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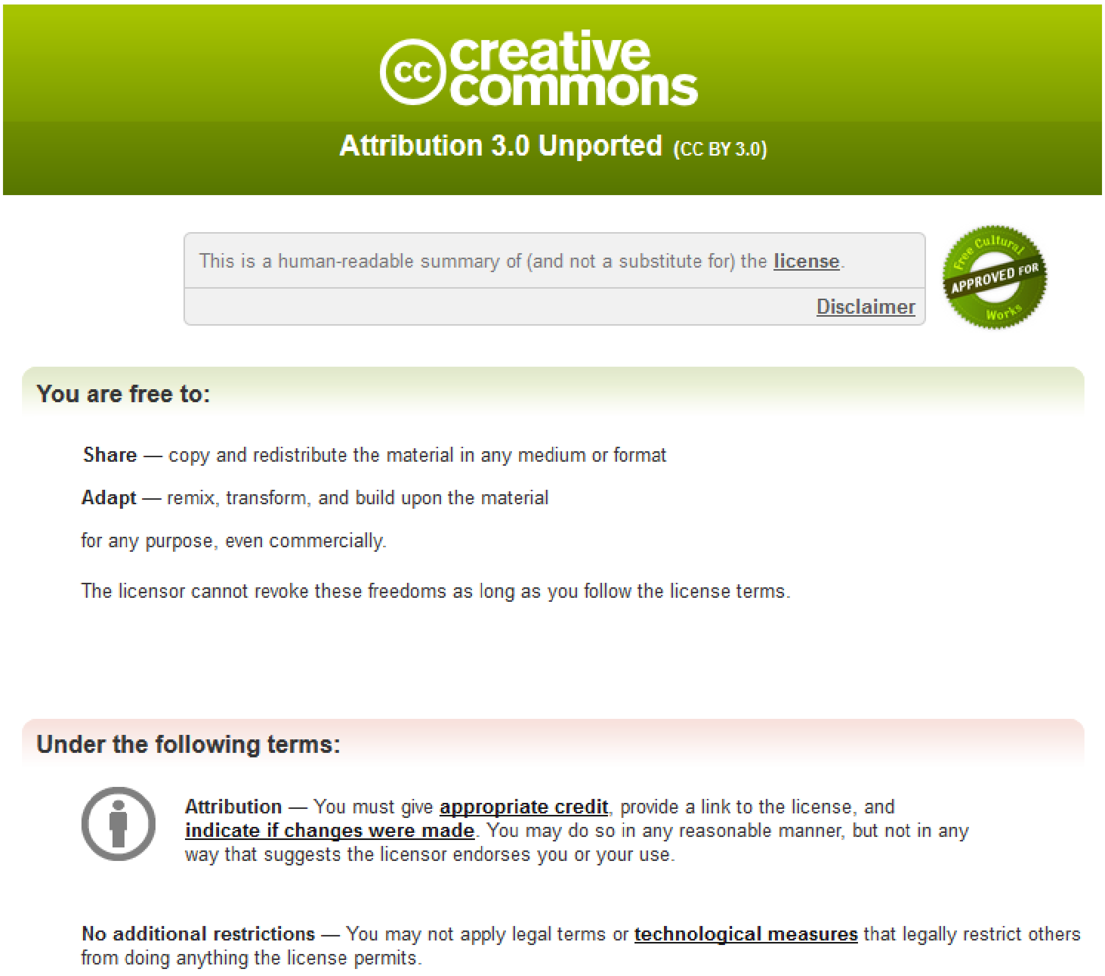

# Measurement of the $ZZ$ Production Cross Section and Limits on Anomalous Neutral Triple Gauge Couplings in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

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A measurement of the $ZZ$ production cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV using data corresponding to an integrated luminosity of 1.02 $\mathrm{fb}^{-1}$ recorded by the ATLAS experiment at the LHC is presented. Twelve events containing two $Z$ boson candidates decaying to electrons and/or muons are observed, with an expected background of $0.3 \pm 0.3(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst})$ events. The cross section measured in a phase-space region with good detector acceptance and for dilepton masses within the range 66 to 116 GeV is $\sigma^{\mathrm{fid}}_{ZZ\to\ell^+\ell^-\ell^+\ell^-} = 19.4^{+6.3}_{-5.2}(\mathrm{stat})^{+0.9}_{-0.7}(\mathrm{syst}) \pm 0.7(\mathrm{lumi})$ fb. The resulting total cross section for on-shell $ZZ$ production, $\sigma^{\mathrm{tot}}_{ZZ} = 8.5^{+2.7}_{-2.3}(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst}) \pm 0.3(\mathrm{lumi})$ pb, is consistent with the standard model expectation of $6.5^{+0.3}_{-0.2}$ pb calculated at the next-to-leading order in QCD. Limits on anomalous neutral triple gauge boson couplings are derived.

