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Measurement of the WW cross section in √s = 7 TeV pp collisions with the ATLAS detector and limits on anomalous gauge couplings
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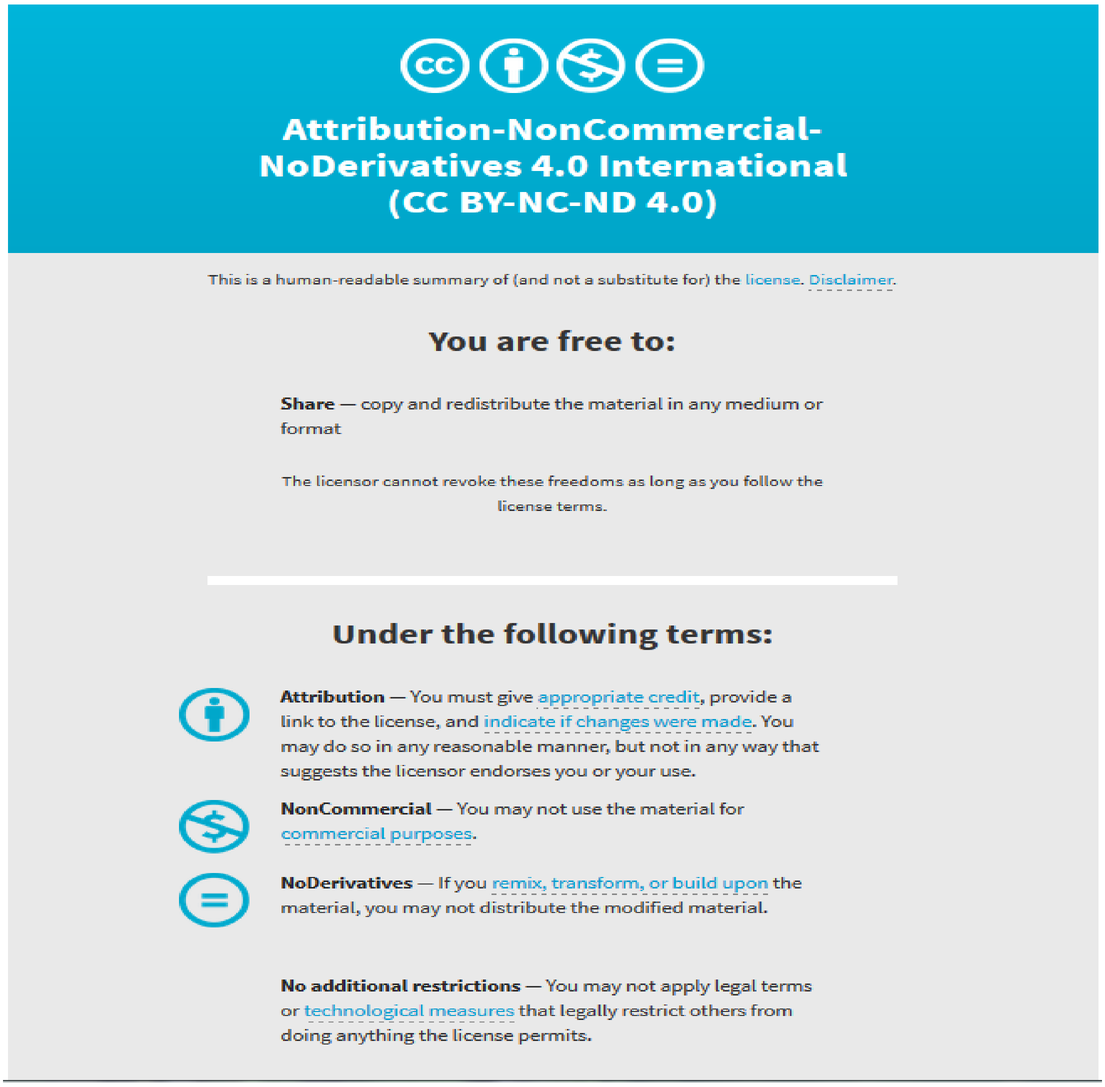

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ABSTRACT

This Letter reports a measurement of the WW production cross section in $\sqrt{s} = 7$ TeV pp collisions using data corresponding to an integrated luminosity of 1.02 fb^{-1} collected with the ATLAS detector. Using leptonic decays of oppositely charged W bosons, the total measured cross section is $\sigma(pp \to WW) = 54.4 \pm 4.0$ (stat.) ± 3.9 (syst.) ± 2.0 (lumi.) pb, consistent with the Standard Model prediction of $\sigma(pp \to WW) = 44.4 \pm 2.8$ pb. Limits on anomalous electroweak triple-gauge couplings are extracted from a fit to the transverse-momentum distribution of the leading charged lepton in the event.

1. Introduction

Measurements of WW production at the LHC provide important tests of the Standard Model (SM), in particular of the WWZ and $WW\gamma$ triple gauge couplings (TGCs) resulting from the non-Abelian nature of the $SU(2)_L \times U(1)_Y$ symmetry group. Precise measurements of TGCs are sensitive probes of new physics in the electroweak sector and are complementary to direct searches. Furthermore, since WW production is a background to possible new processes such as the production of the SM Higgs boson, a precise measurement of the WW cross section is an important step in the search for new physics.

This Letter describes the measurements of the WW cross section and of TGCs in pp collisions at $\sqrt{s} = 7$ TeV. The dominant SM WW production mechanisms are s-channel and t-channel quark–antiquark annihilation, with a 3% contribution from gluon–gluon fusion. The cross section is measured in the fiducial phase space of the detector using $WW \to l\nu l\nu$ decays in final states with electrons and muons, and is extrapolated to the total phase space. The fiducial phase space includes geometric and kinematic acceptance. The total production cross section of oppositely charged W bosons is measured according to the equation [1]

$$\sigma(pp \to WW) = \frac{N_{\text{data}} - N_{\text{bg}}}{A_{WW} C_{WW} \mathcal{L} \mathcal{B}}, \tag{1}$$

where N_{data} and N_{bg} are the number of observed data events and estimated background events, respectively, A_{WW} is the kinematic and geometric acceptance, C_{WW} is the ratio of the number of measured events to the number of events produced in the fiducial phase space, $\mathcal{L}$ is the integrated luminosity of the data sample, and $\mathcal{B}$ is the branching ratio for both W bosons to decay to $e\nu$ or $\mu\nu$ (including decays through tau leptons with additional neutrinos). The fiducial cross section is defined as $\sigma \times A_{WW} \times \mathcal{B}$ [1].

