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Measurement of the ZZ Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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The ZZ production cross section in proton-proton collisions at 13 TeV center-of-mass energy is measured using 3.2 fb^{-1} of data recorded with the ATLAS detector at the Large Hadron Collider. The considered Z boson candidates decay to an electron or muon pair of mass 66–116 GeV. The cross section is measured in a fiducial phase space reflecting the detector acceptance. It is also extrapolated to a total phase space for Z bosons in the same mass range and of all decay modes, giving $16.7^{+2.2}_{-2.0}(\mathrm{stat})\,^{+0.9}_{-0.7}(\mathrm{syst})\,^{+1.0}_{-0.7}(\mathrm{lumi})$ pb. The results agree with standard model predictions.

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Studying the production of pairs of Z bosons in proton-proton (pp) interactions at the Large Hadron Collider (LHC) tests the electroweak sector of the standard model (SM) at the highest available energies. In pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV, ZZ production is dominated by quark-antiquark ($q\bar{q}$) interactions, with an $\mathcal{O}(10\%)$ contribution from loop-induced gluon-gluon (gg) interactions [1,2]. The SM ZZ production can proceed via a Higgs boson propagator, although this contribution is suppressed in the region where both Z bosons are produced on-shell. As such, non-Higgs ZZ production is an important background in studies of the Higgs boson [3–5]. It is also a background in searches for new physics producing pairs of Z bosons at high invariant mass [6,7] and sensitive to triple neutral-gauge-boson couplings, which are not allowed in the SM [8].

This Letter presents the first measurement of the ZZ production cross section in pp interactions at $\sqrt{s} = 13$ TeV. Throughout it, "Z boson" refers to the superposition of a Z boson and virtual photon with mass in the range 66–116 GeV. The analyzed data correspond to an integrated luminosity of 3.2 ± 0.2 fb^{-1}, collected with the ATLAS detector [9]. The uncertainty of the integrated luminosity is derived, following a methodology similar to that detailed in Ref. [10], from a preliminary calibration of the luminosity scale using a pair of x-y beam-separation scans performed in June 2015. The ZZ production cross section was previously measured at $\sqrt{s} = 7$ and 8 TeV by the ATLAS and CMS Collaborations [11–13] and found to be consistent with SM predictions.

Candidate events are reconstructed in the fully leptonic $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ decay channel where ℓ and ℓ' can be an electron or a muon. The cross section $\sigma^{\mathrm{fid}}_{ZZ\to\ell^+\ell^-\ell'^+\ell'^-}$ is found by counting candidate events, subtracting the expected contribution from background events, correcting for detector effects, and dividing by the integrated luminosity. It is measured in a fiducial phase space that corresponds closely to the experimental acceptance. In addition, an extrapolation of the cross section to a total phase space for Z bosons, $\sigma^{\mathrm{tot}}_{ZZ}$, is performed. The presented cross-section measurements are inclusive with respect to additional jets. Small contributions from triboson production with two leptonically decaying Z bosons and a third hadronically decaying weak boson and contributions from double parton scattering are included in the measurement.

The fiducial phase space, which is designed to reflect the acceptance of the ATLAS detector (described below), is defined for simulated events by applying the following criteria to the final-state particle-level objects. Final-state electrons and muons are required to be prompt (i.e., to not originate from hadron or τ decay) and their kinematics are computed including the contributions from prompt photons with a distance in η-ϕ coordinates of $\Delta R_{\ell,\gamma} = \sqrt{(\Delta\eta_{\ell,\gamma})^2 + (\Delta\phi_{\ell,\gamma})^2} < 0.1$ between the charged lepton and the photon, as motivated in Ref. [14]. (ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z axis along the beam pipe. The x axis points to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln[\tan(\theta/2)]$.) The leptons are required to be well separated with $\Delta R_{\ell,\ell'} > 0.2$ between any two leptons. Each lepton must have a momentum component transverse to the beam direction $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.7$. Events must have exactly four leptons satisfying the above

