and Standard Model backgrounds are suppressed. The $p_T^{e\mu}$ distribution is shown in Fig. 13 for data compared to the Standard Model prediction and various aQGC scenarios. The aQGCs enhance the exclusive signal at high $p_T^{e\mu}$, while the background is negligible with $p_T^{e\mu} > 80$ GeV. The 95% CL limits on the couplings a_0^W/Λ^2 and a_C^W/Λ^2 are extracted with a likelihood test using the one observed data event as a constraint.

To extract one-dimensional (1D) limits, one of the aQGCs is set to zero. The 95% CL allowed ranges for the cases with a dipole form factor defined in Eq. (2) with $\Lambda_{\text{cutoff}} = 500$ GeV and without a form factor ($\Lambda_{\text{cutoff}} \to \infty$) are listed in Table IX. The uncertainties in the yields are included in the likelihood test as nuisance parameters. Also, limits on the two aQGC parameters are shown in Fig. 14 for the case with a dipole form factor with $\Lambda_{\text{cutoff}} = 500$ GeV. The region outside the contour is ruled out at 95% confidence level. The limits are comparable to the CMS combined 7 and 8 TeV results [14].
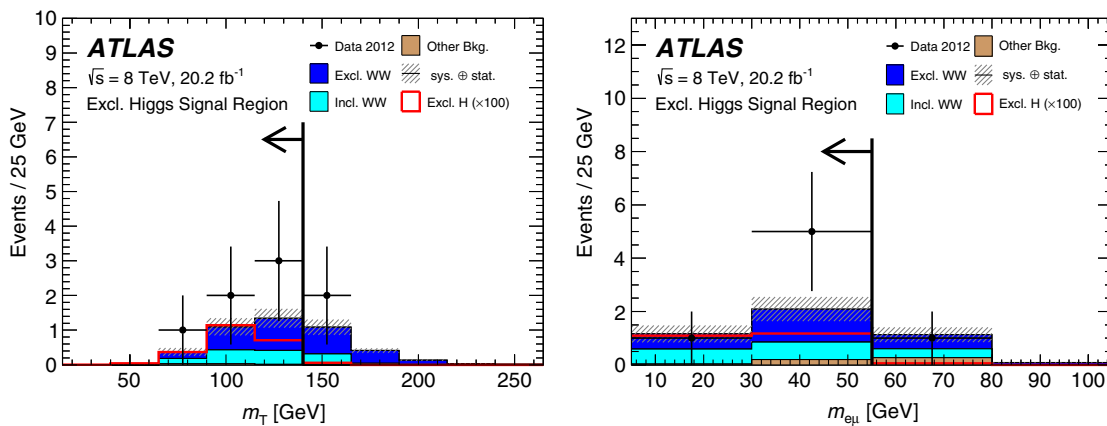

FIG. 15. Distributions in the exclusive Higgs boson signal region, without including the selection on the variable plotted. The dominant processes are inclusive and exclusive W^+W^- production. The expected signal is scaled by a factor of 100 for visibility. The arrows denote the selection.

The 95% CL limits on the dimension-8 $f_{M,0,1,2,3}/\Lambda^4$ couplings are given in Table X for the cases with and without a form factor. They are derived from the $a^W_{0,C}/\Lambda^2$ couplings using Eq. (3).