Previous measurements of WW production using the CMS and ATLAS detectors, both based on the data recorded in 2010 and corresponding to an integrated luminosity of 36 pb^{-1}, have found $\sigma(pp \to WW) = 41.1 \pm 15.3$ (stat.) ± 5.8 (syst.) ± 4.5 (lumi.) pb [2] and $\sigma(pp \to WW) = 41^{+20}_{-16}$ (stat.) ± 5 (syst.) ± 1 (lumi.) pb [3], respectively. CMS has additionally used these data to set limits on anomalous gauge-coupling parameters at higher center of mass energies than corresponding measurements at the Tevatron [4] and LEP [5].

2. ATLAS detector

The ATLAS detector [6] consists of an inner tracking system (inner detector, or ID) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroid magnets arranged with an eight-fold azimuthal coil symmetry around the calorimeters. The ID consists of silicon pixel and microstrip detectors, surrounded by a transition radiation tracker. The electromagnetic calorimeter is a lead/liquid-argon (LAr) detector. Hadron calorimetry is based on two different detector technologies, with scintillator tiles or LAr as active media, and with either steel, copper, or tungsten as the absorber material. The MS comprises three layers of chambers for the trigger and for track measurements.

A three-level trigger system is used to select events. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This is followed by two software-based trigger levels, level-2 and the event filter, which together reduce the event rate to about 200 Hz recorded for analysis.

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The nominal *pp* interaction point at the center of the detector is defined as the origin of a right-handed coordinate system. The positive x-axis is defined by the direction from the interaction point to the center of the LHC ring, with the positive y-axis pointing upwards, while the z-axis is along the beam direction. The azimuthal angle ϕ is measured around the beam axis and the polar angle θ is the angle from the z-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

3. Data sample and event selection

The data used for this analysis correspond to an integrated luminosity of 1.02 ± 0.04 fb^{-1} [7], recorded between April and June of 2011. Events are selected with triggers requiring either a single electron with $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.5$ or a single muon with $p_\mathrm{T} > 18$ GeV and $|\eta| < 2.4$. Additional data collected with a trigger requiring a single muon with $p_\mathrm{T} > 40$ GeV, $|\eta| < 1.05$, and looser identification criteria are used to increase efficiency. The combination of triggers results in $\approx 100\%$ (98%) trigger efficiency for events with WW decays to $e\nu\mu\nu$ and $e\nu e\nu$ ($\mu\nu\mu\nu$) passing the selection described below.

The WW event selection begins with the identification of electrons and muons, requiring exactly two of these particles with opposite charge. Electrons are reconstructed with a clustering algorithm in the electromagnetic calorimeter and matched to an ID track. To distinguish electrons from hadrons, selection criteria [8] are applied based on the quality of the position and momentum match between the extrapolated track and the calorimeter cluster, the consistency of the longitudinal and lateral shower profiles with an incident electron, and the observed transition radiation in the TRT. Electrons are required to lie within the fiducial regions of the calorimeters ($|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$), have $p_\mathrm{T} > 25$ GeV ($p_\mathrm{T} > 20$ GeV for the lower p_T electron in the $e\nu e\nu$ decay channel), and be isolated in the calorimeter and tracker. Calorimeter isolation requires the summed transverse energies deposited in calorimeter cells, excluding those belonging to the electron cluster, in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the electron direction to be < 4 GeV. Tracker isolation requires the summed p_T of ID tracks in a cone of radius $\Delta R = 0.2$ centered on and excluding the electron track to be $< 10\%$ of the electron p_T.

The muon reconstruction algorithm begins with a track from the MS to determine the muon's η, and then combines it with an ID track to determine the muon's momentum [9]. Muons are required to have $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.4$, and in the $\mu\nu\mu\nu$ channel at least one muon must have $p_\mathrm{T} > 25$ GeV. Decays of hadrons to muons are suppressed using calorimeter and track isolation. The calorimeter isolation requires the summed transverse energies deposited in calorimeter cells in a cone of radius $\Delta R = 0.2$ around the muon track to be less than 15% of the muon's p_T. The track isolation requirement is the same as for electrons. The tracks associated with muon and electron candidates must have longitudinal and transverse impact parameters consistent with originating from the primary reconstructed vertex. The primary vertex is defined as the vertex with the highest $\sum p_\mathrm{T}^2$ of associated ID tracks.

The presence of neutrinos is characterized by an imbalance of transverse momentum in the event. The missing transverse momentum ($E_\mathrm{T}^\mathrm{miss}$) is the modulus of the event $-\vec{p}_\mathrm{T}$ vector, calculated by summing the transverse momentum determined from each calorimeter cell's energy and direction with respect to the primary vertex. Cells with $|\eta| < 4.5$ are used in the calculation and a correction is applied to account for the momentum of measured muons.

Misreconstructed leptons and jets, as well as leptons from tau decays, are suppressed by applying cuts on $E_\mathrm{T}^\mathrm{miss} \times \sin\Delta\phi$ when $\Delta\phi < \pi/2$. Here, $\Delta\phi$ is the azimuthal angle between the missing transverse momentum and the nearest charged lepton or jet; small $\Delta\phi$ indicates that $E_\mathrm{T}^\mathrm{miss}$ is dominated by a mismeasured lepton or jet, or by the presence of neutrinos in the direction of the lepton or jet, as would occur in a tau decay. The lower cuts on $E_\mathrm{T}^\mathrm{miss}$, or $E_\mathrm{T}^\mathrm{miss} \times \sin\Delta\phi$ for $\Delta\phi < \pi/2$, are 25 GeV in the $e\nu\mu\nu$ channel, 40 GeV in the $e\nu e\nu$ channel, and 45 GeV in the $\mu\nu\mu\nu$ channel. The thresholds in the $e\nu e\nu$ and $\mu\nu\mu\nu$ channels are more stringent than in the $e\nu\mu\nu$ channel to suppress the background from Drell–Yan (DY) production of ee and $\mu\mu$ pairs.