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criteria forming two pairs of leptons of the same flavor and oppositely charged ($\mu^+\mu^-$ or e^+e^-). This gives rise to three signal channels: $4e$, 4μ, and $2e2\mu$. Each lepton pair must have an invariant mass in the range 66–116 GeV. In the $4e$ and 4μ channels, where there are two possible ways to form same-flavor oppositely charged lepton pairs, the combination that minimizes $|m_{\ell\ell,a} - m_Z| + |m_{\ell\ell,b} - m_Z|$ is chosen, where $m_{\ell\ell,a}$ and $m_{\ell\ell,b}$ are the invariant masses of the lepton pairs and m_Z is the mass of the Z boson.

The ATLAS detector is a multipurpose particle detector with a cylindrical geometry. It consists of layers of inner tracking detectors, calorimeters, and muon chambers. The inner detector (ID) covers the pseudorapidity range $|\eta| < 2.5$. The calorimeter covers the pseudorapidity range $|\eta| < 4.9$. Within $|\eta| < 2.47$ the finely segmented electromagnetic calorimeter identifies electromagnetic showers and measures their energy and position, providing electron identification together with the ID. The muon spectrometer (MS) surrounds the calorimeters and provides muon identification and measurement in the region $|\eta| < 2.7$ and triggering in the region $|\eta| < 2.4$.

A muon is reconstructed by matching a track (or track segment) reconstructed in the MS to a track reconstructed in the ID. Its momentum is calculated by combining the information from the two systems and correcting for energy deposited in the calorimeters. In regions of limited coverage of the MS ($|\eta| < 0.1$) or outside the ID acceptance ($2.5 < |\eta| < 2.7$), muons can also be reconstructed by matching calorimeter signals consistent with muons to ID tracks (calorimeter-tagged muons) or standalone in the MS [15], respectively.

An electron is reconstructed from an energy deposit (cluster) in the electromagnetic calorimeter matched to a track in the ID. Its momentum is computed from the cluster energy and the direction of the track. Electrons are distinguished from other particles using several identification criteria that rely on the shapes of electromagnetic showers as well as tracking and track-to-cluster matching quantities. The output of a likelihood function taking these quantities as input, similar to that described in Ref. [16], is used to identify electrons. Electrons sharing an ID track with a selected muon are ignored.

The leptons are required to be isolated from other particles using ID track information, and for muons using calorimeter information also (since standalone muons are outside the ID acceptance). The exact requirements depend on the lepton p_T and η and are designed to give a uniform 99% efficiency.

Leptons are required to originate from the primary vertex, defined as the reconstructed vertex with the largest sum of the p_T^2 of the associated tracks. To this end, the longitudinal impact parameter of each lepton track, calculated with respect to the vertex and multiplied by $\sin\theta$ of the track, is required to be less than 0.5 mm. Furthermore, the significance of the transverse impact parameter calculated with respect to the beam line is required to be less than 3 (5) for muons (electrons). Standalone muons are exempt from both impact parameter requirements, as they do not have an ID track.

Candidate events are preselected by either a single-muon or dielectron trigger. As in the fiducial phase space described above, leptons must have $p_T > 20$ GeV. There are slight differences from the fiducial phase space: electrons must satisfy $|\eta| < 2.47$ due to the limited experimental acceptance, and at least one muon in the 4μ channel must satisfy $|\eta| < 2.4$, corresponding to the acceptance of the muon trigger. The other muons must satisfy $|\eta| < 2.7$. Events are ignored if more than one selected muon is calorimeter tagged or standalone. Apart from the above differences, reconstructed candidate events are selected using exactly the same criteria that define the fiducial phase space. A total of 63 events are observed, of which 15, 30, and 18 are in the $4e$, $2e2\mu$, and 4μ channels, respectively.

