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ATLAS measurements of WW, WZ, and ZZ production

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Using data corresponding to 4.6-4.7 fb^{-1} of integrated luminosity from $\sqrt{s} = 7$ TeV pp collisions at the LHC, the ATLAS Collaboration has measured the production cross section of heavy dibosons (WW, WZ, and ZZ) in the fully leptonic decay channels. A first measurement of ZZ production at $\sqrt{s} = 8$ TeV with data corresponding to 5.8 fb^{-1} of integrated luminosity has also been performed. Differential cross sections are measured for WZ production, and limits are set on anomalous WWZ and $WW\gamma$ couplings.

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1. Introduction

The study of diboson production at the LHC probes the non-Abelian gauge couplings of the electroweak force at unprecedented energies. The significant cancellation of diagrams with and without such couplings in diboson production enhances sensitivity to these triple-gauge couplings. Furthermore, diboson final states are key signatures of Higgs boson production, and contributed significantly to the excess in the recent observation of a new boson at the LHC [1].

ATLAS [2] has performed a variety of measurements of WW, WZ, and ZZ production in data corresponding to 4.6-4.7 fb^{-1} (5.8 fb^{-1}) of integrated luminosity in $\sqrt{s} = 7$ (8) TeV pp collisions. The measurements yield the following results: (1) the inclusive and unfolded differential cross sections in well-defined fiducial regions; (2) the total cross section, extrapolated using a Monte Carlo model; and (3) limits on anomalous triple-gauge couplings, through kinematic fits.

The fiducial cross section σ_{fid} is defined as

$$\sigma_{fid} = \frac{N_{data} - N_{bg}}{\mathscr{L} C_{VV}}, \tag{1.1}$$

where N_{data} is the number of observed events, N_{bg} is the number of predicted background events, $\mathscr{L}$ is the integrated luminosity, and C_{VV} is the ratio of events measured to those produced in the fiducial region. The total cross section $\sigma(pp \to VV)$ is obtained by dividing by the fiducial acceptance A_{VV} and the branching ratio of the vector bosons VV to the measured final state particles.

To study gauge-boson self-couplings, the C- and P-conserving WWV terms in the Lagrangian are parameterized as

$$\mathscr{L}_{WWV} = ig_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}, \tag{1.2}$$

where the Standard Model (SM) parameter values are $g_1^{V,SM} = \kappa_V^{SM} = 1$ and $\lambda_V^{SM} = 0$. Any deviations would break SU(2)×U(1) gauge invariance, making the theory non-renormalizable. To restore gauge invariance at high energy, a suppression factor is frequently introduced:

$$\lambda(s) = \frac{\lambda}{(1 + s/\Lambda^2)^2}, \tag{1.3}$$

where Λ is the suppression scale. Similar equations hold for $\Delta g_1^V = g_1^V - g_1^{V,SM}$ and $\Delta\kappa_V = \kappa_V - \kappa_V^{SM}$.

2. Measurements of WW production

At next-to-leading order (NLO) in QCD, the inclusive SM $pp \to WW$ production cross section is 45.1 ± 2.8 pb [3] at $\sqrt{s} = 7$ TeV. Using data corresponding to 4.7 fb^{-1} of integrated luminosity, ATLAS has measured the cross section in the fully leptonic final states $e\nu\mu\nu$, $e\nu e\nu$, and $\mu\nu\mu\nu$, with additional neutrinos possible from decays of a W boson through a tau lepton and neutrino. In the selected fiducial regions, the expected cross sections are 237.4 ± 19.4 fb, 44.9 ± 3.7 fb, and 38.0 ± 3.1 fb, respectively. The fiducial regions are defined as

- $e\nu\mu\nu$: $p_{T,Rel}^{\nu} > 25$ GeV and $m_{e\mu} > 10$ GeV;

