

Electroweak physics at the LHC

J Berryhill¹ and A Oh²

¹ Fermi National Accelerator Laboratory, Batavia, IL, USA

² School of Physics and Astronomy, University of Manchester, Manchester, UK

Abstract. The Large Hadron Collider (LHC) has completed in 2012 its first running phase and the experiments have collected data sets of proton-proton collisions at center-of-mass energies of 7 and 8 TeV with an integrated luminosity of about 5 and 20 fb⁻¹, respectively. Analyses of these data sets have produced a rich set of results in the electroweak sector of the standard model. This article reviews the status of electroweak measurements of the ATLAS, CMS and LHCb experiments at the LHC.

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1. Introduction

With the discovery of the Higgs boson in 2012 [1, 2] the standard model of particle physics seemed complete, but fundamental questions remain to be answered, including the constituents of dark matter, the relative abundance of matter over anti-matter, and the unification of forces at the Planck scale.

The standard model of the electroweak interactions is a quantum field theory unifying the electromagnetic and the weak force into one gauge theory transforming under the gauge group $SU_L(2) \otimes U_{EM}(1)$. The electroweak Lagrangian can be represented as

$$\mathcal{L}_{EW} = \mathcal{L}_{boson} + \mathcal{L}_{fermion} + \mathcal{L}_{higgs} + \mathcal{L}_{yukawa}$$

with \mathcal{L}_{boson} the kinetic and self-interaction term of bosons, $\mathcal{L}_{fermion}$ the kinetic term describing the interaction of fermions with bosons, \mathcal{L}_{higgs} the Higgs term which generates the gauge boson masses and coupling to the Higgs field, and the Yukawa term \mathcal{L}_{yukawa} describing the interaction between the fermion and Higgs field. Precision measurements in the electroweak sector allow to test the plausibility of various extensions to the standard model Lagrangian. In the framework of anomalous gauge couplings and its reformulation as effective field theory, the standard model can be extended with additional generic terms in the Lagrangian to describe new physics. The measurement of electroweak production processes allows to verify the validity of the standard model in this framework at the high collision energies the Large Hadron Collider (LHC) is providing.

The LHC was designed to primarily search for the Higgs boson and new phenomena, but the requirements of proton-proton collisions at high collision energy and luminosity also enable precision electroweak measurements. The LHC provides a rich testing ground to benchmark perturbative QCD over a wide range of scales, and to determine the structure of the proton. Both are essential ingredients to make precise electroweak measurements, as higher order corrections in perturbative QCD have a substantial effect on the theoretical predictions to standard model processes, and the knowledge of the proton structure becomes a major uncertainty for processes with very high partonic center-of-mass, i.e. the region where new physics is expected to become visible.

The LHC collides protons on protons in a circular ring of 27 km circumference with an energy of up to 7 TeV per beam, corresponding to a collision energy at the center-of-mass of $\sqrt{s} = 14$ TeV, and a design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The two general purpose detectors at the LHC, ATLAS and CMS, are able to record a wide range of physics process. They differ in the technical details of detector layout and data-acquisition design but have common design goals, namely good detector coverage for charged and neutral particles, excellent resolution to measure the positions and momenta of charged particles, and precision calorimetry. The other two main experiments at the LHC are optimized for recording collision of heavy ions in the case of ALICE or for precision measurements of b-hadrons and CP violation (LHC-b).

In the run period from 2010 to 2011 about 6 fb^{-1} of integrated luminosity at a center-of-mass energy $\sqrt{s} = 7 \text{ TeV}$ were delivered. In 2012 the energy was raised to $\sqrt{s} = 8 \text{ TeV}$ and the integrated luminosity produced was 23 fb^{-1} . After a long shutdown LHC resumed running in 2015 at an increased energy of $\sqrt{s} = 13 \text{ TeV}$, and was able to provide 4.5 fb^{-1} of collision data. The experiments ATLAS and CMS have published results on all three data sets, but the majority of electroweak results available up to now are based mainly on the 7 TeV data set and to some extent on the 8 TeV data sets. Generally, the precision measurements of cross section and differential distributions involve more analysis effort compared to e.g. searches for new resonances, hence the different time-scale for this category of measurements.

In the following we will give a brief review of recent theory developments (section 2), and a comprehensive summary of the electroweak results from ATLAS and CMS. In section 3 we summarise the results on inclusive vector boson production (Drell-Yan process, inclusive di-boson and tri-boson production), and continue in section 4 with exclusive boson production in the vector boson fusion and vector boson scattering processes. Finally, the LHC results on electroweak precision tests are discussed in section 5.

2. Theory overview and recent developments

We confine discussion of results in this review to experimental tests at the LHC which directly and uniquely test the electroweak interactions of the known standard model particles, excluding the Higgs boson. A simple but general framework to study those interactions is through effective field theory extensions of the standard model which respect the standard model $SU_C(3) \otimes SU_L(2) \otimes U_{EM}(1)$ symmetry [3, 4, 5]. These extensions can be generally written in an operator product expansion (OPE)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^{2n}} \mathcal{O}_i + \dots$$

where c_i are dimensionless coefficients, Λ is some energy scale corresponding to the scale of new physics, and \mathcal{O}_i are operators constructed from standard model fields. In principle, given an ultraviolet-complete theory of new physics with possibly new particle content, the c_i at the electroweak scale are calculable and can be compared with the observed experimental footprint. In the context of electroweak studies, especially for the study of gauge-boson self-interactions, this is often restricted to CP -even operators of mass dimension six (the lowest allowable). In that case, there are only three independent operators with three independently measurable Wilson coefficients. The precise definition of the independent coefficients depends upon the basis chosen to express the operators. The most common contemporary convention is the LEP basis, for which the coefficients are labeled $c_{WW\gamma}$, c_W , and c_B [6, 7], which correspond to combinations of $WW\gamma$ and WWZ interactions. Prior to the most recent Run 1 results, these same operators (up to a simple linear combination) were constrained via

dimensionless couplings, known as λ , κ , and g_1 ; these can be easily translated into the Wilson coefficients c_i by a linear transformation [7]. By measuring total or differential cross sections of processes which isolate triple gauge boson self-interactions (TGCs), predictions from the EFT can be compared to the data and allow for bounding the values of the coefficients, typically expressed as the dimensionful ratio c_i/Λ^2 .

In understanding all of the conceivable quartic gauge boson interactions (QGCs), it is useful to also consider EFTs for which dimension 6 operators are suppressed, and the leading order OPE has terms of mass dimension 8, with dimensionful coefficients c_i/Λ^4 . Dimension 8 theories have up to 19 independent gauge boson self-interaction operators, including the following quartic combinations: $WWWW$, $WWZZ$, $WWZ\gamma$, $WW\gamma\gamma$, as well as non-SM interactions $ZZZZ$, $ZZZ\gamma$, $ZZ\gamma\gamma$, and $Z\gamma\gamma\gamma$ [8, 9].

Not all c_i/Λ^n give rise to unitary or perturbatively calculable field theories, therefore care must be taken to specify, for each experimental observable, which range is applicable. Alternatively, different unitarization procedures can be adopted: an energy cutoff on the cross section, a form factor which moderates the high-energy behavior (usually of the form $(1 + q^2/\Lambda^2)^{-2}$), or a K -matrix unitarization procedure [10, 11]. In general, the Run 1 data on dimension-6 EFTs do not explore the range of coefficients and energies which would escape unitarity bounds, in which case the bare results have a straightforward interpretation. It is typical, however, for dimension-8 EFTs to violate unitarity at the Run 1 LHC energies and sensitivities, so the details of unitarization are critical in presenting and interpreting those results.

Another framework for testing the electroweak theory is through global fits of the SM electroweak parameters to the high-precision electroweak data available in W and Z production. Poor goodness-of-fit for one or more precision observables is indicative of new electroweak interactions at the loop level contributing to electroweak boson production and decay; these constraints can also be translated into bounds on EFT coefficients [12]. The most recent global fits [13, 14] include, among others, the LEP and SLD precision data in Z production, the Tevatron measurement of the W mass, and the high-precision measurements of the top quark and Higgs boson masses at the LHC. These fits generally predict values for the W mass and weak-mixing angle $\sin^2 \theta_W^{eff}$ more accurate than have been directly obtained, providing an opportunity at the LHC to over-constrain the global fit further.

Improving upon either of these frameworks for electroweak model parameters at the LHC is only possible with state-of-the-art understanding of perturbative QCD, parton distribution functions (PDF), and electroweak radiative corrections. In general, for Run 1 LHC results multiboson production has been studied with next-to-leading order (NLO) QCD matrix elements combined with parton showering to provide a particle-level simulation and some emulation of higher-order radiative and non-perturbative corrections. The PDFs and underlying event modelling typically include the LHC data themselves. For precision single boson production next-to-next-to-leading order (NNLO) calculations were used, along with NLO electroweak radiative corrections. The LHC data typically improve upon contemporary PDFs in this domain, motivating precision

measurement of boson production to constrain them further. In the future, multiboson and vector-boson scattering studies will require NNLO QCD and NLO electroweak matrix elements, as well as parton-shower matching, and PDFs consistently provided at that order including all of the Run 1 LHC data, as the Run 1 data are already precise enough to be sensitive to these effects in some areas [15].

3. Inclusive boson production

3.1. Drell-Yan production

At a hadron collider, the most fundamental tests of electroweak boson couplings to fermions are measurements of the kinematic properties of Drell-Yan (DY) lepton pair production. At leading order, Drell-Yan production occurs when a quark–anti-quark pair in the initial state annihilates into an electroweak boson, which subsequently decays to a lepton pair. Differential cross section calculations exist for next-to-next-to leading order (NNLO) QCD corrections as well as NLO electroweak corrections. In the EFT context, such a process is sensitive to four-fermion contact interactions of the type

$$\begin{aligned} \mathcal{L} = \frac{g^2}{\Lambda^2} [& \eta_{LL} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_L \gamma^\mu \ell_L) \\ & + \eta_{RR} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_R \gamma^\mu \ell_R) \\ & + \eta_{LR} (\bar{q}_L \gamma_\mu q_L) (\bar{\ell}_R \gamma^\mu \ell_R) \\ & + \eta_{RL} (\bar{q}_R \gamma_\mu q_R) (\bar{\ell}_L \gamma^\mu \ell_L)] , \end{aligned} \quad (1)$$

where g is a coupling constant, Λ is the contact interaction scale, and $q_{L,R}$ and $\ell_{L,R}$ are left-handed and right-handed quark and lepton fields, respectively. The parameters $\eta_{i,j}$ denote the relative interference of the operators; the experiments have considered the cases $\eta_{LR} = \eta_{RL} = \pm 1$, $\eta_{LL} = \pm 1$, or $\eta_{RR} = \pm 1$.