Monte Carlo (MC)-simulated event samples are used to obtain corrections for detector effects and to estimate background contributions. The principal signal sample is generated with the POWHEG method and framework [17–19], with a diboson event generator [20,21] used to simulate the ZZ production process at next-to-leading order (NLO). (Throughout this Letter, orders of calculations refer to perturbative expansions in the strong coupling constant α_S unless stated otherwise). The simulation of parton showering, of the underlying event, and of hadronization is performed with PYTHIA8 [22,23] using the AZNLO set of tuned parameters (tune) [24]. SHERPA [25–31] is used to generate a sample with the $q\bar{q}$-initiated process simulated at NLO for ZZ plus zero or one additional jet and at leading order (LO) for two or three additional jets, as well as a sample with the loop-induced gg-initiated process simulated at LO with zero or one additional jet. These are used to include the loop-induced gg-initiated production, which is not included in the POWHEG+PYTHIA8 sample, as well as to estimate, by comparison of the various samples, a systematic uncertainty due to the choice of event generator. The CT10 NLO [32] parton distribution functions (PDFs) are used in the event generation for all samples above. Additional samples are generated to estimate the contribution from background events. Triboson events are simulated with SHERPA, using CT10 PDFs, and $t\bar{t}Z$ events are simulated with MADGRAPH [33] interfaced with PYTHIA8 using the NNPDF 2.3 LO PDFs [34] and the A14 tune [35].

In all MC samples, additional pp interactions occurring in the same bunch crossing as the ZZ production, or in nearby ones, are simulated with PYTHIA8 with MSTW 2008 LO PDFs [36] and the A2 tune [37]. The samples are then passed through a simulation of the ATLAS detector [38] based on GEANT4 [39]. Scale factors are applied to the simulated events to correct for the small differences from data in the trigger, reconstruction, identification, isolation, and impact parameter efficiencies for electrons and muons [15,16]. Furthermore, the lepton momentum scales and resolutions are adjusted to match the data.

Background events from processes with at least four prompt leptons in the final state are estimated with the MC samples described above, including uncertainties from the cross-section values, luminosity, and reconstruction effects. Contributions of 0.07 ± 0.02 events from ZZ processes where at least one Z boson decays to τ leptons, 0.17 ± 0.05 events from nonhadronic triboson processes, and 0.30 ± 0.09 events from all-leptonic $t\bar{t}Z$ processes are predicted. Events from processes with two or three prompt leptons, e.g., Z, WW, WZ, $t\bar{t}$, and ZZ events where one Z boson decays hadronically, where associated jets or photons contain or fake a nonprompt lepton, can pass the event selection. This background contribution is estimated to be $0.09^{+1.08}_{-0.04}$ events, using control samples and a data-driven technique described in Ref. [11]. The uncertainty is dominated by the small number of events in the control samples. It can be asymmetric due to truncation, as background contributions cannot be negative. Background from two single Z bosons produced in different pp collisions in the same bunch crossing is estimated to be negligible. The total expected number of background events is 0.20 ± 0.05 ($0.25^{+0.40}_{-0.05}$, $0.17^{+1.00}_{-0.04}$) in the $4e$ ($2e2\mu$, 4μ) channel, giving a total of $0.62^{+1.08}_{-0.11}$ events.

A factor C_{ZZ} is applied to correct for detector inefficiencies and resolution effects. It relates the background-subtracted number of selected events to the number in the fiducial phase space, and is defined as the ratio of generated signal events passing the selection criteria using reconstructed objects to the number passing the fiducial criteria using generator-level objects. C_{ZZ} is determined with a combination of the POWHEG ZZ MC sample and the SHERPA loop-induced gg-initiated sample. The normalization of the latter is scaled to $\mathcal{O}(\alpha_S^3)$ accuracy [2] in order to improve the model used to correct the measurement. The C_{ZZ} value and its total uncertainty is determined to be 0.55 ± 0.02 (0.63 ± 0.02, 0.81 ± 0.03) in the $4e$ ($2e2\mu$, 4μ) channel. The dominant systematic uncertainties come from the uncertainties of the scale factors used to correct lepton reconstruction and identification efficiencies in the simulation and the choice of MC generator. Other smaller uncertainties come from the scale and resolution of the lepton momenta, PDFs, and statistical fluctuations in the MC sample. Table I gives a breakdown of the systematic uncertainties.