Decay channel	N_{data}	N_{bg}	σ_{fid} (fb)	$\sigma(pp \to WW)$ (pb)
$e\nu\mu\nu$	1041	303 ± 35	$284.9 \pm 12.7 \pm 14.1 \pm 11.1$	$54.3 \pm 2.4 \pm 4.4 \pm 2.1$
$e\nu e\nu$	196	114 ± 14	$41.4 \pm 6.5 \pm 5.7 \pm 1.6$	$41.5 \pm 6.5 \pm 7.8 \pm 1.6$
$\mu\nu\mu\nu$	287	113 ± 10	$48.2 \pm 4.6 \pm 3.8 \pm 1.9$	$57.3 \pm 5.5 \pm 5.4 \pm 2.2$

Table 1: The observed numbers of data events (N_{data}), expected background events (N_{bg}), measured cross sections in the fiducial regions (σ_{fid}), and total cross section measured in each decay channel [$\sigma(pp \to WW)$]. The uncertainties on the cross sections are due to, in order: statistics, systematic uncertainties, and the uncertainty on the luminosity [3].

- $e\nu e\nu$: $p^{\nu}_{T,Rel} > 50$ GeV, $m_{ee} > 15$ GeV and $|m_{ee} - m_Z| > 15$ GeV; and
- $\mu\nu\mu\nu$: $p^{\nu}_{T,Rel} > 55$ GeV, $m_{\mu\mu} > 15$ GeV and $|m_{\mu\mu} - m_Z| > 15$ GeV;

where $p^{\nu}_{T,Rel}$ is the transverse component of the sum of the neutrino momenta ($|\vec{p}^{\,\nu}_T|$), multiplied by the sine of the smallest $\Delta\phi(\vec{p}^{\,l}_T, \vec{p}^{\,\nu}_T)$ when $\Delta\phi < \pi/2$ [3]. The fiducial regions are exclusive of jets: no jet can have $p_T > 25$ GeV (or $p_T > 20$ GeV if it contains a b-hadron), $|\eta| < 4.5$, and $\Delta R(e,\text{jet}) > 0.3$. Fiducial muons have $p_T > 20$ GeV (or $p_T > 25$ for the highest p_T muon in the $\mu\nu\mu\nu$ final state) and $|\eta| < 2.4$. Fiducial electrons have $p_T > 20$ GeV and either $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. In the definition of charged lepton p_T, photons within $\Delta R = 0.1$ are added to the momentum of the charged lepton to mimic the effect of electron reconstruction in the detector.

Table 1 shows the WW measurements in each decay channel. The total cross section is determined by dividing the fiducial cross section by A_{WW} and the branching ratio for each W boson to decay to an electron or muon and at least one neutrino (including decays through tau leptons). Combining the results gives a measured inclusive cross section of

$$\sigma(pp \to WW) = 53.4 \pm 2.1\ (\text{stat}) \pm 4.5\ (\text{sys}) \pm 2.1\ (\text{lum})\ \text{pb}. \tag{2.1}$$

The 10.1% relative uncertainty is dominated by the systematic uncertainty of 8.4%, which receives roughly equal contributions from signal modelling (6.7%) and background estimation (5.1%).

Using data corresponding to 1 fb^{-1} of integrated luminosity [4], ATLAS has fit the spectrum of the leading lepton p_T as a function of anomalous triple-gauge coupling values. This spectrum and the best-fit values are shown in Fig. 1. For comparison, the figure shows anomalous-coupling measurements from D0 and LEP using $\sqrt{s} = 1.96$ TeV $p\bar{p}$ and $\sqrt{s} \leq 209$ GeV e^+e^- collision data, respectively. The ATLAS, D0 and LEP results are shown for the LEP coupling scenario, which has three free parameters Δg^Z_1, $\Delta\kappa_Z$, and λ_Z, and three relations $\Delta g^{\gamma}_1 = 0$, $\lambda_{\gamma} = \lambda_Z$, and $\Delta\kappa_{\gamma} = -\cot^2\theta_W(\Delta\kappa_Z - \Delta g^Z_1)$. Additionally, Fig. 1 shows results from CMS and CDF in the HISZ scenario, which adds the constraint $\Delta g^Z_1 = \Delta\kappa_{\gamma}/(2\cos^2\theta_W)$. Not shown are ATLAS results [4] in the HISZ scenario and in the Equal Couplings scenario where WWZ and $WW\gamma$ vertices have equal anomalous couplings: $\Delta\kappa_Z = \Delta\kappa_{\gamma}$ and $\lambda_Z = \lambda_{\gamma}$.