Experiments select electron or muon pairs above trigger thresholds: CMS selects leading lepton $p_T > 17$ GeV and second leading lepton $p_T > 8$ GeV inclusively, and ATLAS selects high mass events with both lepton $p_T > 25$ GeV. Backgrounds to Drell-Yan production are relatively small, and consist of real prompt lepton pair production from top quark or boson pairs, as well as fake electrons from QCD jets. The real lepton pair background is flavor democratic, and can therefore be reliably estimated from $e\mu$ pair production. Fake electron production is typically estimated from background enriched QCD jet samples, from which the fake electron rate can be measured, convolved with electron-jet control samples.

Figure 1 shows the Drell-Yan cross section at high electron pair mass measured by ATLAS at 7 TeV [16]. The cross section uncertainty is predominantly systematic below 400 GeV in pair mass and predominantly statistical above 400 GeV. The data are compared with an NNLO QCD prediction with NLO electroweak corrections, provided by the FEWZ 3.1 generator [17, 18, 19]. The prediction also includes photon induced lepton pair production, which generally increases cross section estimates by a few percent. The FEWZ prediction generally underestimates the cross section, however a correlated chi-squared analysis concludes that this is not statistically significant.

Figure 2 shows the Drell-Yan cross section for electron or muon pairs measured by CMS at 8 TeV [20]. Agreement with the FEWZ prediction is observed over the entire measured mass range, from 15 GeV to 2000 GeV. CMS has also measured the double differential cross section with respect to dilepton rapidity in several bins of dilepton mass, as well as a differential cross section ratio between the 8 TeV and 7 TeV data, which has small experimental and theoretical uncertainties.

In the absence of observed disagreements with predictions at the highest dilepton masses, the data are analyzed to constrain the size of anomalous contact interactions. Assuming a fixed, strong value for the coupling ($g^2/4\pi = 1$), limits can be obtained on the contact interaction scale Λ . ATLAS estimates a lower limit of 17 to 26 TeV on Λ , where the strongest lower limits correspond to constructive interference scenarios (especially LR+RL), and the weakest to destructive interference scenarios [21]. CMS has limits with similar sensitivity estimated for LL contact interactions [22].

3.2. Inclusive di-boson production

3.2.1. ZZ production The production of ZZ in proton-proton collisions has been one of the first di-boson processes measured at the LHC. The SM process is an important and irreducible background to resonance searches and Higgs production. The production at leading order is dominated by quark anti-quark annihilation in the t and u -channel, whereas the s -channel process is forbidden in the SM (see Figure 3). The gluon fusion process contributes about 6% to the total production cross section.

Precision measurements use the leptonic decay modes of the Z to reduce the impact of the QCD background. The four lepton final state provides an almost background free signature, at the expense of a relatively small branching ratio $\mathcal{B}(ZZ) \rightarrow \ell^+\ell^-\ell^+\ell^- = 0.101^2 \cdot \frac{4}{9} = 0.0045$ [24]. The di-lepton and missing energy channel can exploit the one order-of-magnitude higher branching ratio of $\mathcal{B}(ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}) = 0.101 \cdot 0.20 \cdot 2 \cdot \frac{2}{3} = 0.0269$, but has also relatively large backgrounds.

The ATLAS collaboration has published results on the 7 TeV data-set in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final state [25], and at 13 TeV in the $\ell^+\ell^-\ell^+\ell^-$ final state [26]. The CMS collaboration has analysed the full 7 and 8 TeV data sets in both the $\ell^+\ell^-\ell^+\ell^-$ [27, 28] and $\ell^+\ell^-\nu\bar{\nu}$ final state [29]. Theoretical predictions for ZZ production are available at NLO [30] and NNLO in α_s [31]. In addition, electroweak corrections at NLO have been calculated [32, 33].

The event selection for the $\ell^+\ell^-\ell^+\ell^-$ final state requires exactly four leptons fulfilling a set of cuts on kinematic quantities. While ATLAS uses $l = e, \mu$, CMS includes also $Z \rightarrow \tau^+\tau^-$ with subsequent hadronic and leptonic τ decays. ATLAS uses in addition forward leptons outside the ID tracker to increase the acceptance by 6% for electrons and 10% for muons. The $\ell^+\ell^-\ell^+\ell^-$ channels offers the cleanest event sample with a background level of only 2 – 3% from $Z + jets$, $\gamma\gamma$, and di-boson events. The background is estimated from data in control regions with looser selection criteria.

Events in the $\ell^+\ell^-\nu\bar{\nu}$ final state are characterized by exactly two leptons and missing

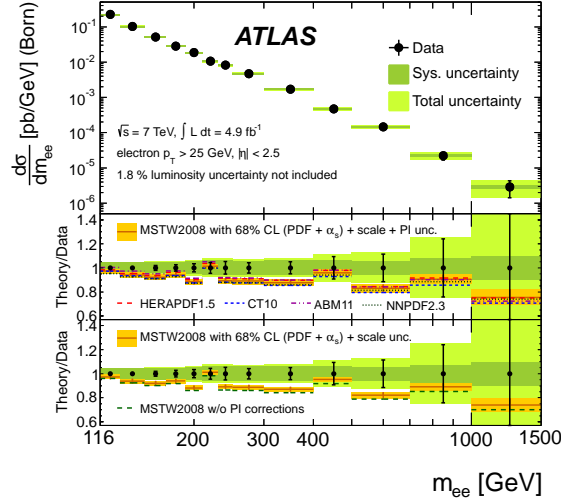


Figure 1. Measured differential cross-section at the Born level within the fiducial region (electron $p_T > 25$ GeV and $|\eta| < 2.5$) with statistical, systematic, and combined statistical and systematic (total) uncertainties, excluding the 1.8% uncertainty on the luminosity from ATLAS [16]. In the upper ratio plot, the photon-induced (PI) corrections have been added to the predictions obtained from the MSTW2008, HERAPDF1.5, CT10, ABM11 and NNPDF2.3 NNLO PDFs, and for the MSTW2008 prediction the total uncertainty band arising from the PDF, α_s , renormalisation and factorization scale, and photon-induced uncertainties is drawn. The lower ratio plot shows the influence of the photon-induced corrections on the MSTW2008 prediction, the uncertainty band including only the PDF, α_s and scale uncertainties.

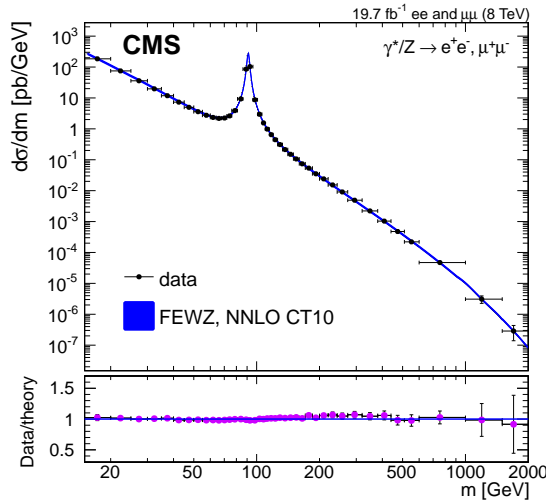


Figure 2. The DY differential cross section as measured by CMS [20] in the combined dilepton channel and as predicted by NNLO FEWZ 3.1 with CT10 PDF calculations, for the full phase space.

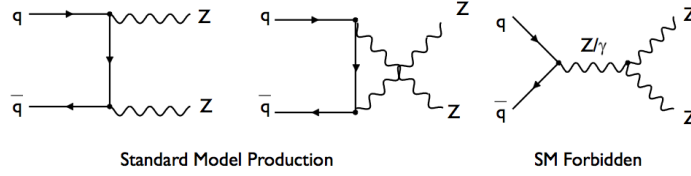


Figure 3. Leading order Feynman diagrams of ZZ production in the dominant $q\bar{q}$ channel [23]. The production of ZZ via the s -channel is forbidden in the SM.

energy. The event selection requires a $Z \rightarrow \ell^+\ell^-$ candidate and missing energy in the event. Both experiments use refined observables of missing energy with additional information to improve the rejection against instrumental background. The background level is of the same order as the signal and substantially higher than for the $\ell^+\ell^-\ell^+\ell^-$ channel. Main background sources are $V + jets$, and di-boson production. ATLAS and CMS use data driven techniques to constrain the dominant background sources.

Besides the total cross section for the $pp \rightarrow ZZ$ production process, both experiments measure also fiducial and differential cross sections. The results are summarized in Table 1. ATLAS and CMS use different definitions of the fiducial phase thus a direct comparison is not possible. For the total cross section definition the two experiments differ slightly in the Z mass range, where CMS prefers a wider range of $60 \text{ GeV} < m_Z < 120 \text{ GeV}$ than ATLAS with $66 \text{ GeV} < m_Z < 116 \text{ GeV}$. This difference contributes to the variation in the quoted predicted cross section. Good agreement between experimental and theoretical cross section values is observed in both ATLAS and CMS analyses.

Experiment	decay channel	\sqrt{s} [TeV]	measured σ_{total} [pb]	predicted σ_{total} [pb]	reference
ATLAS	$\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-\nu\bar{\nu}$	7	6.7 ± 0.7 (stat.) $^{+0.4}_{-0.3}$ (syst.) ± 0.3 (lumi.)	$6.18^{+0.25}_{-0.18}$	[25]
CMS	$\ell^+\ell^-\ell^+\ell^-$	7	$6.2^{+0.9}_{-0.8}$ (stat.) $^{+0.4}_{-0.3}$ (syst.) ± 0.1 (lumi.)	6.3 ± 0.4	[27]
CMS	$\ell^+\ell^-\nu\bar{\nu}$	7	$5.2^{+1.5}_{-1.4}$ (stat.) $^{+1.4}_{-1.1}$ (syst.) ± 0.2 (lumi.)	6.1 ± 0.3	[27]
CMS	$\ell^+\ell^-\ell^+\ell^-$	8	7.7 ± 0.5 (stat.) $^{+0.5}_{-0.4}$ (syst.) ± 0.2 (lumi.)	7.7 ± 0.6	[28]
CMS	$\ell^+\ell^-\nu\bar{\nu}$	8	6.9 ± 0.8 (stat.) $^{+1.8}_{-1.4}$ (syst.) ± 0.3 (lumi.)	7.6 ± 0.3	[27]
ATLAS	$\ell^+\ell^-\ell^+\ell^-$	13	$16.7^{+2.2}_{-2.0}$ (stat.) $^{+0.9}_{-0.7}$ (syst.) $^{+1.0}_{-0.7}$ (lumi.)	$15.6^{+0.4}_{-0.4}$	[26]

Table 1. Summary of measured ZZ production cross sections from ATLAS and CMS at 7, 8 and 13 TeV center-of-mass energies in the four lepton and $\ell^+\ell^-\nu\bar{\nu}$ final state.

Limits on anomalous triple gauge boson coupling (ATGC) parameters are determined with differential distributions of the invariant di-boson mass (CMS, four lepton channel), the transverse momentum of the leading lepton (CMS, $\ell^+\ell^-\nu\bar{\nu}$ -channel), or the transverse momentum of the leading Z (ATLAS, all channels). Both experiments use the vertex function parametrization with coefficients of the form f_i^V as defined in reference [34], and not the EFT approach [7]. A comparison of the measured and predicted differential cross sections in bins of the four-lepton invariant mass from CMS is shown in Figure 4. The prediction for the case of a non-zero value of the anomalous coupling parameter $f_4^Z = 0.015$ shows an enhancement over the SM value at

high invariant masses.