Table 1
The estimated background event yields in the selected WW data sample. The first uncertainty is statistical, the second systematic.

Production process	$e\nu\mu\nu$ selection	$e\nu e\nu$ selection	$\mu\nu\mu\nu$ selection
DY	$13.0 \pm 2.1 \pm 1.6$	$12.5 \pm 2.3 \pm 1.4$	$10.9 \pm 2.5 \pm 1.4$
Top	$11.9 \pm 1.8 \pm 2.4$	$3.1 \pm 0.5 \pm 0.6$	$3.8 \pm 0.6 \pm 0.8$
W + jet	$10.0 \pm 1.6 \pm 2.1$	$4.1 \pm 1.3 \pm 0.9$	$4.2 \pm 1.1 \pm 1.3$
Diboson	$5.1 \pm 1.0 \pm 0.7$	$2.1 \pm 0.8 \pm 0.3$	$2.9 \pm 0.4 \pm 0.4$
Total background	$40.0 \pm 3.3 \pm 3.6$	$21.7 \pm 2.8 \pm 1.8$	$21.8 \pm 2.8 \pm 2.1$

Background from top-quark production is rejected by vetoing events containing a reconstructed jet with $p_\mathrm{T} > 25$ GeV and $|\eta| < 4.5$. Jets are reconstructed with the anti-k_t algorithm [10] with a radius parameter of $R = 0.4$. A further 30% reduction of top-quark background is achieved by rejecting events with a jet with $p_\mathrm{T} > 20$ GeV, $|\eta| < 2.5$, and identified as originating from a b-quark (b-jet). The identification of b-jets combines information from the impact parameters and the reconstructed vertices of tracks within the jet [11]. The additional b-jet rejection reduces WW acceptance by 1.3%.

Resonances with dilepton decays are removed by requiring ee and $\mu\mu$ invariant masses to be greater than 15 GeV and not within 15 GeV of the Z-boson mass. To suppress backgrounds from heavy-flavour hadron decays, events with an $e\mu$ invariant mass below 10 GeV are also removed. The complete event selection yields 202 $e\nu\mu\nu$, 59 $e\nu e\nu$, and 64 $\mu\nu\mu\nu$ candidates.

4. Background estimation

The selected data sample contains $26 \pm 3\%$ background to the WW production process (Table 1). In decreasing order of size, the main background processes are: DY production of dileptons, with significant $E_\mathrm{T}^\mathrm{miss}$ arising from misreconstructed jet(s) or charged lepton(s); $t\bar{t}$ and tWb production, where the b-quarks in the $WWb\bar{b}$ final state are not rejected by the jet veto; $(W \to l\nu) +$ jet, where the jet is misidentified as a lepton; $WZ \to l\nu ll$ production, where one lepton is not reconstructed; $(W \to l\nu) + \gamma$, where the photon converts in the inner detector and is misreconstructed as an electron; $ZZ \to ll\nu\nu$ production; and cosmic-ray muons overlapping a *pp* collision (which is negligible).

Backgrounds are estimated using a combination of Monte Carlo (MC) samples including a full GEANT [12] simulation of the ATLAS detector [13], and control samples (independent of the measurement sample) from data. The simulation includes the modeling of multiple *pp* interactions in the same bunch crossing (pile-up), as well as corrections (determined from data) to improve the modeling of reconstructed objects.

The DY background is estimated using the ALPGEN [14] Monte Carlo generator interfaced to PYTHIA [15] for parton showering. To test the modeling of $E_\mathrm{T}^\mathrm{miss}$, data are compared to simulated Z/γ^* events where the lepton pair forms an invariant mass within 15 GeV of the Z-boson mass. The DY MC accurately models the number of events above the thresholds on $E_\mathrm{T}^\mathrm{miss}$ or $E_\mathrm{T}^\mathrm{miss} \times \sin\Delta\phi$ used to select WW events, after subtracting the $\approx 20\%$ non-DY

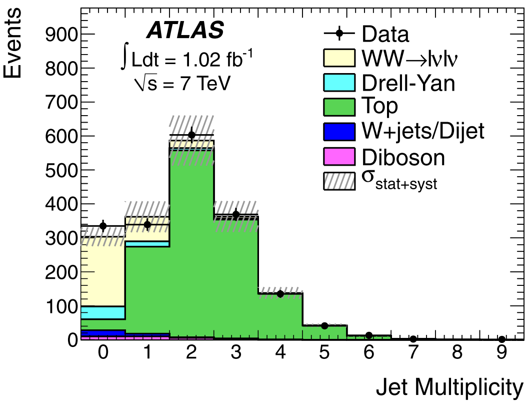

Fig. 1. The multiplicity distribution of jets with $p_\mathrm{T} > 25$ GeV for the combined dilepton channels, after all WW selection cuts except the jet veto requirement. The systematic uncertainties shown in the > 0-jet bins include only those on the integrated luminosity and the theoretical cross sections.

contributions. A 12% relative systematic uncertainty on the DY prediction is taken from the statistical precision of the MC validation in the control sample.

Background from top-quark production arises when the final-state b-quarks have low transverse momentum ($p_\mathrm{T} < 20$ GeV), are not identified as b-jets (for $20 < p_\mathrm{T} < 25$ GeV), or are in the far forward region ($|\eta| > 4.5$). To model this background, MC@NLO [16] samples of $t\bar{t}$ and AcerMC [17] samples of tWb production are used, respectively, with corrections derived from the data. An overall normalization factor is determined from the ratio of events in data to those predicted by the top-quark MC using the WW selection without any jet rejection. This sample is dominated by top-quark decays, as shown in Fig. 1; a 24% contribution from other processes is subtracted in the normalization. The subtraction of the WW component is based on the SM prediction of WW production, with an uncertainty that covers the difference between the prediction and the cross section measurement reported in this Letter. The relative cross sections of $t\bar{t}$ to tWb are set by the generator calculations of $\sigma = 164.6$ pb and $\sigma = 15.6$ pb, respectively.