3. Measurements of WZ production

The study of WZ production probes the WWZ coupling with negligible contribution from the $WW\gamma$ vertex. For $66 < m_Z < 116$ GeV, the inclusive $pp \to WZ$ production cross section in the SM

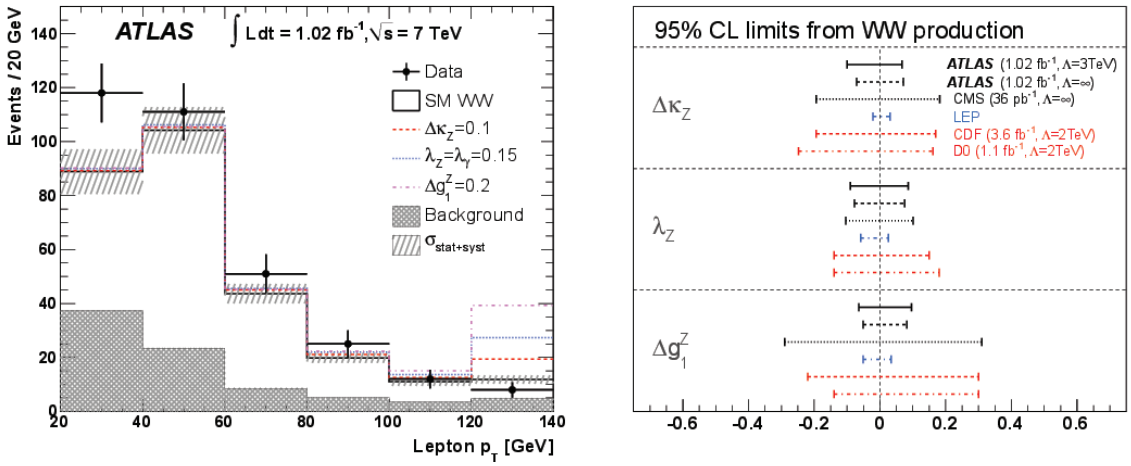

Figure 1: Left: The reconstructed p_T of the highest p_T charged lepton. Shown are the data (points), the SM contribution (solid histogram) and various anomalous coupling scenarios (other open histograms). Right: The best-fit values of the anomalous couplings in the LEP coupling scenario (ATLAS, D0, and LEP) and the HISZ coupling scenario (CMS, CDF), for various values of the suppression scale Λ [4].

is $17.6^{+1.1}_{-1.0}$ pb [5], about a factor of three lower than $\sigma(pp \to WW)$. The branching ratio for $Z \to ll$ is another factor of three lower than $W \to l\nu$; however, the presence of three charged leptons in the WZ final state results in lower backgrounds, allowing a more inclusive selection with higher acceptance.

Using data corresponding to 4.6 fb^{-1} of luminosity, ATLAS has observed 317 candidates for WZ decay to $lll\nu$, where l is an electron or muon. With 68 ± 8 expected background events, the sample is nearly 80% pure. In the fiducial phase space of the combined channels,

- $p_T^l > 15$ GeV and $|m_{ll} - m_Z| < 10$ GeV for the candidate leptons from the Z boson decay,
- $p_T^l > 20$ GeV and $M_T^{l\nu} > 20$ GeV for the charged lepton candidate from the W boson decay,
- $p_T^\nu > 25$ GeV, and
- $|\eta^l| < 2.5$,

the cross section is measured to be

$$\sigma_{WZ}^{fid} = 92^{+7}_{-6}\,(\text{stat}) \pm 4\,(\text{sys}) \pm 2\,(\text{lum})\ \text{fb}. \tag{3.1}$$

All charged leptons are required to be $\Delta R > 0.3$ from each other; the measurement is inclusive in jets. Figure 2 shows the differential fiducial measurements of the Z boson candidate p_T and the mass of the WZ system, after subtracting backgrounds and unfolding detector effects. Extrapolating to the total inclusive cross section gives

$$\sigma(pp \to WZ) = 19.0^{+1.4}_{-1.3}\,(\text{stat}) \pm 0.9\,(\text{sys}) \pm 0.4\,(\text{lum})\ \text{pb}. \tag{3.2}$$

To test the predicted triple-gauge couplings of the SM, the p_T^Z distribution is fit as a function of anomalous coupling values. Figure 3 shows this distribution and the results of the fit, with comparisons to results from CDF and D0.