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The production of pairs of $Z$ bosons at the LHC is of great interest since it provides an excellent opportunity to test the predictions of the electroweak sector of the standard model at the TeV energy scale; moreover it is the irreducible background to the search for the Higgs boson in the $H \to ZZ$ decay channel. In the standard model, $ZZ$ production proceeds at leading order (LO) via $t$-channel quark-antiquark interactions; the $ZZZ$ and $ZZ\gamma$ neutral triple gauge boson couplings (nTGCs) are absent; hence there is no contribution from $s$-channel $q\bar{q}$ annihilation at tree level. At the one-loop level, fermion triangles generate nTGCs of $\mathcal{O}(10^{-4})$ [1]. Many models of physics beyond the standard model predict values of nTGCs at the level of $10^{-4}$ to $10^{-3}$ [2]. The signature of nonzero nTGCs is an increase of the $ZZ$ cross section at high $ZZ$ invariant mass and high transverse momentum of the $Z$ bosons [3]. $ZZ$ production has been studied in $e^+e^-$ collisions at LEP [4,5] and in $p\bar{p}$ collisions at the Tevatron [6,7]. No deviation of the measured cross section from the standard model expectation has been observed, and limits on anomalous nTGCs have been set [5,6].

This Letter presents the first measurement of $ZZ$ [8] production in proton-proton collisions at a center-of-mass energy $\sqrt{s}$ of 7 TeV, and limits on the anomalous nTGCs. The cross section for on-shell $ZZ$ production (i.e., in the zero-width approximation) is predicted at next-to-leading order (NLO) in QCD to be $6.5^{+0.3}_{-0.2}$ pb [9]; this includes a $\sim$6% contribution from gluon fusion. Candidate $ZZ$ events are reconstructed in the $ZZ \to \ell^+\ell^-\ell^+\ell^-$ decay channel, where $\ell$ can be an electron or muon. Although this channel constitutes only $\sim$0.5% of the total $ZZ$ cross section, its final state with four high transverse-momentum, isolated leptons has a very high expected signal to background ratio of $\sim$30.

To reduce systematic uncertainties, the cross section is measured within a phase-space that corresponds closely to the experimental acceptance; this is termed the "fiducial" cross section. The fiducial phase-space definition requires the invariant mass of both lepton pairs to be between 66 and 116 GeV and all four leptons to be within the pseudorapidity [10] range $|\eta| < 2.5$ and have transverse momentum $p_{\mathrm{T}} > 15$ GeV. The four-momenta of all photons present after the simulation of the parton shower which are within $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.1$ of a lepton are summed into the four-momentum of that lepton. The total $ZZ$ cross section in the on-shell approximation is obtained from the fiducial cross section using the known $Z \to \ell^+\ell^-$ branching ratio and a correction factor for the kinematic and geometrical acceptance.

Anomalous nTGCs for on-shell $ZZ$ production can be parametrized by two $CP$-violating ($f_4^V$) and two $CP$-conserving ($f_5^V$) complex parameters ($V = Z, \gamma$) which are zero in the standard model [3]. To ensure partial-wave unitarity, a form-factor parametrization is introduced to cause the couplings to vanish at high parton center-of-mass energy $\sqrt{\hat{s}}$: $f_i^V = f_{i0}^V/(1 + \hat{s}/\Lambda^2)^n$. Here, $\Lambda$ is the energy scale at which physics beyond the standard model will be directly observable, $f_{i0}^V$ are the low-energy approximations of the couplings, and $n$ is the form-factor power. Following Ref. [3], $n = 3$ and $\Lambda = 2$ TeV are chosen, so that expected limits are within the values provided by unitarity at LHC energies. The results with energy cutoff $\Lambda = \infty$ are also presented as a comparison in the unitarity violation scheme.

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The ATLAS detector [11] consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field. The inner detector, in combination with the 2 T field from the solenoid, provides precision tracking of charged particles for $|\eta| < 2.5$. It consists of a silicon pixel detector, a silicon strip detector, and a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. It is composed of sampling calorimeters with either liquid argon or scintillating tiles as the active media. In the region $|\eta| < 2.5$ the electromagnetic liquid argon calorimeter is finely segmented and plays an important role in electron identification. The muon spectrometer has separate trigger and high-precision tracking chambers which provide muon identification and measurement in $|\eta| < 2.7$.