A key aspect of the top-quark background prediction is the modeling of the jet veto acceptance. To reduce the associated uncertainties, a data-based correction is derived using a top-quark-dominated sample based on the WW selection but with the requirement of at least one b-jet with $p_\mathrm{T} > 25$ GeV [18]. In this sample, the ratio P_1 of events with one jet to the total number of events is sensitive to the modeling of the jet energy spectrum in top-quark events. A multiplicative correction based on the ratio $P_1^{\mathrm{data}}/P_1^{MC}$ is applied to reduce the uncertainties resulting from the jet veto requirement. The residual uncertainty on the background prediction due to jet energy scale and resolution is small (4%) compared to uncertainties from the b-quark identification efficiency (6%), parton shower modeling (12%), statistical uncertainty on the $P_1^{\mathrm{data}}/P_1^{MC}$-based correction (12%), and unmodeled $t\bar{t}$–tWb interference and higher order QCD corrections (15%). As a cross-check, the normalization of the top-quark background is extracted from a fit to the jet multiplicity distribution; the result is consistent with the primary estimate.

The $W +$ jet process contributes to the selected sample when one or more hadrons in the jet decay to, or are misidentified as, a charged lepton. Jets reconstructed as electrons or muons predominantly arise from misidentification or heavy-flavour quark decays, respectively. This background is estimated with a pass-to-fail ratio f_e (f_μ), defined as the ratio of the number of electron (muon) candidates passing the electron (muon) identification criteria to the number of candidates failing the criteria. These ratios are measured in data samples dominated by hadronic jets collected with a trigger requiring an electromagnetic cluster or a muon candidate. All candidates are required to pass a loose set of selection criteria, including an isolation requirement. The measured f_e and f_μ are then applied as multiplicative factors to events satisfying all WW selection cuts except with one lepton failing the identification criteria but passing the looser criteria.

The above procedure measures f_e and f_μ ratios averaged over misidentified jets and heavy-flavour quark decays in jet-dominated samples. If, for example, the ratio f_e differs for these two contributions, the $W +$ jet prediction could be biased. To address this issue, two sets of loose criteria are applied to electron candidates, one based on the track and the shower profile and expected to enhance the misidentification fraction, and the other based on the isolation and expected to enhance the heavy flavour fraction. The f_e ratio is measured for these criteria separately in events where there is an additional b-jet and events where there is no such jet. From the combination of measurements, the heavy-flavour and misidentification contributions are separated; the resulting $W +$ jet background is consistent with that obtained using the inclusive f_e for the misidentification and heavy-flavour components. A similar separation is not performed for f_μ, since heavy-flavour decays dominate the contribution of background muons from the $W +$ jet process.

The systematic uncertainty on the $W +$ jet prediction is dominated by a 30% variation of the ratios f_e and f_μ with the jet p_T threshold. This variation is sensitive to the relative fraction of quarks and gluons in the samples used to measure f_e and f_μ, and thus encompasses potential differences in f_e and f_μ ratios between these samples and those used to estimate the $W +$ jet background.

Several alternative methods are used to check the $W +$ jet prediction and give consistent results. The first method applies the measured f_e and f_μ ratios to an inclusive $W +$ jets data sample, and then determines the fraction of expected events with no additional jets using $W +$ jets Monte Carlo events with two identified leptons. The second method defines different sets of “loose” lepton criteria and independently measures efficiencies for lepton identification and rates for misidentified or decaying hadrons to pass the standard identification criteria. Background from dijet production is estimated with this method and is found to be small; it is implicitly included in the primary estimate.

Monte Carlo estimates of the $W\gamma$, WZ, and ZZ backgrounds are obtained using a combination of ALPGEN and PYTHIA (for $W\gamma$) and HERWIG [19] with JIMMY [20] (for the others), normalized to the next-to-leading order (NLO) cross sections calculated with MCFM [21]. The $\mathcal{O}(10\%)$ systematic uncertainty on these backgrounds is dominated by the uncertainty on the jet energy scale.

5. *WW* acceptance modeling

The WW total cross section measurement requires the knowledge of the A_{WW} and C_{WW} factors given in Eq. (1). The acceptance factor A_{WW} is defined as the ratio of generated WW events in the fiducial phase space to those in the total phase space. The correction factor C_{WW} is defined as the ratio of measured events to generator-level events in the fiducial phase space. The value of this ratio is determined primarily by lepton trigger and identification efficiencies, with a small contribution from differences in generated and measured phase space due to detector resolutions. The fiducial phase space is defined at generator level as:

- Muon $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.4$ ($p_\mathrm{T} > 25$ GeV for at least one muon in the $\mu\nu\mu\nu$ channel);

Table 2
The total WW acceptance $A_{WW} \times C_{WW}$ in the individual decay channels, and the expected number of SM WW events (N_{WW}) for an integrated luminosity of 1.02 fb^{-1}.

	$e\nu\mu\nu$ selection		$e\nu e\nu$ selection		$\mu\nu\mu\nu$ selection	
	$WW \to e\nu\mu\nu$	$WW \to l\nu\tau\nu$	$WW \to e\nu e\nu$	$WW \to e\nu\tau\nu$	$WW \to \mu\nu\mu\nu$	$WW \to \mu\nu\tau\nu$
$A_{WW} \times C_{WW}$	10.8%	3.0%	4.4%	1.1%	7.6%	1.6%
N_{WW}	114.9	12.0	23.4	2.3	40.3	3.3

Table 3
Relative uncertainties, in percent, on the estimate of the product $A_{WW} \times C_{WW}$ for the individual WW decay channels. The uncertainty on A_{WW} (C_{WW}) receives contributions from the last three (first six) sources.