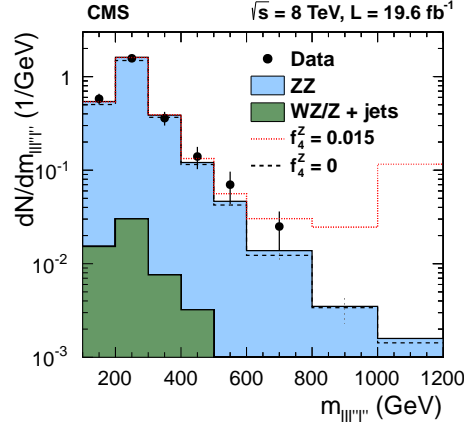


Figure 4. Distribution of the four-lepton reconstructed mass for the combined $4e$, 4μ , and $2e2\mu$ channels from CMS [28]. Points represent the data, the shaded histogram labeled ZZ represents the predictions for ZZ signal, the histograms labeled $W^\pm Z/Z+\text{jets}$ shows background estimated from data. The dashed and dotted histograms indicate the SM expectation ($f_4^Z = 0$) and in the presence of an ATGC ($f_4^Z = 0.015$) with all the other anomalous couplings set to zero. The last bin includes all entries with masses above 1000 GeV.

Both experiments publish 95% CL limits on ATGC without form factors in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ channels. The results are in agreement with the SM and summarized in Figure 5 taken from Ref. [35]. The precision of the LHC results is driven by the steep increase of sensitivity with higher center-of-mass energy and are about 2 orders-of-magnitude better compared to the combined LEP result [36].

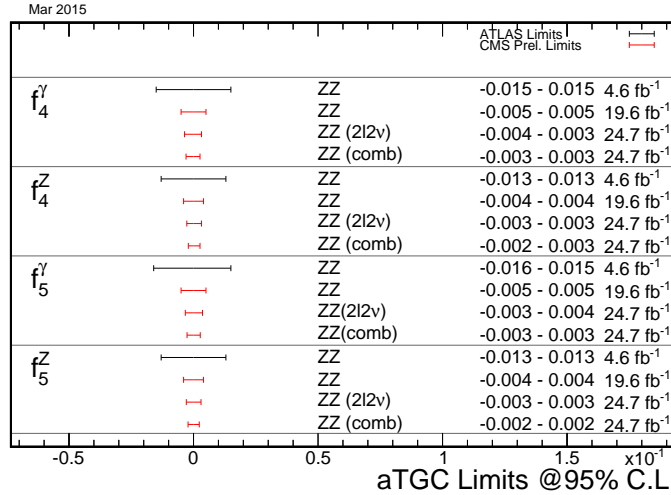


Figure 5. Comparison of the limits on f_{40}^V and f_{50}^V from ATLAS and CMS in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ channel at 7 and 8 TeV [35].

3.2.2. WZ production At the LHC, $W^\pm Z$ di-bosons are produced from quark-antiquark initial states at leading order and quark-gluon initial states at next-to-leading order. The SM-allowed s -channel diagram has a triple boson vertex and is sensitive to ATGC.

The ATLAS experiment measured the $W^\pm Z$ production cross section in the fully leptonic decay channel $\ell^+ \ell^- \ell \nu$ at $\sqrt{s} = 7$ TeV [37] and $\sqrt{s} = 8$ TeV [38] and set limits on charged ATGC. In these analyses the final states involving electrons or muons are considered as signal, whereas boson decays to taus are considered as background. The dominant background sources are Z +jet and ZZ production, accounting for about 40% of the overall background. The overall signal to background ratio is about 4. The leading systematic uncertainty is related to the data-driven estimation method of the background.

The fiducial cross section for the 7 TeV (8 TeV) analysis is defined by $p_T^{\mu,e} > 15$ GeV for the leptons from the Z decay, $p_T^{\mu,e} > 20$ GeV for the lepton from the W , $|\eta^{\mu,e}| < 2.5$, $p_T^\nu > 25$ GeV, $|m_{ll} - m_Z| < 10(25)$ GeV, $M_T^W > 20(30)$ GeV and $\Delta R > 0.3$ for the three possible $\ell\ell$ pairings. The total cross section requires the mass of the Z to be in the range of $66 \text{ GeV} < |m_Z| < 116 \text{ GeV}$ to suppress the contribution from γ^* . The fiducial and total cross sections are compared to the SM expectation at NLO in Table 3.2.2.

Experiment	cross section	\sqrt{s} [TeV]	measured	predicted	reference
ATLAS	total	7	$19^{+1.4}_{-1.3}$ (stat.) ± 0.9 (syst.) ± 0.4 (lumi.) pb	$17.6^{+1.1}_{-1.0}$ pb	[37]
ATLAS	total	8	24.3 ± 0.6 (stat.) ± 0.6 (syst.) ± 0.4 (theo.) ± 0.5 (lumi.) pb	21.0 ± 1.6 pb	[38]
ATLAS	fiducial	7	92^{+7}_{-6} (stat.) ± 4 (syst.) ± 2 (lumi.) fb	—	[37]
ATLAS	fiducial	8	35 ± 0.9 (stat.) ± 0.8 (syst.) ± 0.8 (lumi.) fb	30 ± 0.5 (PDF) ± 0.8 (scale) fb	[38]

Table 2. Summary of measured fiducial and total $W^\pm Z$ production cross sections from ATLAS at 7 TeV center-of-mass energies in the $\ell^+ \ell^- \ell \nu$ final state. The fiducial definitions differ from the 7 and 8 TeV analysis. Furthermore, the 7 TeV analysis quotes the sum for the e and μ channels, the 8 TeV analysis quotes the combination of channels. Thus, the two fiducial cross sections cannot be compared directly.

In Figure 7 the differential cross section measured in bins of p_T^Z is shown, compared to SM prediction and a set of anomalous TGC couplings. The normalized p_T^Z spectrum is unfolded and compared to the NLO calculation of MC@NLO [39] in Figure 7, showing good agreement with the SM.

Limits on the charged ATGC parameters $\Delta\kappa_Z$, λ_Z and g_1^Z are extracted from the transverse momentum distribution of the Z , p_T^Z [37], or from the transverse mass of the WZ system [38]. The ATGC parameter 95% CL limits using a dipole form factor with a cut-off of $\Lambda = 2$ TeV and without a form factor are quoted in Table 5 from the more constraining 8 TeV data set analysis [38].

3.2.3. WW production The W^+W^- production process has the highest production cross section among the massive vector di-boson processes. It is also an important background process to Higgs production and to searches for new physics. ATLAS and CMS, observed the W^+W^- production process in the fully leptonic channel and

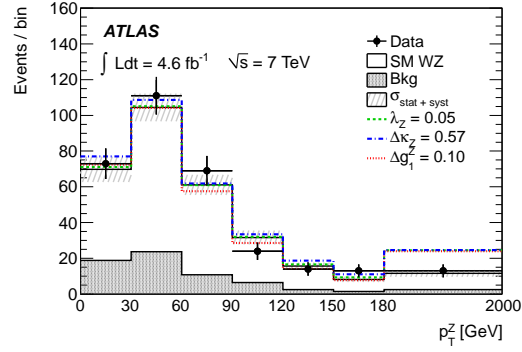


Figure 6. ATLAS measurement [37] of the transverse momentum of the Z in $W^\pm Z$ events (p_T^Z) compared with the SM prediction at $\sqrt{s} = 7$ TeV. For illustration, calculations for a set of anomalous couplings values are also shown. The full uncertainty contains statistical and systematic uncertainties.

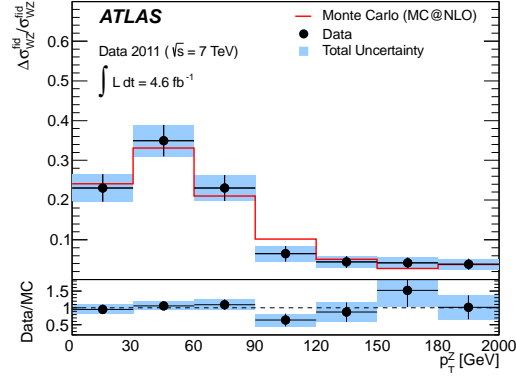


Figure 7. ATLAS measurement [37] of the normalized fiducial cross-sections in bins of p_T^Z compared with the SM prediction at $\sqrt{s} = 7$ TeV. The full uncertainty contains statistical and systematic uncertainties.

Λ [TeV]	Coupling	Expected	Observed
2	g_1^Z	$[-0.023, 0.055]$	$[-0.029, 0.050]$
2	$\Delta\kappa_Z$	$[-0.22, 0.36]$	$[-0.23, 0.46]$
2	λ_Z	$[-0.026, 0.026]$	$[-0.028, 0.028]$
∞	g_1^Z	$[-0.016, 0.032]$	$[-0.019, 0.029]$
∞	$\Delta\kappa_Z$	$[-0.17, 0.25]$	$[-0.19, 0.30]$
∞	λ_Z	$[-0.016, 0.016]$	$[-0.016, 0.016]$

Table 3. Expected and observed 95% CL limits on $\Delta\kappa_Z$, λ_Z and g_1^Z for a cut-off parameter $\Lambda = 2$ TeV and $\Lambda = \infty$ TeV obtained with the full 8 TeV dataset from ATLAS [38].

published results for 7 TeV (ATLAS [40], CMS [41]) and 8 TeV (CMS [42]) center-of-mass energy. Three final states, namely ee , $\mu\mu$, and $e\mu$ are included in the analyses. The contribution from leptonically decaying τ leptons is included in the signal definition. Although the production cross section is relatively high, the signature of two opposite sign leptons and missing transverse energy is shared with many processes and a careful control of the backgrounds is necessary to achieve a precise measurement.

Candidate W^+W^- events are selected by requiring two oppositely-charged leptons accompanied with large E_T^{miss} . The dominant background sources are $t\bar{t}$ and single top quark, W^\pm/jets , followed by $Z/\gamma^*+\text{jets}$ production. To suppress the dominant $t\bar{t}$ background, events with one or more jets are rejected. Additional requirements on E_T^{miss} and the use of top quark taggers further reduce the residual background to about 30%. The dominant systematic uncertainty is related to the jet veto efficiency and estimated to be about 5% for the W^+W^- production. The experiments quote a theoretical uncertainty on the signal acceptance due to variations of the parton distribution functions and renormalization and factorization scales in the range of 1-2%.

Both ATLAS and CMS provide a measurement of the total cross section for the process $pp \rightarrow W^+W^-$ and compare to theoretical calculations. The Higgs process contributes with about 4% to the total cross section and has not been taken into account in the comparison to the SM predictions. The total cross section results are summarized in Table 3.2.3. A good agreement between the experiments for the measured cross section as well as for the theoretical predictions is observed. A normalized differential measurement of the fiducial cross section in bins of p_T of the leading lepton is presented by ATLAS, as shown in Figure 8. The unfolded spectrum is in agreement with the SM prediction.