Figure 1 shows the invariant mass of the leading-$p_{T,\ell\ell}$ and the subleading-$p_{T,\ell\ell}$ lepton pair ($\ell\ell$), as well as the invariant mass, transverse momentum, and rapidity of the four-lepton system. Distributions from data are compared to the signal and background expectations, with good agreement in general.

The fiducial cross section is determined using a maximum-likelihood fit to the event counts in the three signal channels. A Poisson probability function is used to parametrize the number of expected events, multiplied by Gaussian distributions that model the nuisance parameters representing systematic uncertainties. This procedure can lead to asymmetric uncertainties as Poisson-distributed variables cannot be negative.

TABLE I. Relative uncertainties of the correction factor C_{ZZ} by signal channel, expressed in percent.

Source	$4e$	$2e2\mu$	4μ
Statistical (signal samples)	0.7	0.5	0.5
Theoretical (generator, PDFs)	2.5	2.5	2.5
Experimental efficiencies	2.3	2.2	2.0
Momentum scales and resolutions	0.4	0.2	0.1
Total	3.5	3.3	3.2

The cross section measured in the fiducial phase space is also extrapolated to the total phase space, which includes a correction for QED final-state radiation effects. The extrapolation factor is obtained from the same combination of MC samples as used in the C_{ZZ} determination. The ratio of the fiducial to full phase-space cross section is 0.39 ± 0.02, in all three channels. It is corrected for the $\sim$3% increase bias introduced by the pairing algorithm in the $4e$ and 4μ channels. The dominant systematic uncertainty comes from the difference between the nominal value and that obtained using the SHERPA samples. Smaller uncertainties are derived from PDF variations in the CT10 error set, differences between using PYTHIA8 and HERWIG++ [40] for simulating the rest of the event, and varying the QCD renormalization and factorization scales independently by a factor of 2. In order to extrapolate to the total cross section, the fiducial cross sections are divided by the ratio 0.39 ± 0.02 and corrected for the leptonic branching fraction $(3.3658\%)^2$ [41] (this value excludes γ^* contributions; including these, the branching fraction $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ is about 1.01–1.02 times larger).

The measured fiducial cross sections are shown in Table II and Fig. 2(a) along with a comparison to $\mathcal{O}(\alpha_S^2)$ calculations [1]. Table II also shows the total combined cross section. The CT10 next-to-next-to-leading order PDFs [45] and a dynamic scale equal to the mass of the four-lepton system are used in the calculation. The loop-induced gg-initiated process is included, and contributes 7.0% (5.8%) of the cross section in the fiducial (total) phase space. The predicted cross sections in the fiducial phase space are corrected for QED final-state radiation effects, which amount to a 4% reduction. The measurements agree with the SM predictions.

The theoretical predictions do not include the following effects. The loop-induced gg-initiated process calculated at $\mathcal{O}(\alpha_S^2)$ could receive large corrections at $\mathcal{O}(\alpha_S^3)$ of 70% [2], which would increase the prediction by 4%–5%. Electroweak corrections at next-to-leading order [46,47]