A three-level trigger system selects events to be recorded for offline analysis. The events used in this analysis were selected with single-lepton triggers with nominal transverse-momentum thresholds of 20 GeV for electrons and 18 GeV for muons. The efficiencies of the single-lepton triggers have been determined as a function of lepton $p_{\mathrm{T}}$ using large samples of $Z \rightarrow \ell^+\ell^-$ events. The trigger efficiency for events passing the offline selection described below is 99.9% with an uncertainty of 0.1%.

This measurement uses a data sample of proton-proton collisions at $\sqrt{s} = 7$ TeV recorded between February and June 2011. After data quality requirements, the total integrated luminosity used in the analysis is 1.02 $\mathrm{fb}^{-1}$. The integrated luminosity uncertainty is 3.7% [12].

Events are required to contain a primary vertex formed from at least three associated tracks. The vertex with the largest sum of the $p_{\mathrm{T}}^2$ computed from the associated tracks is selected as the primary vertex.

Signal events are characterized by four high-$p_{\mathrm{T}}$, isolated electrons or muons, in three channels: $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, and $e^+e^-\mu^+\mu^-$. Lepton candidates are required to be consistent with originating from the primary vertex. Muons are identified by matching tracks (or track segments) reconstructed in the muon spectrometer to tracks reconstructed in the inner detector [13]. Their momentum is calculated by combining the information from the two systems and correcting for the energy deposited in the calorimeters. Only muons with $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.5$ are considered. In order to reject muons from the decay of heavy quarks, isolated muons are selected by requiring the scalar sum of the transverse momenta ($\Sigma p_{\mathrm{T}}$) of other tracks with $p_{\mathrm{T}} > 1$ GeV inside a cone of size $\Delta R = 0.2$ around the muon to be no more than 15% of the muon $p_{\mathrm{T}}$. The overall reconstruction, identification, and isolation efficiency, measured in data using a large sample of $Z \rightarrow \mu^+\mu^-$ events, varies as a function of $p_{\mathrm{T}}$ from 92% at 15 GeV to 95% at 45 GeV.

Electrons are reconstructed from a cluster in the electromagnetic calorimeter matched to a track in the inner detector [13]. Electron candidates are required to pass the "medium" identification criteria described in Ref. [13], to have a transverse momentum (measured in the calorimeter) of at least 15 GeV, and have a pseudorapidity of $|\eta| < 2.47$. They must be isolated, using the same criterion as for muons, calculating the $\Sigma p_{\mathrm{T}}$ around the electron track. Electron candidates within $\Delta R = 0.1$ of any selected muon are rejected, and if two electron candidates are within $\Delta R = 0.1$ of each other the one with the lower $p_{\mathrm{T}}$ is rejected. The overall reconstruction, identification, and isolation efficiency varies as a function of $p_{\mathrm{T}}$ from 63% at 15 GeV to 81% at 45 GeV.

Selected events are required to have exactly four leptons, and to have passed a single-muon or single-electron trigger. To ensure high trigger efficiency, at least one of these leptons must have $p_{\mathrm{T}} > 20$ GeV (25 GeV) for a muon (electron) and match to a muon (electron) reconstructed online by the trigger system within $\Delta R < 0.1$ (0.15).

Same-flavor, oppositely-charged lepton pairs are combined to form $Z$ candidates. An event must contain two such pairs. In the $e^+e^-e^+e^-$ and $\mu^+\mu^-\mu^+\mu^-$ channels, ambiguities are resolved by choosing the pairing which results in the smaller value of the sum of the two $|m_{\ell^+\ell^-} - m_Z|$ values. Figure 1 shows the correlation between the invariant mass of the leading (higher $p_{\mathrm{T}}$) and the subleading (lower $p_{\mathrm{T}}$) lepton pair. The events cluster in the region where both masses are around $m_Z$. Events are required to contain two $Z$ candidates with invariant masses satisfying 66 GeV $< m_{\ell^+\ell^-} <$ 116 GeV.