Experiment	cross section	\sqrt{s} [TeV]	measured [pb]	predicted [pb]	reference
ATLAS	total	7	51.9 ± 2.0 (stat.) ± 3.9 (syst.) ± 2.0 (lumi.)	$44.7^{+2.1}_{-1.9}$	[40]
CMS	total	7	52.4 ± 2.0 (stat.) ± 4.5 (syst.) ± 1.2 (lumi.)	47.0 ± 2.0	[41]
CMS	total	8	69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lumi.)	$57.3^{+2.3}_{-1.6}$	[41]

Table 4. Summary of measured fiducial and total W^+W^- production cross sections from ATLAS and CMS at 7 and 8 TeV center-of-mass energies in the $\ell\nu\ell\nu$ final state. The prediction are calculated at NLO in α_s .

The leading lepton p_T spectrum of the W^+W^- process is sensitive to anomalous gauge boson coupling parameters $\Delta\kappa_\gamma$, $\Delta\kappa_Z$, λ_γ , λ_Z , and Δg_1^Z . Both ATLAS and CMS quote limits in the LEP parametrization [43] that introduces $SU(2) \times U(1)$ gauge invariance constraints to reduce the number of free parameters to Δg_1^Z , $\Delta\kappa_\gamma$, and λ_Z . The obtained limits assuming no form factor are compared for both expected and measured 95% CL limits in Table 5.

3.2.4. Semi-leptonic VV production The cross sections for W^+W^- and $W^\pm Z$ production have been measured also in the semileptonic decay channel in the $W^\pm V \rightarrow$

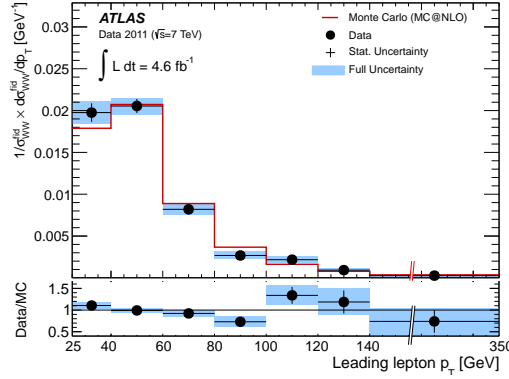


Figure 8. ATLAS measurement [40] of the transverse momentum of the leading lepton in W^+W^- events compared with the SM prediction at $\sqrt{s} = 7$ TeV. The full uncertainty contains statistical and systematic uncertainties.

	Observed (CMS)	Observed (ATLAS)	Expected (ATLAS)
Δg_1^Z	$[-0.095, 0.095]$	$[-0.039, 0.052]$	$[-0.039, 0.052]$
$\Delta \kappa_\gamma$	$[-0.21, 0.22]$	$[-0.14, 0.14]$	$[-0.13, 0.13]$
λ_Z	$[-0.048, 0.048]$	$[-0.062, 0.059]$	$[-0.060, 0.059]$

Table 5. Expected and observed 95% CL limits on the ATGC parameters $\Delta \kappa_\gamma$, λ_Z and Δg_1^Z in the LEP parametrization derived from the leading lepton p_T spectrum in W^+W^- production at 7 TeV (ATLAS [40], CMS [41]). No form-factor is applied to the ATGC parameters.

$\ell^\pm \nu q \bar{q}$ final state with $V = W^\pm, Z$. The semileptonic final state has a relatively large background mainly from V production with associated jets compared to the fully leptonic decay channels, but offers a substantially larger branching fraction. The increased statistics of signal events at high partonic center-of-mass compared to the fully leptonic decay modes enhances specifically the sensitivity to ATGC. ATLAS and CMS have published measurements of the inclusive production cross section $W^+W^- + W^\pm Z$ and set limits on charged ATGC with the full data set of the $\sqrt{s} = 7$ TeV run [44, 45].

Both analyses use the semileptonic decay channel with an electron or muon and two jets in the final state. The event selection sets requirements on the lepton p_T , the E_T^{miss} , di-jet invariant mass, and the event topology. The signal fraction of $W^+W^- + W^\pm Z$ in the event sample after selection is only about 1%, and no further selection criteria are applied to distinguish between W^+W^- and $W^\pm Z$ production. The dominant background from Z/W^\pm +jets production is constrained with data driven methods, followed by the sub-leading background contributions from $t\bar{t}$ and multi-jet production. The cross section is extracted with a simultaneous fit of the di-jet invariant mass spectrum comprising the signal and background components. In Figure 9 the di-jet invariant mass spectrum and the extracted signal after background subtraction from Ref. [44] are shown. The largest systematic uncertainty is related to the modelling of the Z/W^\pm +jets background with about 20% uncertainty for the cross section. The

measured and predicted cross sections are compared in Table 3.2.4.

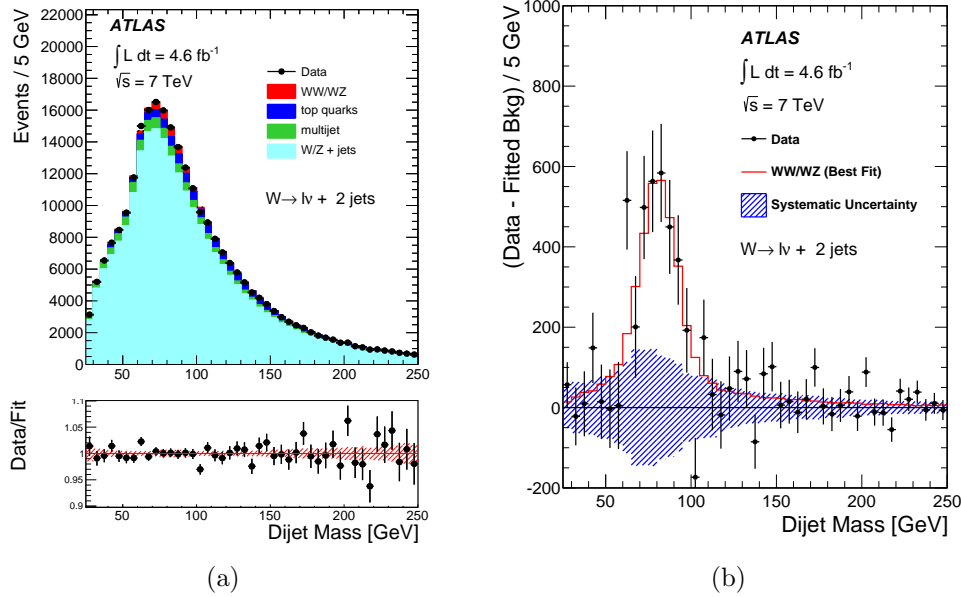


Figure 9. From the ATLAS analysis of the 7 TeV data set [44] : (a) The di-jet invariant mass spectrum for the sum of electron and muon channels, and the ratio of data over fitted background and signal contributions. (b) The distribution of the background subtracted data with the histogram showing the fitted signal contribution and the hatched band indicating the systematic uncertainty on the background prediction.

Experiment	cross section	\sqrt{s} [TeV]	measured [pb]	predicted [pb]	reference
ATLAS	total	7	68 ± 7 (stat.) ± 19 (syst.+lumi.)	61.1 ± 2.2	[44]
CMS	total	7	68.9 ± 8.7 (stat.) ± 9.7 (syst.) ± 1.5 (lumi.)	65.6 ± 2.2	[45]

Table 6. Summary of measured total $W^\pm Z + W^+ W^-$ production cross sections from ATLAS and CMS at 7 TeV center-of-mass energy in the $W^\pm V \rightarrow \ell^\pm \nu q \bar{q}$ final state.

To extract limits on ATGC parameters the transverse momentum of the di-jet system $p_T(jj)$ is used by ATLAS and CMS. The resulting 95% CL limits are listed in Table 7. The ATLAS limits use the LEP scenario [43], while the CMS limits are derived in the HISZ [46, 47] scenario. The achieved precision is comparable to the fully leptonic channel.

A measurement of the $W^\pm Z$ and ZZ production cross sections at $\sqrt{s} = 8$ TeV with a data-set of 18.9 fb^{-1} in the semileptonic final state with two b -quark jets from the $Z \rightarrow b\bar{b}$ decay and a leptonically decaying W^\pm or Z into a $\ell^+ \ell^-$, $\nu \bar{\nu}$ or $\ell \nu$ final state has been published by CMS [48], so far the only published results at 8 TeV for these channels. The measured cross sections $\sigma(pp \rightarrow W^\pm Z) = 30.7 \pm 9.3(\text{stat}) \pm 7.1(\text{syst}) \pm 4.1(\text{theo}) \pm 1.0(\text{lumi})$ pb and $\sigma(pp \rightarrow ZZ) = 6.5 \pm 1.7(\text{stat}) \pm 1.0(\text{syst}) \pm 0.9(\text{theo}) \pm 0.2(\text{lumi})$ pb are consistent with the calculation at NLO

	CMS	ATLAS	
	Observed	Observed	Expected
$\lambda_Z = \lambda_\gamma$	$[-0.038, 0.030]$	$[-0.039, 0.040]$	$[-0.048, 0.047]$
$\Delta\kappa_\gamma$	$[-0.11, 0.14]$	$[-0.21, 0.22]$	$[-0.23, 0.25]$
Δg_1^Z	–	$[-0.055, 0.071]$	$[-0.072, 0.085]$

Table 7. Expected and observed 95% CL on $\Delta\kappa_\gamma$, $\lambda_Z = \lambda_\gamma$ and Δg_1^Z in measured in the $W^\pm V \rightarrow \ell^\pm \nu q \bar{q}$ final state from the ATLAS [44] and CMS [45] collaborations.

in α_s of $\sigma(pp \rightarrow ZZ) = 22.3 \pm 1.1$ pb and $\sigma(pp \rightarrow ZZ) = 7.7 \pm 0.4$ pb, with the precision being still statistically limited.

3.2.5. Leptonic $V\gamma$ production The di-boson system of a massive vector boson and a photon has a similar electroweak production rate as the massive di-boson final states. Initial and final state QED radiation from the incoming quarks and outgoing charged decay products are dominating the total cross section for this final state. To compare to theory, fiducial cross sections are defined that enhance the electroweak component. The $W^\pm\gamma$ process has been studied in the leptonic decay $W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$ and limits on charged ATGC are set. The $Z\gamma$ process has two leptonic decay modes $Z\gamma \rightarrow \ell^+\ell^-\gamma$ and $Z\gamma \rightarrow \nu\bar{\nu}\gamma$, which are both sensitive to neutral ATGC. Due to the absence of final state radiation in $Z \rightarrow \nu\bar{\nu}$ and the higher branching ratio compared to $Z \rightarrow \ell^+\ell^-$ the $\nu\bar{\nu}$ final state is more sensitive to ATGC. The main background arises from W^\pm +jets and Z +jets production, where one jet is misidentified as an isolated photon. Data driven techniques are employed to estimate this background. Other important sources of backgrounds are multi-jet production and $t\bar{t}$ pair production in association with a photon, and are estimated from simulation. The achieved signal to background ratios range from about 0.8 – 1.5 for $W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$ to 3.5 – 7 for $Z \rightarrow \ell^+\ell^-$ depending on channel and experiment.