B. Limits on exclusive Higgs boson production

As described in Sec. III, exclusive production of Higgs bosons is simulated using the FPMC generator. Exclusive W^+W^- contamination in the exclusive Higgs boson signal region is estimated by using HERWIG++ samples that are scaled by $f_\gamma = 3.30$ to account for single-dissociative and double-dissociative processes. The predicted background from exclusive W^+W^- is derived from the observed cross section in the exclusive W^+W^- signal region (Sec. X A). As discussed in Secs. VIII B–VIII D, the estimate for inclusive W^+W^- and minor contributions of $Z/\gamma^* \to \tau^+\tau^-$ and $W +$ jets is obtained from the inclusive W^+W^- samples scaled by a factor of 0.79. The contribution from inclusive Higgs production is expected to be negligible. Exclusive dileptons are not scaled by f_γ because LPAIR simulates SD and DD processes as discussed in Sec. VII, except for $\gamma\gamma \to \tau^+\tau^-$ production of which only SD is simulated. The rest of the background sources are scaled by their respective correction factors to account for the mismodeling of the underlying event. Six candidates are observed in the data, while 3.0 ± 0.8 events are predicted from background and 0.023 ± 0.003 from signal. The quoted uncertainty is the sum in quadrature of systematic uncertainties. Table XI summarizes expected and observed yields in the signal region and at earlier selection points in the selection criteria summarized in Table III. The exclusive Higgs boson prediction quoted here is from elastic contribution only. Observed data reasonably agree with predictions. Figure 15 shows kinematic distributions in the signal region.

Yields summarized in the preceding paragraph are converted to upper limits on the exclusive Higgs boson total production cross section using the CL_S technique [72]. The branching ratio $BR(H \to W^+W^-)$ used to compute these limits is $(21.5 \pm 0.9)\%$ [73]. Table XII shows a summary of the 95% CL upper limits on the exclusive Higgs boson total production cross section. The observed upper limit is 1.2 pb, which is 1.1σ higher than the expected upper limit of 0.7 pb. The statistical uncertainty in the predicted background dominates the uncertainty involved in calculating this upper limit, while systematic uncertainties worsen the upper limits by at most 10%. This upper

TABLE XII. Upper limits on σ_H [pb] at 95% CL. The $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties quoted here are on the expected upper limit.

$+2\sigma$ [pb]	$+1\sigma$ [pb]	Expected [pb]	-1σ [pb]	-2σ [pb]	Observed [pb]
1.6	1.0	0.7	0.5	0.4	1.2

limit value is 400 times the cross section predicted [24]. However, the limit would not change if the model prediction, which is for elastic production only, increased by an order of magnitude. This limit calculation inherently assumes that the acceptance and efficiency for dissociative events is not significantly different than for elastic events; hence, the associated systematic uncertainty is insignificant.

XI. CONCLUSION

A measurement of the exclusive W^+W^- production cross section and a search for exclusive Higgs boson production via diffraction using $e^\pm\mu^\mp$ final states are presented using a data sample that corresponds to 20.2 fb^{-1} of LHC pp collisions at $\sqrt{s} = 8$ TeV collected with the ATLAS detector. A track-based technique for selecting exclusive candidates was developed and validated in the $\mu^+\mu^-$ final state, resulting in a ratio of data to the EPA prediction for the exclusive $\gamma\gamma \to \ell^+\ell^-$ process of $f_{EL} = 0.76 \pm 0.04(\text{stat}) \pm 0.10(\text{sys})$ in agreement with previous ATLAS measurements at $\sqrt{s} = 7$ TeV. For exclusive W^+W^- production, the cross section is determined to be $\sigma(\gamma\gamma \to W^+W^- \to e^\pm\mu^\mp X) = 6.9 \pm 2.2(\text{stat}) \pm 1.4(\text{sys})$ fb from 23 observed candidates with 8.3 ± 2.6 predicted background events. While evidence of SM exclusive W^+W^- production is at the 3.0σ level, no evidence for an excess was seen in the kinematic region that would be enhanced by anomalous quartic gauge couplings. Rather, independent limits are placed on anomalous quartic gauge couplings that are more stringent than earlier published results from the OPAL, D0, and CMS experiments. Six candidates consistent with exclusive Higgs boson production are observed in the data, with an expected SM background of 3.0 ± 0.8 events. This result corresponds to an upper limit at 95% CL on the total production cross section of the exclusive Higgs boson of 1.2 pb, whereas the expected limit is 0.7 pb.

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