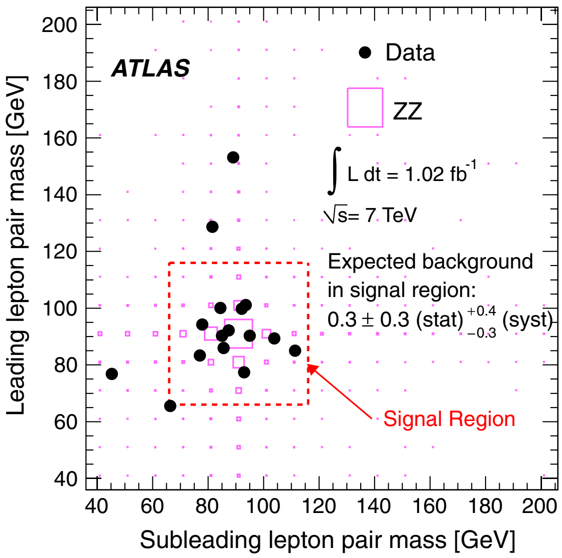


FIG. 1 (color online). The mass of the leading lepton pair versus the mass of the subleading lepton pair. The events observed in the data are shown as solid circles and the $ZZ$ signal prediction from simulation as boxes. The large dashed box indicates the signal region defined by the requirements on the lepton-pair masses.

The reconstruction efficiency for $ZZ$ events is determined from a detailed Monte Carlo simulation. The LO generator PYTHIA [14] with the MRST modified LO parton density function (PDF) set [15] is used to model $pp \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ events, where $\ell$ includes electrons, muons, and $\tau$ leptons. The PYTHIA simulation includes the interference terms between the $Z$ and $\gamma^*$ diagrams; the mass threshold for the $Z/\gamma$ boson is set to 12 GeV. The detector response is simulated [16] with a program based on GEANT4 [17]. Additional inelastic $pp$ events are included in the simulation, distributed so as to reproduce the number of collisions per bunch crossing in the data. The simulation is also corrected with scale factors, and the lepton momentum resolution adjusted, to reproduce the lepton reconstruction and identification efficiencies measured in data.

The overall efficiencies of the reconstruction and selection criteria for events generated within the fiducial phase space are $(40 \pm 3)\%$, $(79 \pm 2)\%$, and $(57 \pm 2)\%$ for $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, and $e^+e^-\mu^+\mu^-$, respectively. The dominant systematic uncertainties arise from electron identification (6.6% in the $e^+e^-e^+e^-$ final state, 3.1% in the $e^+e^-\mu^+\mu^-$ final state) and from the muon reconstruction efficiency (2.0% in $\mu^+\mu^-\mu^+\mu^-$ and 1.0% in $e^+e^-\mu^+\mu^-$).

Background to the $ZZ$ signal originates from events with a $Z$ (or $W^\pm$) boson decaying to leptons plus additional jets or photons ($W/Z + X$), from top-quark production and from other diboson final states. Such events may contain electrons or muons from the decay of heavy-flavored hadrons, or muons from in-flight decay of pions and kaons; jets or photons may be misidentified as electrons. The majority of these background leptons are rejected by the isolation requirement.

To estimate the background contribution from four-lepton events in which one lepton originates from a jet, a sample of events containing three leptons passing all selection criteria plus one "leptonlike jet" is identified; such events are denoted $\ell\ell\ell j$. For muons, the leptonlike jets are muon candidates that fail the isolation requirement. For electrons, the leptonlike jets are clusters in the electromagnetic calorimeter matched to inner detector tracks that fail either or both of the full electron selection and the isolation requirement. The events are otherwise required to pass the full event selection, treating the leptonlike jet as if it were a fully identified lepton. This event sample is dominated by $Z + X$ events. The background is then estimated by scaling this control sample by a measured factor $f$ which is the ratio of the probability for a jet to satisfy the full lepton criteria to the probability to satisfy the leptonlike jet criteria. The background in which two selected leptons originate from jets is treated similarly, by identifying a data sample with two leptons and two leptonlike jets; such events are denoted $\ell\ell jj$. To avoid double counting in the background estimate, and to take into account the expected $ZZ$ contribution in the control region, $N(ZZ)$, the total number of background events $N(\mathrm{BG})$ is calculated as:

$$N(\mathrm{BG}) = N(\ell\ell\ell j)f - N(\ell\ell jj)f^2 - N(ZZ). \qquad (1)$$

The factor $f$ is measured in a sample of data selected with single-lepton triggers with criteria applied to suppress isolated leptons from $W^\pm$ and $Z$ bosons, and corrected for the remaining small contribution of true leptons using simulation. It is measured independently in $\eta$ and $p_\mathrm{T}$ and the values combined assuming they are uncorrelated. A similar analysis is performed on Monte Carlo simulations of background processes; the larger of the statistical uncertainty on $f$ determined from the data and the difference between data and simulation is taken as the systematic uncertainty in each $p_\mathrm{T}$ (or $\eta$) bin. This results in a systematic uncertainty which varies as a function of $p_\mathrm{T}$ from 57% (85%) at 15 GeV to 55% (77%) at 45 GeV for electrons (muons).