ATLAS and CMS have published measurements of fiducial production cross sections of $W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$, $Z\gamma \rightarrow \ell^+\ell^-\gamma$ at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The fiducial volume is defined at particle level with kinematic selection criteria on objects and at the event level. ATLAS and CMS differ in the definitions of the fiducial cross section, leading to differences in the predicted cross sections. The cross-section for $Z\gamma \rightarrow \ell^+\ell^-\gamma$ and $W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$ is defined as $p_T(\gamma) > 15$ GeV, $\Delta(\ell, \gamma) > 0.7$, and additionally for $Z\gamma$ $m(\ell\ell) > 50(40)$ GeV for CMS (ATLAS). ATLAS further requires $|\eta(\ell)| < 2.47$, $|\eta(\gamma)| < 2.37$, and $E_T(jet) > 30$ GeV, $|\eta(jet)| < 4.4$, $\Delta R(jet, x) > 0.3$ for jets with x being a lepton, jet, or photon. For the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ process the cross section is defined as $E_T(\gamma) > 145(100, 130)$ GeV, $|\eta(\gamma)| < 1.4(2.37)$, $p_T(\nu\nu) > 130(90, 100)$ for CMS (ATLAS 7 TeV [49], and 8 TeV [50]). A summary of the measurements is given in Table 3.2.5. Overall the agreement of the measured and NLO predicted exclusive cross sections is good, while the measured inclusive cross sections tend to be higher than the NLO prediction, which may be partially attributed to corrections at NNLO in α_s .

Experiment	process	cross section	\sqrt{s} [TeV]	measured	predicted	reference
ATLAS	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	inclusive	7	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi) pb	1.96 ± 0.17 pb	[51]
ATLAS	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	exclusive	7	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi) pb	1.39 ± 0.13 pb	[51]
ATLAS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	inclusive	7	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi) pb	1.18 ± 0.05 pb	[51]
ATLAS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	exclusive	7	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi) pb	1.06 ± 0.05 pb	[51]
ATLAS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	inclusive	7	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi) pb	0.156 ± 0.012 pb	[49]
ATLAS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	exclusive	7	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi) pb	0.115 ± 0.009 pb	[49]
CMS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	inclusive	7	5.33 ± 0.08 (stat) ± 0.25 (syst) ± 0.12 (lumi) pb	5.45 ± 0.27 pb	[52]
CMS	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	inclusive	7	37.0 ± 0.8 (stat) ± 4.0 (syst) ± 0.8 (lumi) pb	31.8 ± 1.8 pb	[52]
CMS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	inclusive	7	21.1 ± 4.2 (stat.) ± 4.3 (syst) ± 0.5 (lumi) fb	21.9 ± 1.1 fb	[49]
ATLAS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	inclusive	8	1.51 ± 0.01 (stat) ± 0.08 (syst) ± 0.03 (lumi) pb	1.35 ± 0.07 pb	[50]
ATLAS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	exclusive	8	1.19 ± 0.01 (stat) ± 0.07 (syst) ± 0.02 (lumi) pb	1.19 ± 0.08 pb	[50]
ATLAS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	inclusive	8	68 ± 4 (stat) ± 32 (syst) ± 1 (lumi) fb	68 ± 2 fb	[50]
ATLAS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	exclusive	8	43 ± 2 (stat) ± 10 (syst) ± 1 (lumi) fb	51 ± 2 fb	[50]
CMS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	inclusive	8	2063 ± 19 (stat) ± 98 (syst) ± 54 (lumi) fb	2100 ± 120 fb	[53]
CMS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	exclusive	8	1770 ± 18 (stat) ± 115 (syst) ± 46 (lumi) fb	1800 ± 120 fb	[53]
CMS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	inclusive	8	52.7 ± 2.1 (stat) ± 6.4 (syst) ± 1.4 (lumi) fb	40.7 ± 4.9 fb	[54]

Table 8. Summary of measured $V\gamma$ production cross sections from ATLAS and CMS at 7 and 8 TeV center-of-mass energies in the $W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$, $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ and $Z\gamma \rightarrow \ell^+\ell^-\gamma$ final states. The inclusive cross section is for $n_{jet} \geq 0$ and the exclusive cross section is for $n_{jet} = 0$. The cross section definitions differ for ATLAS and CMS and the numerical values are not directly comparable. For the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ process ATLAS uses a different cross section definition between the 7 TeV and 8 TeV measurements.

To extract limits on ATGC parameters the transverse momentum of the photon $p_T(\gamma)$ is used by CMS, while ATLAS uses a more conservative approach by combining the observed number of exclusive $V\gamma$ candidate events with $E_T(\gamma) > 100$ GeV. The channel most sensitive to the neutral TGC couplings h_{30}^V , h_{40}^V as defined in [55] is $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ due to the high branching ratio of Z to neutrinos of 20%. Figure 10 shows the transverse momentum of the photon at 8 TeV measured by CMS in the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ channel [54] together with a hypothetical TGC signal.

The resulting 95% CL limits for charged ($W^\pm\gamma$) and neutral ($Z\gamma$) TGC are listed in Table 9. For comparison, only limits obtained without the use of a form factor are listed. ATLAS also provides limits with unitarity-preserving form factors, and in case of the $\sqrt{s} = 8$ TeV analysis limits as a function of the dipole form factor scale Λ [50].

3.3. Inclusive tri-boson production

One avenue for testing quartic gauge boson interactions is through inclusive tri-boson production: $pp \rightarrow VV'V''$ for $V = \gamma, W, Z$. Using the Run 1 data sample, the channels with three massive vector bosons (WWW, WWZ, WZZ, ZZZ) are not accessible with SM rates, due to their small 8 TeV cross sections and comparably large multi-lepton backgrounds. The photonic channels do not suffer as much from these limitations, and sensitivity is at or near SM rates in Run 1.

An ATLAS analysis [56] has found evidence for $W\gamma\gamma$ production. In this process, a W is produced in the hard quark scattering, and the two photons can originate from either initial- or final-state radiation, or interaction with the W via triple or quartic gauge boson interactions. Events are selected with lepton $p_T > 20$ GeV, $E_T^{\text{miss}} > 25$

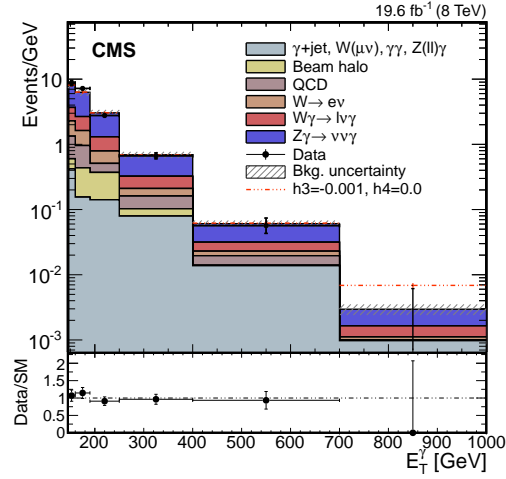


Figure 10. The $E_T(\gamma)$ distribution from CMS [54] in data (points) compared to signal and estimated background contributions (histogram). A ATGC signal with $h_{30}^V = -0.001$ is shown (dot-dashed histogram) for comparison. The background uncertainty includes statistical and systematic contributions.

	Process	\sqrt{s} [TeV]	\mathcal{L} [fb $^{-1}$] ATLAS, CMS	ATLAS		CMS
				Observed	Expected	Observed
$\Delta\kappa_\gamma$	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	7	4.6, 5	$[-0.41, 0.46]$	$[-0.38, 0.43]$	$[-0.38, 0.29]$
λ_γ	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	7	4.6, 5	$[-0.065, 0.061]$	$[-0.060, 0.056]$	$[-0.050, 0.037]$
h_{30}^γ	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	7	4.6, 5.0	$[-0.015, 0.016]$	$[-0.017, 0.018]$	$< 2.9 \cdot 10^{-3}$
h_{30}^Z	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	7	4.6, 5.0	$[-0.013, 0.014]$	$[-0.015, 0.016]$	$< 2.7 \cdot 10^{-3}$
h_{40}^γ	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	7	4.6, 5.0	$[-9.4 \cdot 10^{-5}, 9.2 \cdot 10^{-5}]$	$[-1.0 \cdot 10^{-4}, 1.0 \cdot 10^{-4}]$	$< 1.5 \cdot 10^{-5}$
h_{40}^Z	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	7	4.6, 5.0	$[-8.7 \cdot 10^{-5}, 8.7 \cdot 10^{-5}]$	$[-9.7 \cdot 10^{-5}, 9.7 \cdot 10^{-5}]$	$< 1.3 \cdot 10^{-5}$
h_{30}^γ	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	20.3, -	$[-9.5 \cdot 10^{-4}, 9.9 \cdot 10^{-4}]$	$[-1.8 \cdot 10^{-3}, 1.8 \cdot 10^{-3}]$	-
h_{30}^Z	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	20.3, -	$[-7.8 \cdot 10^{-4}, 8.6 \cdot 10^{-4}]$	$[-1.5 \cdot 10^{-3}, 1.5 \cdot 10^{-3}]$	-
h_{40}^γ	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	20.3, -	$[-3.2 \cdot 10^{-6}, 3.2 \cdot 10^{-6}]$	$[-6.0 \cdot 10^{-6}, 5.9 \cdot 10^{-6}]$	-
h_{40}^Z	$Z\gamma \rightarrow \ell^+\ell^-\gamma, Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	20.3, -	$[-3.0 \cdot 10^{-6}, 2.9 \cdot 10^{-6}]$	$[-5.5 \cdot 10^{-6}, 5.4 \cdot 10^{-6}]$	-
h_{30}^γ	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	8	-, 19.5	-	-	$[-4.6 \cdot 10^{-3}, 4.6 \cdot 10^{-3}]$
h_{30}^Z	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	8	-, 19.5	-	-	$[-3.8 \cdot 10^{-3}, 3.7 \cdot 10^{-3}]$
h_{40}^γ	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	8	-, 19.5	-	-	$[-3.6 \cdot 10^{-5}, 3.5 \cdot 10^{-5}]$
h_{40}^Z	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	8	-, 19.5	-	-	$[-3.1 \cdot 10^{-5}, 3.0 \cdot 10^{-5}]$
h_{30}^γ	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	-, 19.5	-	-	$[-1.1 \cdot 10^{-3}, 0.9 \cdot 10^{-3}]$
h_{30}^Z	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	-, 19.5	-	-	$[-1.5 \cdot 10^{-3}, 1.6 \cdot 10^{-3}]$
h_{40}^γ	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	-, 19.5	-	-	$[-3.8 \cdot 10^{-6}, 4.3 \cdot 10^{-6}]$
h_{40}^Z	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	8	-, 19.5	-	-	$[-3.9 \cdot 10^{-6}, 4.5 \cdot 10^{-6}]$

Table 9. Expected and observed 95% CL on h_{30}^γ , h_{30}^Z , h_{40}^γ , and h_{40}^Z measured in the $Z\gamma \rightarrow \ell^+\ell^-\gamma$ and $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ final states from the ATLAS and CMS collaborations.