Source of uncertainty	Relative uncertainty (%)		
	$e\nu\mu\nu$ selection	$e\nu e\nu$ selection	$\mu\nu\mu\nu$ selection
Trigger efficiency	1.0	1.0	1.0
Lepton efficiency	2.3	4.1	1.8
Lepton p_T scale and resolution	0.4	1.0	0.1
E_T^{miss} modeling	0.6	1.0	2.2
Jet energy scale and resolution	1.1	1.1	1.1
Lepton acceptance	2.0	2.1	1.6
Jet veto acceptance	5.0	5.0	5.0
PDFs	1.4	1.2	1.2
Total	6.2	7.2	6.2

- Electron $p_T > 20$ GeV and either $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ ($p_T > 25$ GeV in the $e\nu\mu\nu$ channel and for at least one electron in the $e\nu e\nu$ channel);
- No anti-k_t jet ($R = 0.4$) with $p_T > 25$ GeV, $|\eta| < 4.5$, and $\Delta R(e, \text{jet}) > 0.3$;
- No anti-k_t jet with $p_T > 20$ GeV, $|\eta| < 2.5$, $\Delta R(e, \text{jet}) > 0.3$, and $\Delta R(b, \text{jet}) < 0.3$, where the b-quark has $p_T > 5$ GeV;
- Neutrino $|\sum \vec{p}_T|$ or $|\sum \vec{p}_T| \times \sin\Delta\phi$ (for $\Delta\phi < \pi/2$) > 45, 40, 25 GeV in the $\mu\nu\mu\nu$, $e\nu e\nu$ and $e\nu\mu\nu$ channels, respectively ($\Delta\phi$ is the azimuthal angle between the neutrino $\sum \vec{p}_T$ and the nearest charged lepton);
- $m_{\ell\ell} > 15$ (10) GeV in the $\mu\nu\mu\nu$ and $e\nu e\nu$ channels ($e\nu\mu\nu$ channel);
- $|m_{\ell\ell} - m_Z| > 15$ GeV in the $\mu\nu\mu\nu$ and $e\nu e\nu$ channels,

where m_Z is the Z boson mass. To reduce the dependence on the model of QED final-state radiation, the electron and muon p_T include contributions from photons within $\Delta R = 0.1$ of the lepton direction.

Estimates of A_{WW} and C_{WW} are based on samples of $q\bar{q} \to WW$ and $gg \to WW$ events generated with MC@NLO and gg2WW [22], respectively. Initial parton momenta are modeled with CTEQ 6.6 [23] parton distribution functions (PDFs). The underlying event and parton showering are modeled with JIMMY, and hadronization and tau-lepton decays with HERWIG. Data-based corrections measured with W and Z boson data are applied to reduce uncertainties, as described below. Because the corrections are applied to WW MC samples, residual uncertainties on the fiducial cross section measurement are based on the kinematics of SM WW production.

The combined factor $A_{WW} \times C_{WW}$ is estimated separately for each leptonic decay channel, including decays to tau leptons (Table 2). Tau-lepton decays to hadrons are not included in the denominator for the acceptances in the table. The impact of pile-up is modeled by adding PYTHIA-generated low-Q^2 events to the WW MC according to the distribution of the number of additional collisions in the same bunch crossing in the data. Effects on detector response from nearby bunches are also modeled using this distribution.

A correction to the $q\bar{q} \to WW$ MC modeling of the jet veto is derived using Z-boson data. The fraction of Z-boson events with no additional jets is compared between data and MC@NLO simulated samples. The ratio of this fraction in data to the fraction in the MC is applied as a multiplicative correction factor of 0.963 to the WW MC. The correction reduces the uncertainties due to jet energy scale and resolution to 1.1%. A theoretical uncertainty of 5.0% on the jet veto acceptance contributes the largest uncertainty to A_{WW}, as shown in Table 3.

Contributions to E_T^{miss} include energy from the interacting protons' remnants (the underlying event), and from pile-up. The dominant uncertainty arises from the detector response to the underlying event, and is evaluated by varying the individual calorimeter cell energy deposits in the MC [24]. To determine the uncertainty due to additional pp interactions in the same bunch crossing as the hard-scattering process, the event $\vec{p}_T$ measured with the calorimeter is compared between data and MC in $Z \to \mu\mu$ events. The mean $|\vec{p}_T|$ as a function of the number of reconstructed vertices agrees to within 3% between data and MC, yielding a negligible uncertainty on the WW acceptance. The effect of collisions from other bunch crossings is studied by splitting Z-boson samples in data and MC according to the bunch position in the LHC train, and by smearing E_T^{miss} in the simulation samples to match the acceptance of a given E_T^{miss} cut in the data samples. The resulting uncertainty on the WW acceptance is small.

The efficiencies for triggering, reconstructing, and identifying charged leptons are measured as a function of lepton p_T and η using Z boson events and (for electrons) W boson events [1]. Corrections to the MC derived from these data are within 1% of unity for trigger and muon identification efficiencies and deviate from unity by up to 11% at low p_T for the electron identification efficiency. Uncertainties on the corrections are largely due to the limited number of events available for the measurements and, in case of electron identification, from the estimate of the jet background contamination.

Finally, there are small uncertainties on the WW production model. Uncertainties on PDFs are determined using the CTEQ eigenvectors and the acceptance differences between the CTEQ 6.6 and MSTW 2008 PDF sets [25]. The impact of unmodeled higher order contributions is estimated by varying the renormalization and factorization scales coherently by factors of 2 and 1/2.

The total acceptance uncertainty on the three channels combined is 6.2%.

Table 4
The measured total ($\sigma(pp \to WW)$) and fiducial (σ_{fid}) cross sections and the components used in the calculations, as well as the SM predictions for the fiducial cross sections ($\sigma_{\text{fid}}^{\text{SM}}$). The first uncertainty is statistical and the second systematic. The 3.7% relative uncertainty on the integrated luminosity is the third uncertainty on the measured cross sections. The uncertainties on $\sigma_{\text{fid}}^{\text{SM}}$ are highly correlated between the channels.