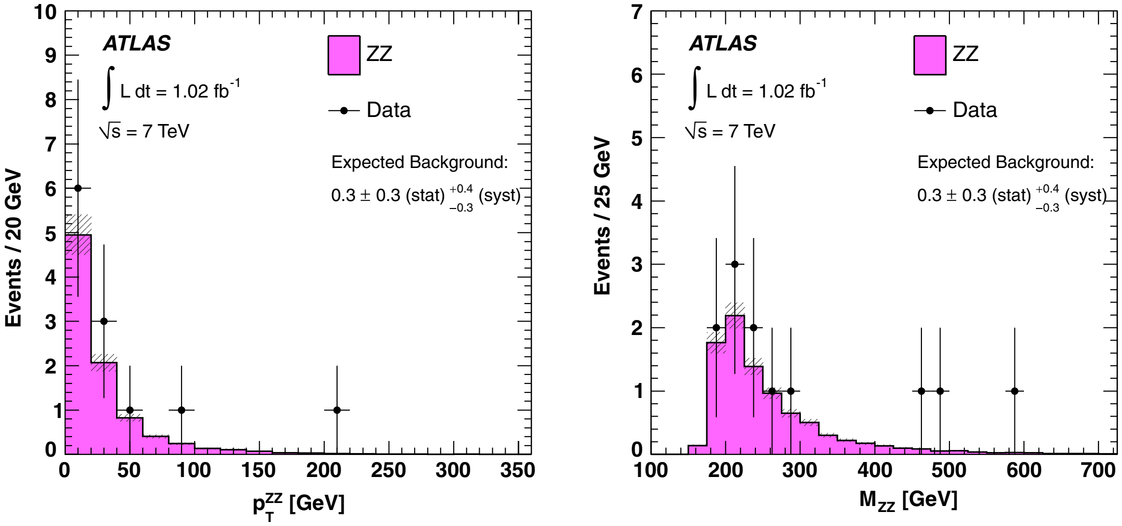
The numbers of expected and observed events after applying all selection criteria are shown in Table I. The expected number of signal events is determined from the PYTHIA simulation normalized to the NLO calculation using MCFM [9] with the MSTW2008 [18] NLO PDF set. The normalization factor, calculated within the phase-space of the fiducial cross section measurement, is 1.41. The expected numbers of signal events include contributions of 1.6% from $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ events generated outside the fiducial phase space and 0.3% from events where one of the $Z$ bosons decays to $\tau$ leptons. Twelve $ZZ$ candidates are observed in data, with a background expectation of $0.3 \pm 0.3(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst})$, corresponding to a $p$ value of $10^{-7}$ equivalent to a one-sided Gaussian significance of $5\sigma$. In the four-muon channel, 8 events are observed where $3.3^{+0.4}_{-0.3}$ signal plus background events are expected. The probability of the expected number fluctuating up to 8 or more is 3.2%.

The transverse-momentum distribution and the invariant mass distribution of the combined four-lepton system for the selected candidates are shown in Fig. 2.

The $ZZ$ fiducial cross section is determined using a maximum likelihood fitting method to combine the three

TABLE I. Summary of observed events in the data, total background contributions, and expected signal in the individual four-lepton and combined channels. The quoted uncertainties represent 68.3% confidence intervals; the first is statistical while the second is systematic. The uncertainties on the integrated luminosity (3.7%) and the theoretical $ZZ$ cross section ($^{+4.7\%}_{-3.1\%}$) are not included.

| Channel | Observed | BG(data-driven) | Expected $ZZ$ |
|---|---|---|---|
| $e^+e^-e^+e^-$ | 2 | $0.01^{+0.03+0.05}_{-0.01-0.01}$ | $1.53 \pm 0.03 \pm 0.10$ |
| $\mu^+\mu^-\mu^+\mu^-$ | 8 | $0.3 \pm 0.3 \pm 0.3$ | $3.03 \pm 0.04 \pm 0.06$ |
| $e^+e^-\mu^+\mu^-$ | 2 | $<0.01^{+0.03}_{-0.01}$ | $4.37 \pm 0.04 \pm 0.14$ |
| $\ell^+\ell^-\ell^+\ell^-$ | 12 | $0.3 \pm 0.3^{+0.4}_{-0.3}$ | $8.9 \pm 0.1 \pm 0.3$ |