GeV, $m_T > 40$ GeV and two photons with $p_T > 20$ GeV. Minimum angular separations between the lepton and photons are also required to reduce the contribution of final-state radiation amplitudes, which do not probe gauge boson interactions. This selection results in 157 events in the 8 TeV data. Roughly half of these events are backgrounds: W or $W\gamma$ plus jets production with jets misidentified as photons, $Z\gamma$ events with leptons misidentified as photons, or $\gamma\gamma$ plus jets events with jets misidentified as leptons. The backgrounds are estimated for electron and muon events separately via template fits to photon isolation distributions in data (W or $W\gamma$ plus jets) or lepton isolation distributions in data ($Z\gamma$ or $\gamma\gamma$ plus jets).

The di-photon invariant mass distributions of selected events, along with estimated backgrounds, are shown in Figure 11. A signal excess is observed in both lepton channels, corresponding to a combined significance larger than 3σ . The fiducial production cross section is estimated for both the inclusive case and an exclusive selection with a jet veto for jets with $p_T > 30$ GeV, similar to the ATLAS $W\gamma$ and $Z\gamma$ analysis. The measured inclusive cross section, $6.1_{-1.0}^{+1.1}(\text{stat.}) \pm 1.2(\text{syst.}) \pm 0.2(\text{lumi.})$ fb, is 1.9σ higher than a NLO prediction from MCFM of 2.90 ± 0.16 fb. The exclusive cross section, $2.9_{-0.7}^{+0.8}(\text{stat.})_{-0.9}^{+1.0}(\text{syst.}) \pm 0.1(\text{lumi.})$ fb, agrees with the MCFM prediction of 1.88 ± 0.20 fb. A similar phenomenon was observed in the $W\gamma/Z\gamma$ analysis, where it is believed missing higher order corrections to the inclusive cross section are substantial. Systematic uncertainties for these cross sections are predominantly from the data-driven background estimation methods.

The exclusive $W\gamma\gamma$ event yield at high di-photon mass ($m_{\gamma\gamma} > 300$ GeV) is used to obtain 95% CL bounds on dimension 8 EFT couplings $f_{T,0}$ and $f_{M,(2,3)}$ [8]. For the case of no unitarizing form factor, the observed limit on $|f_{T,0}/\Lambda^4|$ is 90 TeV^{-4} . For a unitarizing form factor with a cutoff scale of 600 GeV, these limits are relaxed by up to a factor of 8.

CMS has performed a search for $WV\gamma$ production in 8 TeV data [57], where V is a hadronically decaying W or Z . This process is sensitive to the $WW\gamma\gamma$ and $WWZ\gamma$ quartic gauge boson interactions, as depicted in Figure 12. W candidates are selected by requiring either one muon ($p_T > 25$ GeV and $|\eta| < 2.1$) or one electron ($p_T > 30$ GeV and $|\eta| < 2.5$), missing transverse energy in excess of 35 GeV, and vetoes on additional leptons with $p_T > 10(20)$ GeV for muons (electrons). Photon candidates are required to have $E_T > 30$ GeV and $|\eta| < 1.44$; the central η restriction selects for higher purity photons. The third V boson is selected from jet pairs with jet $E_T > 30$ GeV and $|\eta| < 2.4$, a veto on b -quark jet tags, di-jet separation $|\Delta\eta_{jj}| < 1.4$, and di-jet mass $70 < m_{jj} < 100$ GeV. False missing energy is reduced by requiring a minimum azimuthal separation $|\Delta\phi| < 0.4$ between the highest E_T jet and E_T^{miss} , and false photon backgrounds from Z bosons in the electron channel are reduced by vetoing electron-photon pairs consistent with the Z mass ($|M_Z - m_{e\gamma}| < 10$ GeV).

The photon E_T of selected events is shown in Figure 13. The leading background is from $W\gamma$ +jets production and is estimated from extrapolation of the m_{jj} sideband data into the signal region. Multi-jet background is extrapolated from a control sample with low E_T^{miss} , and the other backgrounds such as top quarks are estimated from simulation. 322 events are observed where 342 ± 16 were expected, of which 13 were expected to come from $WV\gamma$ production. An upper limit at 95% confidence level is obtained of 311 fb for the inclusive cross section, which is 3.4 times larger than the standard model prediction of **aMC@NLO** [58] (91.6 ± 21.7 fb).

The binned photon E_T distribution in Figure 13 is used to extract limits on dimension 6 EFT couplings a_0^W/Λ^2 and a_C^W/Λ^2 , which affect $WW\gamma\gamma$ interactions, and κ_0^W/Λ^2 and κ_C^W/Λ^2 , which affect $WWZ\gamma$ interactions. The magnitude of the limits are in the range of 12 TeV^{-2} to 34 TeV^{-2} . Limits on the dimension 8 EFT couplings

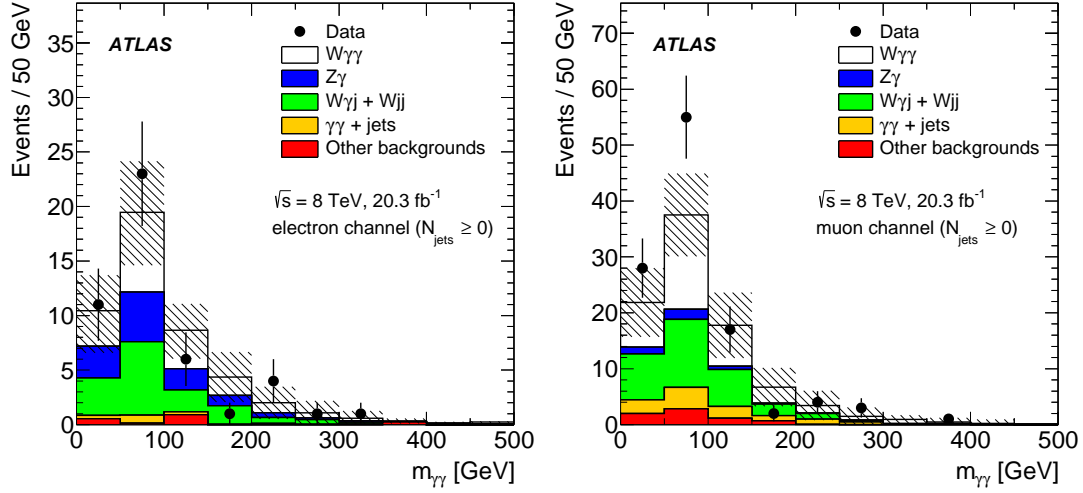


Figure 11. Di-photon invariant mass distribution of $W\gamma\gamma$ candidates selected by ATLAS [56]. Inclusive $e\nu\gamma\gamma$ (left) and $\mu\nu\gamma\gamma$ (right) candidates are shown separately.

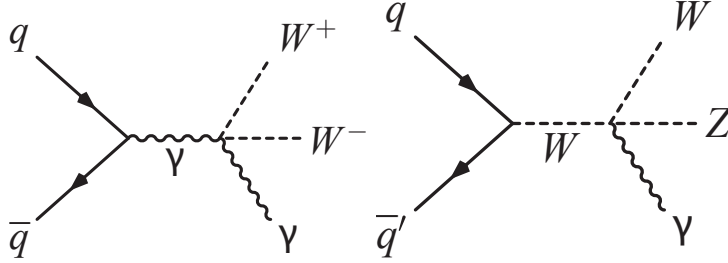


Figure 12. Quartic gauge boson interaction Feynman diagrams for $WW\gamma$ and $WZ\gamma$ production [57].

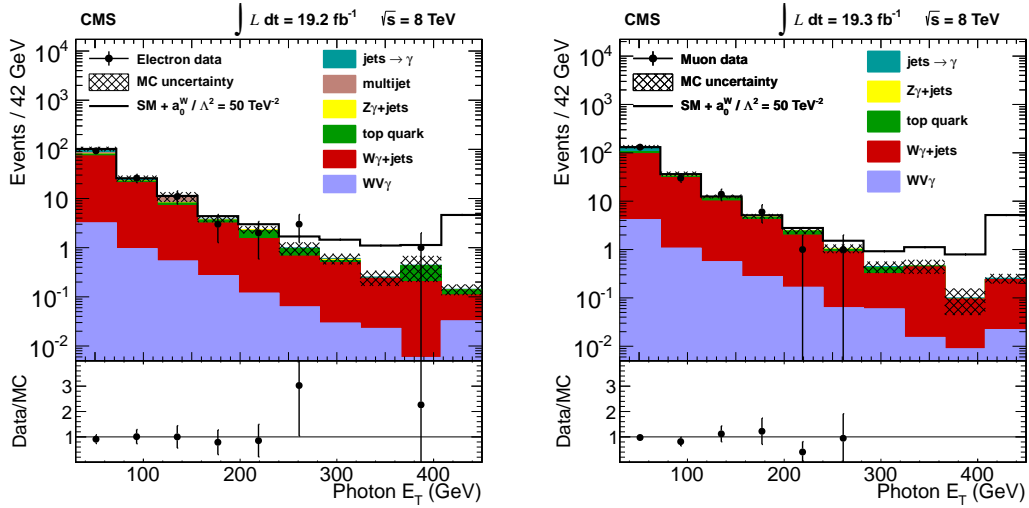


Figure 13. Photon E_T distribution of $WV\gamma$ candidates selected by CMS [57].

$f_{T,0}/\Lambda^4$, $f_{M,0}/\Lambda^4$, $f_{M,1}/\Lambda^4$, $f_{M,2}/\Lambda^4$, and $f_{M,3}/\Lambda^4$ are also obtained, in the range of 25 TeV^{-4} for $f_{T,0}/\Lambda^4$ and $40 - 131 \text{ TeV}^{-4}$ for $f_{M,i}/\Lambda^4$.

4. Exclusive boson production

4.1. Exclusive single boson production, vector-boson fusion

By analysis of more exclusive selection of single or multiple electroweak boson production, it is possible with the LHC Run 1 data to isolate purely electroweak amplitudes of increased complexity and complementary sensitivity to new physics. The first demonstration of this was the observation of an electroweak amplitude in $Z + 2$ jet production by both the ATLAS and CMS experiments [59, 60].

Figure 14 shows the leading order diagrams for $Z + 2$ jet production from purely electroweak contributions. It includes a vector boson fusion component similar to VBF Higgs production, as well as electroweak bremsstrahlung amplitudes. The different amplitudes are strongly interfering and cannot be practically isolated from one another via kinematic selection. In general, $Z + 2$ jet production is dominated by simpler Drell-Yan production accompanied by QCD bremsstrahlung, but in certain exclusive regions of the di-jet phase space the electroweak amplitudes are dominant.