	$e\nu\mu\nu$ selection	$e\nu e\nu$ selection	$\mu\nu\mu\nu$ selection
Data	202	59	64
Background	$40.0 \pm 3.3 \pm 3.6$	$21.7 \pm 2.8 \pm 1.8$	$21.8 \pm 2.8 \pm 2.1$
C_{WW}	$0.541 \pm 0.005 \pm 0.022$	$0.396 \pm 0.005 \pm 0.019$	$0.721 \pm 0.005 \pm 0.025$
A_{WW}	$0.161 \pm 0.001 \pm 0.008$	$0.089 \pm 0.001 \pm 0.005$	$0.082 \pm 0.001 \pm 0.004$
$A_{WW} \times C_{WW}$	$0.087 \pm 0.001 \pm 0.005$	$0.035 \pm 0.001 \pm 0.003$	$0.059 \pm 0.001 \pm 0.004$
$\sigma(pp \to WW)$ [pb]	$56.3 \pm 4.9 \pm 3.9 \pm 2.1$	$64.1 \pm 13.0 \pm 7.4 \pm 2.4$	$43.2 \pm 8.1 \pm 4.5 \pm 1.6$
σ_{fid} [fb]	$294 \pm 26 \pm 15 \pm 11$	$92.0 \pm 18.9 \pm 9.4 \pm 3.4$	$57.2 \pm 10.8 \pm 5.2 \pm 2.1$
$\sigma_{\text{fid}}^{\text{SM}}$ [fb]	230 ± 19	63.4 ± 5.3	59.0 ± 4.7

6. Cross section results

The WW cross section is measured in the fiducial phase space and extrapolated to the total phase space. The total cross section is defined in Eq. (1), while the fiducial cross section is

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bg}}}{\mathcal{L} C_{WW}}. \tag{2}$$

Uncertainties on the fiducial cross section measurement result from modeling lepton and jet efficiency, energy scale and resolution, and $E_{\text{T}}^{\text{miss}}$ (the first five rows of Table 3). Small uncertainties of 1.4% ($\mu\nu\mu\nu$ and $e\nu e\nu$ channels) and 0.5% ($e\nu\mu\nu$ channel) arise from the impact of QCD renormalization and factorization scale variations on lepton momenta (included in the sixth row of Table 3). Table 4 shows C_{WW} and the other components of the cross section measurements for each channel. The measurements are performed by minimizing a likelihood fit to the observed data with respect to the WW and background predictions for the three channels combined. The measured cross sections are consistent with the SM predictions, differing by $+1.7\sigma$ ($e\nu\mu\nu$ channel), $+1.3\sigma$ ($e\nu e\nu$ channel) and -0.1σ ($\mu\nu\mu\nu$ channel). Contributions from a hypothetical SM Higgs boson would be small: 2.9, 0.9, and 1.8 events in the $e\nu\mu\nu$, $e\nu e\nu$ and $\mu\nu\mu\nu$ channels, respectively, for a Higgs boson mass of 125 GeV.

The A_{WW} uncertainty comes from PDFs and scale variations affecting the lepton and jet veto acceptances (the last three rows of Table 3). The combined $A_{WW} \times C_{WW}$ and the total measured cross section in each channel are shown in Table 4. The contribution of leptons from tau decays is included. The channels are combined by maximizing a log likelihood, yielding

$$\sigma(pp \to WW)$$
$$= 54.4 \pm 4.0 \text{ (stat.)} \pm 3.9 \text{ (syst.)} \pm 2.0 \text{ (lumi.) pb},$$

to be compared with the NLO SM prediction of $\sigma(pp \to WW) = 44.4 \pm 2.8$ pb [16,22]. Fig. 2 shows the following distributions for data and MC: $E_{\text{T}}^{\text{miss}}$, transverse mass, the azimuthal angle between the charged leptons [$\Delta\phi(l,l)$], and the invariant mass of the charged leptons [$m_{\ell\ell}$]. The transverse mass is $m_{\text{T}}(llE_{\text{T}}^{\text{miss}}) = \sqrt{(p_{\text{T}}^{l_1} + p_{\text{T}}^{l_2} + E_{\text{T}}^{\text{miss}})^2 - \sum(p_i^{l_1} + p_i^{l_2} + E_i^{\text{miss}})^2}$, where the sum runs over the x and y coordinates and l_1 and l_2 refer to the two charged leptons.

7. Anomalous triple-gauge couplings

The s-channel production of WW events occurs via the triple-gauge couplings $WW\gamma$ and WWZ. Contributions to these couplings from new physics processes at a high energy scale would affect the measured cross section, particularly at high momentum transfer [26]. Below the energy scale of these new physics processes, an effective Lagrangian can be used to describe the effect of non-SM processes on the WWV ($V = \gamma, Z$) couplings. Assuming the dominant non-SM contributions conserve C and P, the general Lagrangian for WWV couplings is

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}, \tag{3}$$

where $g_{WW\gamma} = -e$, $g_{WWZ} = -e\cot\theta_W$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ and $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$. The SM couplings are $g_1^V = \kappa_V = 1$ and $\lambda_V = 0$. Individually, non-zero couplings lead to divergent cross sections at high $\sqrt{s}$, and non-SM values of the g_1^V or κ_V couplings break the gauge cancellation of processes at high momentum transfer. To regulate this behavior, a suppression factor depending on a scale Λ with the general form

$$\lambda(\hat{s}) = \frac{\lambda}{(1 + \hat{s}/\Lambda^2)^2} \tag{4}$$

is defined for λ, $\Delta g_1 \equiv g_1 - 1$ and $\Delta\kappa \equiv \kappa - 1$. Here, λ is the coupling value at low energy and $\sqrt{\hat{s}}$ is the invariant mass of the WW pair. The g_1^γ coupling is fixed to its SM value by electromagnetic gauge invariance.