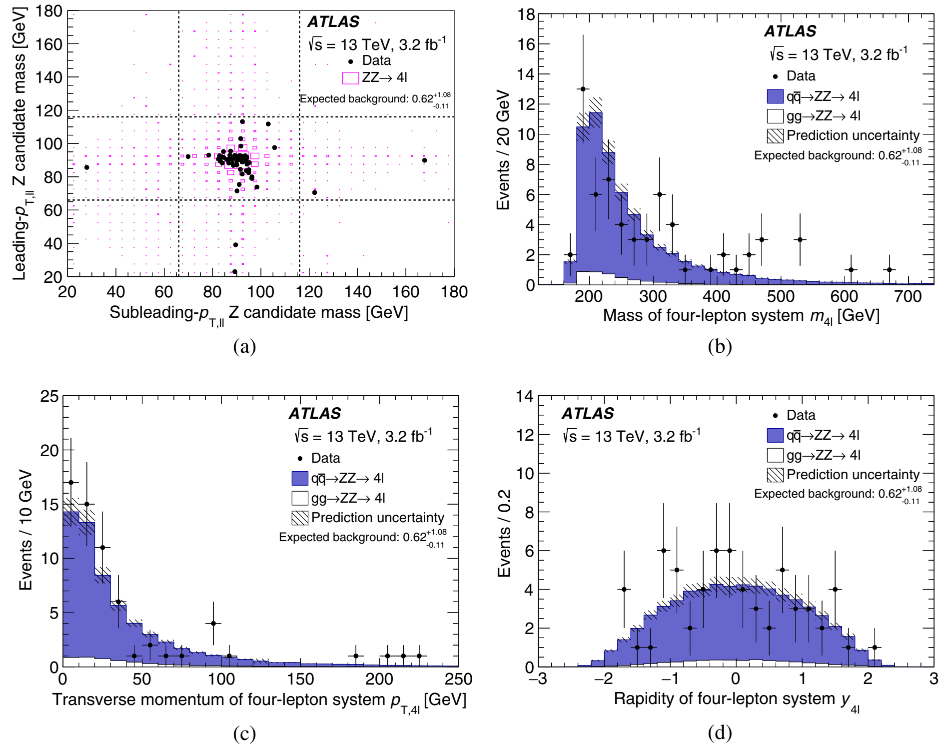


FIG. 1. (a) Invariant mass $m_{\ell\ell}$ of the leading-$p_{T,\ell\ell}$ vs the subleading-$p_{T,\ell\ell}$ lepton pair ($\ell\ell$), before the requirement 66 GeV $< m_{\ell\ell} <$ 116 GeV is applied. The dashed lines indicate this requirement. (b) Invariant mass, (c) transverse momentum, and (d) rapidity of the four-lepton system in selected events. The points represent experimental data. The filled histograms show the signal prediction from simulation, including the $q\bar{q}$ and loop-induced gg-initiated process. The contributions are stacked. In the simulation, the prediction from POWHEG+PYTHIA8 combined with SHERPA is scaled to the $\mathcal{O}(\alpha_S^2)$ prediction. The uncertainties in the simulation are from the same sources as the C_{ZZ} uncertainty. In addition, 6% ZZ cross-section uncertainty and 5% integrated-luminosity uncertainty are included. The expected background of $0.62^{+1.08}_{-0.11}$ events is not shown as a histogram due to its small size.

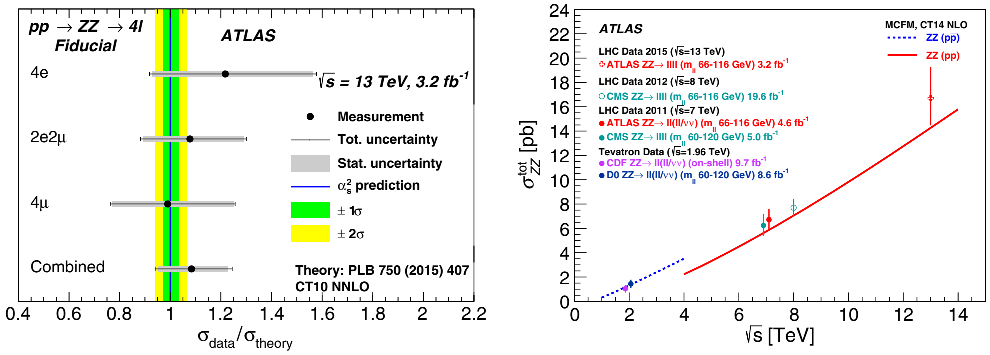
are expected to reduce the cross section by 7%–8% [47]. Furthermore, the contribution from double parton scattering is not accounted for, but is expected to be an effect of less than 1% [48].