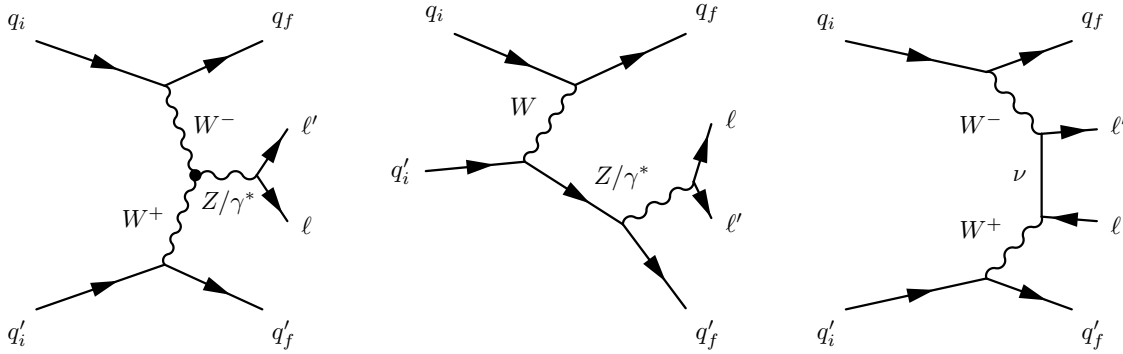


Figure 14. Representative Feynman diagrams for di-lepton production in association with two jets from purely electroweak contributions: (left) vector boson fusion, (middle) bremsstrahlung-like, and (right) multiperipheral production.

The LHC experiments have used several criteria to isolate the electroweak amplitudes. The ATLAS analysis defines a search region with

- minimum p_T of the jets (45-55 GeV) and the Z boson candidate (20 GeV)
- minimum invariant mass of the di-jet system (250 GeV)
- a veto on events with an additional jet in the rapidity gap between the leading two jets
- an upper limit (0.15) on the relative imbalance in the momenta of the four-body di-lepton and di-jet system, where imbalance is defined as the magnitude of the four-body p_T vector sum relative to the four-body scalar sum of transverse momenta.

CMS selects events with minimum p_T of the jets (30-50 GeV), minimum invariant mass of the di-jet system (200 GeV), a maximum magnitude of the difference between the Z rapidity and the average jet rapidity (1.2), and an upper limit (0.14) on the relative imbalance of the three-body Z and di-jet system. Additionally a multivariate discriminant is constructed which includes:

- the di-jet invariant mass
- the sum of the magnitudes of the jet rapidities
- the Z boson rapidity
- the Z boson p_T
- ratio of the difference between the Z rapidity and the average jet rapidity to the di-jet rapidity difference
- a quark/gluon multivariate discriminant evaluated for the leading two jets

The ATLAS analysis extracts an electroweak signal from selected events via a maximum likelihood fit of electroweak $Z + 2$ jet signal and background yields to the di-jet invariant mass distribution. The signal template is obtained from **Sherpa** $Z + 2$ jet simulation and the background template also from **Sherpa**, except its shape is reweighted to obtain agreement with a separate control sample in the data. The result of the fit is shown in Figure 15. An excess of data over background begins to be seen near 1000 GeV in di-jet mass, increasing in significance for higher di-jet masses, totalling close to 1700 events with a statistical significance greater than 5σ . A high-purity fiducial cross section region is defined for events in the search region above 1000 GeV in di-jet mass, where the signal yield is obtained from integrating the signal component of the likelihood fit. The resulting electroweak cross section is

$$\sigma_{EW}(m_{jj} > 1 \text{ TeV}) = 10.7 \pm 0.9(\text{stat}) \pm 1.9(\text{syst}) \pm 0.3(\text{lumi}) \text{ fb}$$

, in agreement with the **Powheg** prediction of $9.4 \pm 0.3 \text{ fb}$. The systematic uncertainty is predominantly from control sample statistics for background reweighting, the simulation modelling of signal and background, and estimates of the effect of neglecting signal-background interference.

Similarly, CMS extracts an electroweak signal via a likelihood fit to the kinematic multivariate discriminant. The signal and background templates are obtained from **MadGraph**, and an interference term is introduced proportional to the square root of the signal strength. The background shape is not reweighted but comparisons between data and simulation control samples bound shape uncertainties. A signal significance greater than 5σ is observed, corresponding to a signal yield close to 1600 events, as shown in Figure. 15. For a fiducial cross section corresponding to all selected events, they obtain

$$\sigma_{EW} = 174 \pm 15(\text{stat}) \pm 40(\text{syst}) \text{ fb}$$

, in agreement with the **MadGraph** prediction of $208 \pm 18 \text{ fb}$. Systematic uncertainties types and sizes are similar to that of ATLAS.

4.2. Exclusive di-boson production, vector-boson scattering

In addition to exclusive single boson production, CMS and ATLAS have evidence for exclusive di-boson production, in two different channels. In one of them, CMS [61] has performed a search for exclusive di-boson production via protons emitting (possibly quasi-) real photons which rescatter to produce W^+W^- pairs: $pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^\pm e^\mp p^{(*)}$, where p^* admits the possibility that the protons dissociate into an undetected system. Such production is characterized by a $\mu^\pm e^\mp$ pair which has no underlying event activity typical of proton-proton hard scattering. By selecting a $\mu^\pm e^\mp$ pair of sufficiently high individual (20 GeV) and joint (30 GeV) transverse momentum, and requiring further that the two lepton tracks intersect with each other, but have no additional tracks nearby, an exclusive production signal is isolated from backgrounds such as exclusive Drell-Yan and inclusive di-lepton production from various hard scattering mechanisms, respectively. Selection efficiency is validated by examining a control sample of exclusive same-flavor Drell-Yan production ($p^{(*)}\mu^\pm\mu^\mp p^{(*)}$ or $p^{(*)}e^\pm e^\mp p^{(*)}$) and comparing it with simulated efficiency. The relative contribution of dissociated proton scattering for signal is also deduced by comparing the observed exclusive Drell-Yan cross section with an exclusive matrix element calculation (LPAIR [62, 63]); proton dissociation is estimated to enhance the signal by a factor of 4.10 ± 0.43 with respect to an exclusive calculation from **MadGraph** [64, 58].

Figure 16 shows the distributions of di-lepton p_T and extra tracks in data compared with expectations from simulation. CMS observes 13 events with an expected background of 3.9 ± 0.6 in the 8 TeV data. In the 7 TeV [65] and 8 TeV data combined, a 3.4σ excess is observed over background as evidence for exclusive (plus dissociative) W^+W^- production. The signal corresponds to a cross section in the 8 TeV data of $11.9^{+5.6}_{-4.5}$ fb, in agreement with a SM prediction of 6.9 ± 0.6 fb. Exclusive W^+W^- production is sensitive to $WW\gamma\gamma$ quartic couplings. The CMS analysis derived limits on the dimension 6 couplings a_0^W/Λ^2 and a_C^W/Λ^2 and, in the context of dimension 8 EFT, the anomalous couplings $f_{M(0,1,2,3)}/\Lambda^4$. The 95% CL upper limits are $1.1(4.4) \times 10^{-4}\text{GeV}^{-2}$ for a_0^W/Λ^2 (a_C^W/Λ^2), and range from $2 - 17 \times 10^{-4}\text{GeV}^{-4}$ for dimension 8 couplings, for models with no form factor. This process is the single best constraint on $WW\gamma\gamma$ QGCs.

The other exclusive di-boson process for which the LHC has evidence is same-sign WW production, via the process $qq \rightarrow WW + 2q \rightarrow \ell^\pm \ell^\pm + 2\text{jet} + E_T^{\text{miss}}$. Similar to exclusive single boson production, the final state of interest is a superposition of several amplitudes at leading order, some of which are purely electroweak and include triple and quartic gauge boson interactions (see Figure 17), and some of which have the final state jets arise from QCD initial- and final-state radiation. Through a suitable choice of final state phase space, the electroweak amplitudes are enhanced and the associated signal strength and distributions can be tested against the electroweak theory. The same-sign WW final state has the advantage over other exclusive diboson channels (W^+W^- or $W^\pm Z$) of a smaller relative QCD amplitude and smaller multi-lepton backgrounds from top quark, Drell-Yan, and $W^\pm Z$ processes due to the same-sign di-lepton requirement.

An ATLAS analysis [66] selects an “inclusive region” which is an admixture of electroweak and QCD contributions, and a VBS signal region which is predominantly electroweak. The inclusive region requires two same-sign leptons with $p_T > 25$ GeV, $E_T^{\text{miss}} > 40$ GeV, and at least two jets with $m_{jj} > 500$ GeV for the two highest p_T jets; the VBS region further requires that the two highest p_T jets are separated in rapidity, $|\Delta y_{jj}| > 2.4$. To reduce Drell-Yan background, events with di-lepton mass less than 20 GeV or di-electrons within 10 GeV of the Z mass are vetoed. Top quark background is reduced by vetoing events with b-tagged jets. Finally, WZ background is reduced by vetoing events with a third lepton with muon $p_T > 6$ GeV or electron $p_T > 7$ GeV. This results in 50 events selected for the inclusive region (as shown in Figure 18) and 34 for the VBS region. About half of selected events in either region are backgrounds from $W^\pm Z$, $W\gamma$ with photon conversion, and misidentified leptons from jets in $V + \text{jet}$ processes. The significance of the signal in the inclusive region is observed (expected) to be 4.5σ (3.4σ), and for the VBS region the significance is observed (expected) to be 3.6σ (2.8σ). The measured cross sections in these two regions are $2.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst})$ fb and $1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ fb, comparing well with SM predictions from **Powheg-Box** [67, 68, 69, 70, 71, 72] of 1.52 ± 0.11 fb and 0.95 ± 0.06 fb, respectively.

The VBS cross section is used to constrain parameters of an effective chiral Lagrangian theory of vector boson scattering [10], calculated by **Whizard** [73, 74]: $0.14 < \alpha_4 < 0.16$ and $0.23 < \alpha_5 < 0.24$ limits are obtained at 95% CL.

A CMS analysis [75] selects events similar to the ATLAS VBS region: two same-sign leptons with $p_T > 20$ GeV, two jets with $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$, and $E_T^{\text{miss}} > 40$ GeV. There is a same-flavor Drell-Yan veto for events with di-lepton mass less than 50 GeV or di-electrons within 15 GeV of the Z mass, a veto of top-like events with secondary vertex or soft muon tags, and a third lepton veto for $p_T > 10$ GeV. In total 12 events are selected, shown in Figure 18. About half of them are expected to be background, mostly from misidentified leptons. The resulting excess has a significance of 1.9σ (2.9σ) observed (expected) for the purely electroweak amplitude. The observed fiducial cross section is $4.0^{+2.4}_{-2.0}(\text{stat})^{+1.1}_{-1.0}(\text{syst})$ fb compared to an expected cross section estimated from **VBFNLO** [76, 77, 78] of 5.8 ± 1.2 fb.