To reduce the number of WWV coupling parameters, three specific scenarios are considered. The first is the "LEP scenario" [27,28], where anomalous couplings arise from dimension-6 operators and electroweak symmetry breaking occurs via a light SM Higgs boson. This leads to the relations

$$\Delta\kappa_\gamma = -\frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\Delta\kappa_Z - \Delta g_1^Z\right) \quad \text{and} \quad \lambda_\gamma = \lambda_Z, \tag{5}$$

leaving three free parameters (Δg_1^Z, $\Delta\kappa_Z$, λ_Z). The parameter space can be further reduced by requiring equal couplings of the $SU(2)$ and $U(1)$ gauge bosons to the Higgs boson in the dimension-6 operators. This adds the constraint $\Delta g_1^Z = \Delta\kappa_\gamma/(2\cos^2\theta_W)$ and is referred to as the "HISZ scenario" [27]. The third "Equal Coupling scenario" assumes common couplings for the WWZ and $WW\gamma$ vertices ($\Delta\kappa_Z = \Delta\kappa_\gamma$, $\lambda_Z = \lambda_\gamma$, $\Delta g_1^Z = \Delta g_1^\gamma = 0$).

The differential cross section as a function of the invariant mass of the WW pair is the most direct probe of anomalous couplings, particularly at high invariant mass. The mass cannot be fully reconstructed but is correlated with the momentum of the individual leptons. The p_{T} distribution of the highest-p_{T} charged lepton is therefore a sensitive probe of anomalous TGCs and is used in a binned likelihood fit to extract the values of the anomalous couplings preferred by the data (Fig. 3). The dependence of the distribution on specific anomalous couplings is modeled by reweighting the MC@NLO SM WW MC to the predictions of the BHO generator

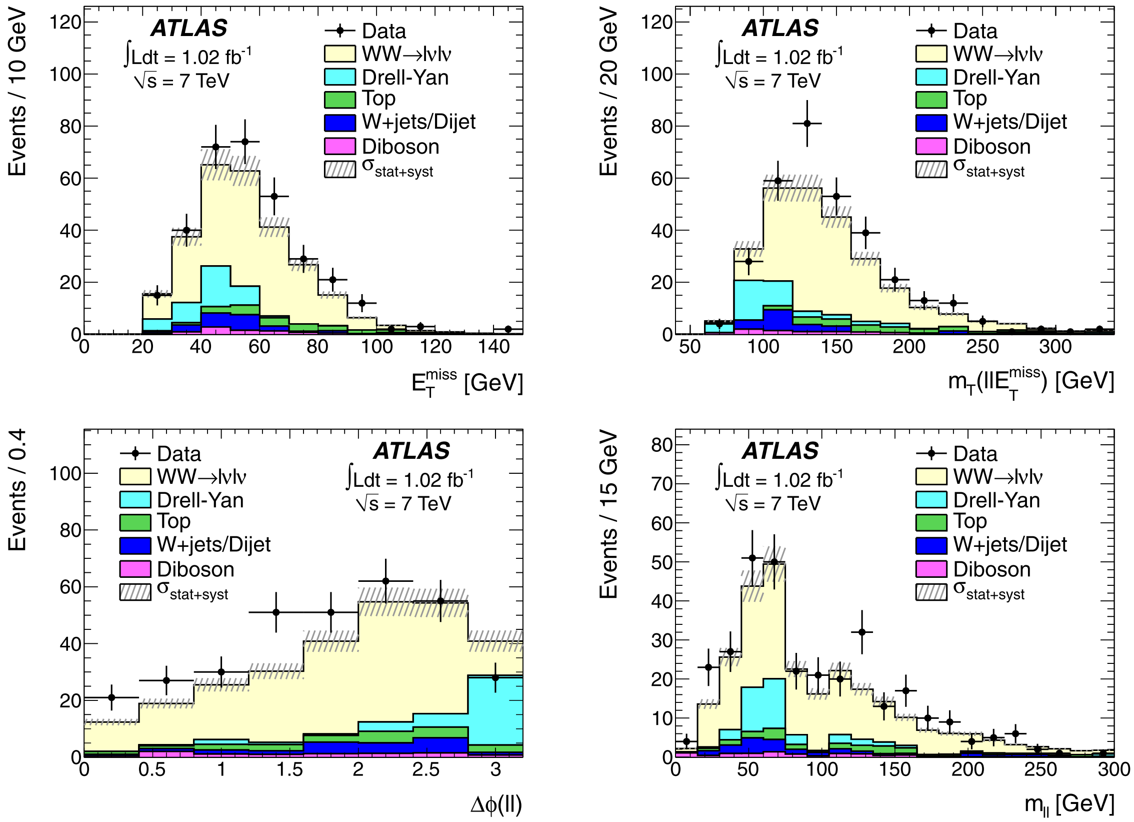

Fig. 2. The $E_{\mathrm{T}}^{\mathrm{miss}}$ (top left), m_{T} (top right), $\Delta\phi(l,l)$ (bottom left) and $m_{\ell\ell}$ (bottom right) distributions for the combined dilepton channels after all selection requirements. The data (dots) are compared to the expectation from WW and the backgrounds (histograms). The $W+$jet and dijet backgrounds are estimated using data. The hashed region shows the $\pm 1\sigma$ uncertainty band on the expectation.

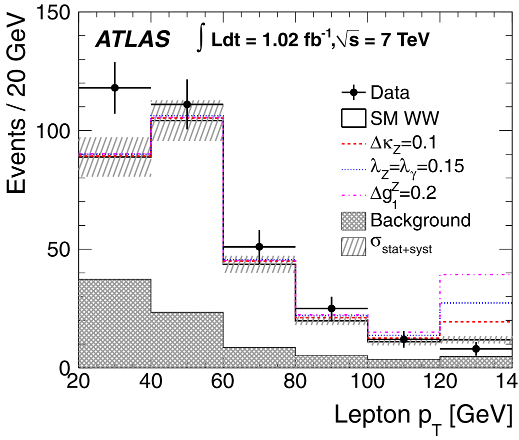

Fig. 3. The p_{T} distribution of the highest-p_{T} charged lepton in WW final states. Shown are the data (dots), the background (shaded histogram), SM WW plus background (solid histogram), and the following WW anomalous couplings added to the background: $\Delta\kappa_Z = 0.1$ (dashed histogram), $\lambda_Z = \lambda_\gamma = 0.15$ (dotted histogram), and $\Delta g_1^Z = 0.2$ (dash-dotted histogram). The last bin corresponds to $p_{\mathrm{T}} > 120$ GeV.