(a) (b)

FIG. 2 (color online). (a) Transverse momentum $p_T^{ZZ}$ and (b) invariant mass $M_{ZZ}$ of the four-lepton system for the selected events. The points represent the observed data and the histograms show the signal prediction from simulation. The shaded band on each histogram shows the combined statistical and systematic uncertainty on the signal prediction. The predicted number of background events from the data-driven background estimate is indicated on the plot.

four-lepton channels. The systematic uncertainties are included in the fitting procedure as nuisance parameters. The measured fiducial cross section is:

$$\sigma^{\text{fid}}_{ZZ\to\ell^+\ell^-\ell^+\ell^-} = 19.4^{+6.3}_{-5.2}(\text{stat})^{+0.9}_{-0.7}(\text{syst}) \pm 0.7(\text{lumi})\ \text{fb},$$

where $\ell^+\ell^-\ell^+\ell^-$ refers to the sum of the $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, and $\mu^+\mu^-\mu^+\mu^-$ final states. The total cross section is determined similarly, correcting for the known $Z\to\ell^+\ell^-$ branching ratios and the acceptance of the fiducial phase space. This acceptance, calculated at NLO using MCFM version 6.0 with the MSTW2008 PDF set, is $0.507 \pm 0.009$, where the error arises primarily from PDF uncertainties with a 1% contribution from QED radiative corrections and off-shell $Z/\gamma^*$ effects evaluated from POWHEG BOX [19]. The measured value of the total on-shell $ZZ$ cross section is:

$$\sigma^{\text{tot}}_{ZZ} = 8.5^{+2.7}_{-2.3}(\text{stat})^{+0.4}_{-0.3}(\text{syst}) \pm 0.3(\text{lumi})\ \text{pb}.$$

The result is consistent within errors with the NLO standard model total cross section for this process of $6.5^{+0.3}_{-0.2}$ pb [9].

Limits on anomalous nTGCs are determined using the total number of observed events only. The $ZZ$ production yield dependency on couplings is parametrized using fully simulated events generated with SHERPA [20] subsequently reweighted using the leading-order matrix element [3] within the framework of Ref. [21]. The reweighting procedure uses simulated samples with standard model as well as non-standard-model coupling values to ensure adequate coverage of all kinematic regions. One dimensional 95% confidence intervals for the anomalous nTGCs are determined using a maximum profile likelihood fit to the observed number of events. The systematic errors are included as nuisance parameters. The resulting limits for each coupling, determined assuming real couplings and with the other couplings fixed at their standard model value, are listed in Table II. The present results are dominated by statistical uncertainties: limits derived using statistical uncertainties alone differ from those in Table II by less than 0.01. These limits are comparable with, or are more stringent than, those derived from measurements at LEP [5] and the Tevatron [6]; it should be noted that limits from LEP do not use a form factor, and those from the Tevatron use $\Lambda = 1.2$ TeV.

In summary, the $ZZ$ production cross section has been measured in proton-proton collisions at $\sqrt{s} = 7$ TeV using

TABLE II. One dimensional 95% confidence intervals for anomalous neutral gauge boson couplings, where the limit for each coupling assumes the other couplings fixed at their standard model value. Limits are presented for form-factor scales of $\Lambda = 2$ TeV and $\Lambda = \infty$ and include both statistical and systematic uncertainties; the statistical uncertainties are dominant.

| $\Lambda$ | $f_{40}^{\gamma}$ | $f_{40}^{Z}$ | $f_{50}^{\gamma}$ | $f_{50}^{Z}$ |
|---|---|---|---|---|
| 2 TeV | [− 0.15, 0.15] | [− 0.12, 0.12] | [− 0.15, 0.15] | [− 0.13, 0.13] |
| $\infty$ | [− 0.08, 0.08] | [− 0.07, 0.07] | [− 0.08, 0.08] | [− 0.07, 0.07] |

the ATLAS detector. Both the fiducial cross section within the detector acceptance and the total cross section have been determined. The latter is in agreement with the standard model expectation. Limits on anomalous nTGCs have been derived.

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