The measured total cross section is compared to measurements at lower center-of-mass energies and to a prediction from MCFM [49] with the CT14 NLO PDFs [50], which is calculated at $\mathcal{O}(\alpha_S^1)$ accuracy for the $q\bar{q}$-initiated process and at $\mathcal{O}(\alpha_S^2)$ accuracy for the loop-induced gg-initiated process and is shown vs center-of-mass energy in Fig. 2(b). The cross section increases by a factor of more than 2 with a center-of-mass energy increase from 8 TeV to 13 TeV.

In summary, ATLAS has measured the ZZ production cross section in 3.2 fb^{-1} of 13 TeV pp collisions at the LHC using the fully leptonic decay channel $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$. Fiducial cross sections as well as a total cross section for Z bosons with mass 66–116 GeV have been measured and agree well with $\mathcal{O}(\alpha_S^2)$ SM predictions.

TABLE II. Cross-section measurement results compared to the $\mathcal{O}(\alpha_S^2)$ standard model predictions. The per-channel and combined fiducial cross sections are shown along with the combined total cross section. For experimental results, the statistical, systematic, and luminosity uncertainties are shown. For theoretical predictions, the PDF and renormalization and factorization scale uncertainties added in quadrature are shown.

	Measurement	$\mathcal{O}(\alpha_S^2)$ prediction
$\sigma^{\text{fid}}_{ZZ\to e^+e^-e^+e^-}$	$8.4^{+2.4}_{-2.0}$(stat) $^{+0.4}_{-0.2}$(syst) $^{+0.5}_{-0.3}$(lumi) fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to e^+e^-\mu^+\mu^-}$	$14.7^{+2.9}_{-2.5}$(stat) $^{+0.6}_{-0.4}$(syst) $^{+0.9}_{-0.6}$(lumi) fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{\text{fid}}_{ZZ\to \mu^+\mu^-\mu^+\mu^-}$	$6.8^{+1.8}_{-1.5}$(stat) $^{+0.3}_{-0.3}$(syst) $^{+0.4}_{-0.3}$(lumi) fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to \ell^+\ell^-\ell'^+\ell'^-}$	$29.7^{+3.9}_{-3.6}$(stat) $^{+1.0}_{-0.8}$(syst) $^{+1.7}_{-1.3}$(lumi) fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$16.7^{+2.2}_{-2.0}$(stat) $^{+0.9}_{-0.7}$(syst) $^{+1.0}_{-0.7}$(lumi) pb	$15.6^{+0.4}_{-0.4}$ pb



(a) (b)

FIG. 2. (a) Comparison between measured fiducial cross sections and $\mathcal{O}(\alpha_S^2)$ predictions. (b) Total cross section compared to measurements at lower center-of-mass energies by ATLAS, CMS, CDF, and D0 [11–13,42,43], and to a prediction from MCFM at $\mathcal{O}(\alpha_S^1)$ accuracy for the $q\bar{q}$-initiated process and at $\mathcal{O}(\alpha_S^2)$ accuracy for the loop-induced gg-initiated process. A full $\mathcal{O}(\alpha_S^2)$ prediction (known to improve agreement at $\sqrt{s} = 13$ TeV) was not yet available for all the different center-of-mass energies. Some data points are shifted horizontally to improve readability. The ZZ cross section as function of $\sqrt{s}$ in the range 130–209 GeV was also measured at the LEP 2 e^+e^- collider [44].

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