[29] at the matrix-element level. Fig. 3 demonstrates the sensitivity to anomalous TGCs at high lepton p_{T}; the coupling measurement is negligibly affected by the excess in the data at low p_{T}. The fiducial cross section is measured in the last bin of Fig. 3. The result $\sigma_{\mathrm{fid}}(p_{\mathrm{T}} \geqslant 120\ \mathrm{GeV}) = 5.6^{+5.4}_{-4.4}$ (stat.) ± 2.9 (syst.) ± 0.2 (lumi.) fb is consistent with the SM WW prediction of $\sigma_{\mathrm{fid}}(p_{\mathrm{T}} \geqslant 120\ \mathrm{GeV}) = 12.2 \pm 1.0$ fb.

Table 5 and Fig. 4 show the results of the coupling fits to one and two parameters respectively in the LEP scenario, with the other parameter(s) fixed by Eq. (5) or set to the SM value(s). One-dimensional limits on λ_Z in the HISZ and Equal Coupling scenarios are the same as in the LEP scenario. In the HISZ scenario, the 95% CL limits on $\Delta\kappa_Z$ are $[-0.049, 0.072]$ and $[-0.037, 0.069]$ for $\Lambda = 3$ TeV and $\Lambda = \infty$, respectively. The corresponding limits in the Equal Coupling scenario are $[-0.089, 0.096]$ and $[-0.065, 0.102]$, respectively.

Table 5
95% CL limits on anomalous TGCs in the LEP scenario assuming the other couplings not fixed in the scenario are set to their SM values.

Λ	Δg_1^Z	$\Delta\kappa_Z$	λ_Z
3 TeV	$[-0.064, 0.096]$	$[-0.100, 0.067]$	$[-0.090, 0.086]$
∞	$[-0.052, 0.082]$	$[-0.071, 0.071]$	$[-0.079, 0.077]$

The anomalous coupling limits in the LEP scenario are compared with limits obtained from CMS, CDF, D0 and the combined LEP results in Fig. 5. The sensitivity of this result is significantly greater than that of the Tevatron due to the higher center-of-mass energy and higher WW production cross section. It is also comparable to the combined results from LEP, which include data from four detectors and all WW decay channels.

8. Summary

Using 1.02 fb^{-1} of $\sqrt{s} = 7$ TeV pp data, the $pp \to WW$ cross section has been measured with the ATLAS detector in the fully leptonic decay channel. The measured total cross section of 54.4 ± 5.9 pb is consistent with the SM prediction of 44.4 ± 2.8 pb and is the most precise measurement to date. In addition, the first measurement of the WW cross section in a fiducial phase space region

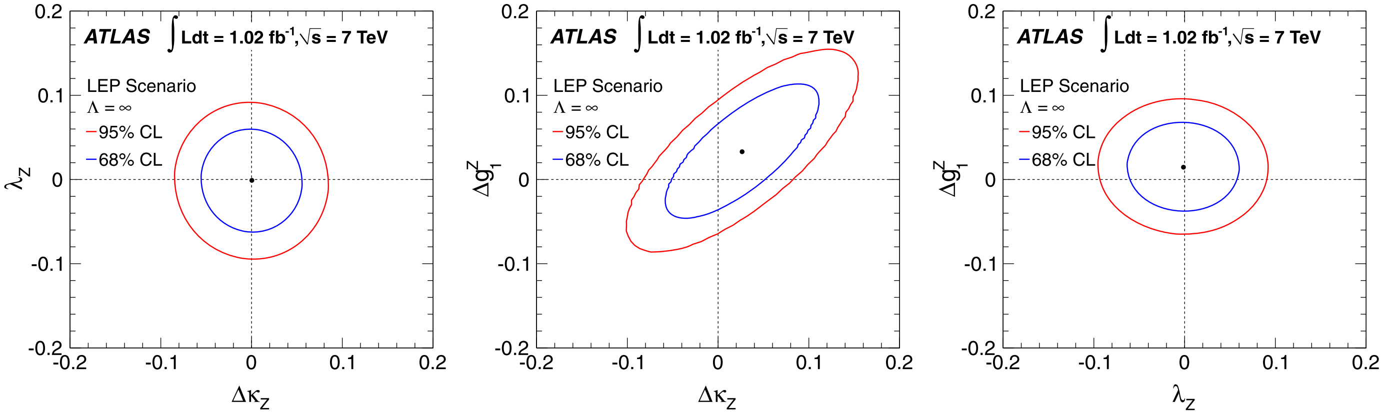

Fig. 4. Two-dimensional fits to the anomalous couplings in the LEP scenario: $\Delta\kappa_Z$ vs. λ_Z (left), $\Delta\kappa_Z$ vs. Δg_1^Z (middle), and λ_Z vs. Δg_1^Z (right). The inner (outer) ellipse encloses the 68% (95%) CL allowed region.

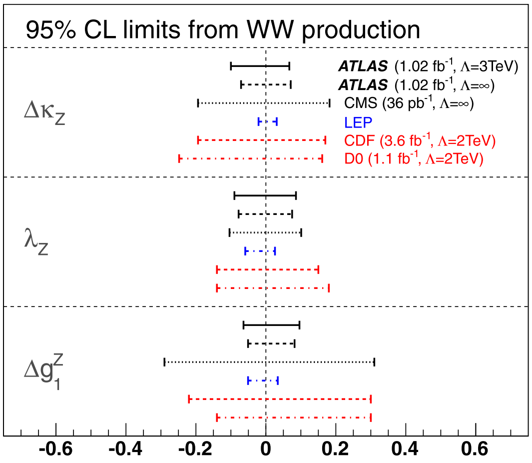

Fig. 5. Anomalous TGC limits from ATLAS, D0 and LEP (based on the LEP scenario) and CDF and CMS (based on the HISZ scenario), as obtained from WW production measurements.

has been presented. Limits on anomalous couplings have been derived in three scenarios using the p_T distribution of the leading charged lepton. No significant deviation is observed with respect to the SM prediction. These limits are competitive with previous results and are sensitive to a higher mass scale for new physical processes.

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