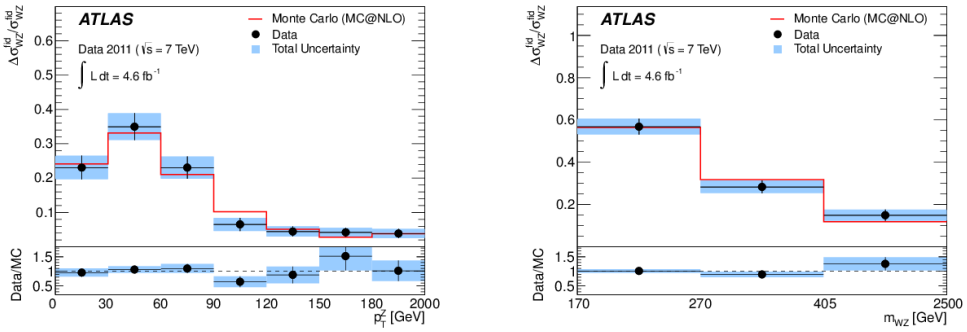

Figure 2: Left: The p_T of the Z boson candidate. Right: The invariant mass of the WZ system. Both distributions are shown after subtracting backgrounds and unfolding detector effects [5].

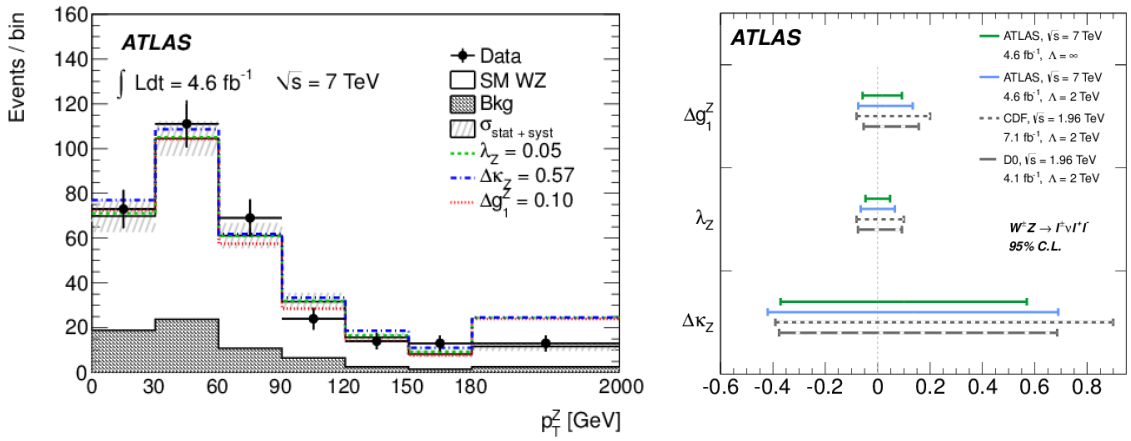

Figure 3: Left: The p_T of the Z boson candidate in the SM and in models with various anomalous couplings. Right: Anomalous coupling results using WZ measurements at ATLAS, CDF, and D0 [5].

4. Measurements of ZZ production

Production of ZZ occurs through gauge-boson couplings to fermions only, as there are no triple-gauge neutral couplings in the SM. The cross section prediction is $6.5^{+0.3}_{-0.2}$ pb at $\sqrt{s} = 7$ TeV for on-shell Z bosons. At $\sqrt{s} = 8$ TeV, the predicted cross section is 7.4 ± 0.4 pb for $66 < m_Z < 116$ GeV. ATLAS has measured the ZZ production cross section using final states with four charged leptons at both energies, and final states with two charged leptons and neutrinos at $\sqrt{s} = 7$ TeV.

In final states with neutrinos, the cross section is measured in the following fiducial region [6]:

- $|m_{ll} - m_Z| < 15$ GeV;
- $-p_T^{\nu\nu} \times \cos(\Delta\phi) > 80$ GeV, where the angle is between $\vec{p}_T^{\,\nu\nu}$ and $\vec{p}_T^{\,ll}$;
- $(p_T^{\nu\nu} - p_T^Z)/p_T^Z < 0.6$;
- $p_T^l > 20$ GeV and $|\eta_l| < 2.5$; and
- no jet with $p_T > 25$ GeV, $|\eta| < 4.5$, and $\Delta R(e,\text{jet}) > 0.3$;

where $\vec{p}_T^{\nu\nu}$ ($\vec{p}_T^{ll}$) is the transverse component of the sum of the neutrino (charged-lepton) momenta and $p_T^{\nu\nu}(p_T^Z)$ is its magnitude. In the final states with electrons or muons, 78 events are observed. Subtracting the background of $40.7 \pm 4.3 \pm 3.7$ events and dividing by the luminosity (4.7 fb^{-1}) and correction factor C_{ZZ}, the fiducial cross section is measured to be

$$\sigma^{fid}_{ZZ\to ll\nu\nu} = 12.2^{+3.0}_{-2.8}\ (\text{stat}) \pm 1.9\ (\text{sys}) \pm 0.5\ (\text{lum})\ \text{fb}. \tag{4.1}$$

Extrapolating the measurement to the total cross section gives

$$\sigma(pp \to ZZ) = 5.4^{+1.3}_{-1.2}\ (\text{stat})^{+1.4}_{-1.0}\ (\text{sys}) \pm 0.2\ (\text{lum})\ \text{pb}. \tag{4.2}$$

The four-lepton final state provides the highest purity sample of dibosons. In data corresponding to 4.7 fb^{-1} of luminosity from $\sqrt{s} = 7$ TeV pp collisions, 62 candidate events are observed with < 1 expected background event. The fiducial measurement region is defined by the presence of two pairs of same-flavor opposite-charge leptons (e or μ) with invariant mass in the 66-116 GeV range. Fiducial leptons have $p_T > 7$ GeV and $|\eta| < 2.7$. The measured fiducial cross section is

$$\sigma^{fid}_{ZZ\to llll} = 21.2^{+3.2}_{-2.7}\ (\text{stat}) \pm^{+1.0}_{-0.9}\ (\text{sys}) \pm 0.8\ (\text{lum})\ \text{fb}. \tag{4.3}$$

A similar measurement has been performed in $\sqrt{s} = 8$ TeV data corresponding to 5.8 fb^{-1} of integrated luminosity [8]. Defining fiducial leptons to have $p_T > 15$ GeV and $|\eta| < 2.5$, ATLAS observes 85 candidate events with a background of 1.3 ± 1.3. The resulting cross section is

$$\sigma^{fid}_{ZZ\to llll} = 21.0^{+2.4}_{-2.2}\ (\text{stat})^{+0.6}_{-0.5}\ (\text{sys}) \pm 0.8\ (\text{lum})\ \text{fb}. \tag{4.4}$$

Extrapolating the four-lepton measurements to total cross sections gives

$$\sigma(pp \to ZZ) = 7.2^{+1.1}_{-0.9}\ (\text{stat})^{+0.4}_{-0.3}\ (\text{sys}) \pm 0.3\ (\text{lum})\ \text{pb}\ (\sqrt{s} = 7\ \text{TeV})\ \text{and} \tag{4.5}$$

$$\sigma(pp \to ZZ) = 9.3^{+1.1}_{-1.0}\ (\text{stat})^{+0.4}_{-0.3}\ (\text{sys}) \pm 0.3\ (\text{lum})\ \text{pb}\ (\sqrt{s} = 8\ \text{TeV}). \tag{4.6}$$

5. Summary

ATLAS has measured diboson cross sections using the full $\sqrt{s} = 7$ TeV data set in the leptonic decay channels. The first diboson unfolded differential fiducial cross sections have been measured in WZ production. Fits to the leading lepton p_T in WW candidate data and to p_T^Z in WZ candidate data have resulted in significant constraints on anomalous triple-gauge couplings. Finally, the first ATLAS diboson measurement at $\sqrt{s} = 8$ TeV has been performed.

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