The $m_{\ell\ell}$ distribution of selected events is used to obtain 95% CL bounds on dimension 8 EFT couplings $f_{S,(0,1)}$, $f_{M,(0,1,6,7)}$, and $f_{T,(0,1,2)}$ [8]. For $f_{S,(0,1)}$, which can correspond to a spin-one VBS resonance, the limits are $-42 \text{ TeV}^{-4} < f_{S,0}/\Lambda^4 < 43 \text{ TeV}^{-4}$ and $-129 \text{ TeV}^{-4} < f_{S,1}/\Lambda^4 < 131 \text{ TeV}^{-4}$.

5. Electro-weak precision tests

5.1. $Z A_{FB}$ and $\sin^2 \theta_W^{\text{eff}}$

In the electroweak theory the weak mixing angle θ_W is a free parameter indicating the degree of mixing between $SU(2)_L$ and $U(1)_Y$ neutral gauge bosons upon

electroweak symmetry breaking to obtain the physical neutral gauge bosons γ and Z . Experimentally, it is typically measured as $\sin^2 \theta_W$ via angular distributions in fermion pair production; it has been most precisely measured at the LEP 1 and SLD experiments via fermion pair production at the Z pole, yielding a combined value of 0.23153 ± 0.00016 [79]. In the standard model it is related to the gauge boson masses at tree level by $1 - m_W^2/m_Z^2$ and modified by higher-order loop corrections, including contributions from Higgs boson loops; the effective angle measured upon introducing loop corrections is denoted as $\sin^2 \theta_W^{eff}$. The recent high-precision Higgs boson mass measurement at the LHC combined with other electroweak measurements can be used to predict a value for $\sin^2 \theta_W^{eff}$ of 0.23149 ± 0.00007 [13], motivating an improvement upon the direct experimental measurement precision by a factor of two or more at the LHC to constrain the electroweak theory further.

At a hadron collider, fermion pair production at and around the Z pole is measured in the process $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^-$, where the differential scattering cross section is characterized by $d^3\sigma/dm dy d\cos\theta = A(m, y)(1 + \cos^2\theta) + B(m, y)\cos\theta$, where m is the final state lepton pair mass, y is the lepton pair rapidity, and $\cos\theta$ is the polar angle of the positive lepton with respect to the quark direction. A non-vanishing forward-backward asymmetry in this angle, $A_{FB}(m, y) = 3B(m, y)/8A(m, y)$, arises from interference between vector and axial-vector currents; the portion of $A_{FB}(m, y)$ corresponding to self-interference of the Z boson currents is directly sensitive to $\sin^2 \theta_W^{eff}$.

In hadron collisions, the quark direction is ambiguous, as it may originate from either incoming hadron and have unknown transverse momentum. The impact of quark transverse momentum on the forward-backward assignment is minimized by defining the quark direction to be the difference between the forward-going and backward-going hadron momentum vectors in the lepton pair rest frame, as originally suggested by Collins and Soper [80]; this angle is typically denoted as $\cos\theta^*$. In proton-proton collisions, the ambiguity due to quark origination is an irreducible dilution in A_{FB} which is strongest at low $|y|$ and decreasing at higher $|y|$ where valence quark/sea anti-quark annihilation is predominant; measurements of $A_{FB}(m, y)$ at high- $|y|$ are therefore intrinsically more sensitive to the undiluted value and have smaller theory uncertainties related to PDFs. In proton-anti-proton collisions, valence quark/valence anti-quark annihilation predominates, and so dilution and its associated uncertainties are vastly reduced, making the Tevatron experimental measurements [81, 82, 83] a competitive alternative to the LHC for current data samples. Three LHC experiments have measured $\sin^2 \theta_W^{eff}$: an initial exploratory measurement by CMS at 7 TeV [84], a measurement by ATLAS with all 7 TeV data [85], and a measurement by LHCb [86, 87] with all 7 and 8 TeV data [88].

The ATLAS measurement was performed with three different samples: muon pairs with $p_T > 20$ GeV and $|\eta| < 2.4$; electron pairs with $E_T > 25$ GeV and $|\eta| < 2.47$; and electron pairs with $E_T > 25$ GeV where one has $|\eta| < 2.47$ and the other has $2.5 < |\eta| < 4.9$. In the last case the forward electron is identified with calorimeters alone, still the resulting pairs have a signal purity at the Z pole of 95%. The data in each

sample i are binned in mass, and the raw measured angular asymmetry in that region of phase space, $A_{FB,i}^{\text{meas}}(m)$, is computed from counting forward ($\cos\theta^* > 0$) and backward ($\cos\theta^* < 0$) candidates after background subtraction. Each $A_{FB,i}$ is used to extract $\sin^2\theta_W^{\text{eff}}$ via a binned χ^2 fit of LO PYTHIA templates of different mixing angle values to the data. Figure 19 shows the $\cos\theta^*$ distribution for selected central-forward electron pairs; an asymmetry between forward and backward angles is visually evident. Figure 19 also show the resulting $A_{FB}^{\text{meas}}(m)$, alongside the best-fit predictions from LO PYTHIA and NLO POWHEG. The three samples give consistent values for $\sin^2\theta_W^{\text{eff}}$ and are combined to give a value of $0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF})$, where the last term denotes the leading uncertainty in $\sin^2\theta_W^{\text{eff}}$ from uncertainties in specially prepared LO PDFs consistent with the LO PYTHIA template generation and 7 TeV ATLAS W and Z data (ATLAS-epWZ12 LO) [89]. A general feature of precision electroweak measurements at the LHC is the predominance of PDF uncertainties, requiring simultaneous PDF measurement with the parameter of interest to obtain the best precision. Other leading systematic uncertainties are the lepton energy scale and MC template statistics, which will improve with larger data sets.

The LHCb measurement employs a very similar technique. They select muon pairs with $p_T > 20$ GeV, $60 < m_{\mu\mu} < 160$ GeV, and $2.0 < |\eta| < 4.5$, with a signal mass resolution and purity similar to ATLAS but in a more forward, and therefore more sensitive, Z production region. LHCb operational instantaneous luminosity is limited to the range $2 - 4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$, however, so the sample size is limited to 1fb^{-1} at 7 TeV and 2fb^{-1} at 8 TeV. The data are binned in mass and $A_{FB}(m)$ is computed for their acceptance, and then subsequently unfolded to account for mass resolution effects. Figure 20 shows the unfolded A_{FB} distribution at 8 TeV compared with NLO predictions from POWHEG-BOX. The unfolded $A_{FB}(m)$ distribution is used to extract $\sin^2\theta_W^{\text{eff}}$ via a χ^2 fit of POWHEG-BOX templates of different mixing angle values to the data. They measure $\sin^2\theta_W^{\text{eff}} = 0.23142 \pm 0.00073(\text{stat.}) \pm 0.00052(\text{syst.}) \pm 0.00056(\text{th.})$, where the last term denotes uncertainties from theoretical modelling ingredients, predominantly PDFs. The PDF uncertainties are evaluated from QCD+QED NLO NNPDF 2.3 [90, 91], which, similar to the ATLAS PDF, includes 7 TeV electroweak production data from the LHC. In contrast to the ATLAS result, the LHCb measurement is statistically limited, but has 30% smaller theoretical uncertainties due to better understood PDF uncertainties in the more forward production region.

A comparison of experimental measurements of $\sin^2\theta_W^{\text{eff}}$ [81] is shown in Figure 21. The best single measurements from the Tevatron are more than twice as precise as the best measurements from the LHC, and the separate $A_{FB}^{0,b}$ and A_l results from e^+e^- collisions are more than four times as precise. There are reasonable prospects for the LHC experiments eventually surpassing these: ATLAS and CMS are expected to have superior statistical uncertainties by the end of Run 2, and all of the systematic and PDF uncertainties are expected to improve as well with larger electroweak data samples.

5.2. W boson mass

As discussed in the previous subsection, high-precision electroweak observables are interrelated, and can be combined to predict any other; deviations from expectations would be evidence for anomalous interactions contributing to the loop corrections which influence them. The mass of the W boson is a significant constraint on the others; historically it has served as a predictive guide in the search for both the top quark and the Higgs boson. Now that both of those have been measured precisely, the situation has reversed, and they can be used to predict a value for M_W of 80.358 ± 0.008 GeV [13], in comparison to the direct experimental measurement 80.385 ± 0.015 GeV [92], motivating an improvement in precision by at least a factor of two.

The LHC experiments have not yet produced a measurement of the W boson mass, but it is a stated goal of ATLAS, CMS, and LHCb to achieve precision competitive with the world average. The statistical uncertainty of Run 1 data samples should be adequate to achieve this; CMS analyses of Run 1 data selected over 120 million W candidates with good signal purity in the muon channel alone [93, 94], whereas the best single measurements from the Tevatron [95, 96] currently use roughly 1 million events each. The LHC experiments face larger systematic uncertainty challenges to the Tevatron, however.

The W^\pm mass is typically estimated from the lepton p_T or lepton- E_T^{miss} transverse mass distributions. This incomplete reconstruction introduces modelling uncertainties from PDFs. In proton-proton collisions at and above 7 TeV, W^\pm production has both valence quark/sea anti-quark and sea quark/sea anti-quark components, whereas proton-anti-proton collisions are predominantly valence quark/valence anti-quark. The latter are much better constrained experimentally than the former, and so significant progress must be made on sea quark PDFs to reduce associated W mass uncertainties to competitive levels. The LHC W^\pm and Z data themselves have been used to constrain light sea and valence quark PDFs via the W^+/W^- production asymmetry [94, 97, 93, 98, 89] and lepton rapidity ratio between W and Z bosons [89, 99]; Figure 22 shows the precision already achievable in these observables compared with contemporary PDFs. The W mass uncertainty expected from these constraints is expected to be of order 10 MeV for individual PDFs [100, 101], therefore more precise constraints than currently available are required to exceed Tevatron precision; this could be achieved through more rigorous use of Run 1 electroweak production data, or Run 2 data.

Another important modelling uncertainty is the W boson transverse momentum and production polarization. This modelling has perturbative, non-perturbative, and PDF uncertainties. Previous measurements at the Tevatron have attempted to constrain these by precisely measuring the Z boson p_T , which constrain underlying model parameters for both the W and Z spectra, and then transfer those to the W p_T spectrum. Consistent treatment of these uncertainties and precision understanding in the LHC data of Z p_T , W p_T , or both are required. Figure 23 shows the Run 1 measurements performed

which include the W transverse momentum distribution. Typical event selection for W mass measurements require $p_T < 15\text{--}20$ GeV, a domain in which soft gluon resummation is an important ingredient; resummed predictions from RESBOS [102, 103, 104] agree with the data at the 10% level in this region, whereas fixed-order NNLO predictions from FEWZ [17, 18, 105, 19] show larger disagreements.

A related issue is the measurement of E_T^{miss} in the presence of pileup. If transverse mass is to be a competitive observable for estimating M_W throughout the Run 1 data sample, the E_T^{miss} resolution must be competitive in pileup conditions of up to 40 interactions per bunch crossing. Pileup mitigation techniques, such as charged hadron subtraction, event topology discriminants, or track-only E_T^{miss} need to be refined, both to improve the M_T resolution and improve W p_T spectra measurements.

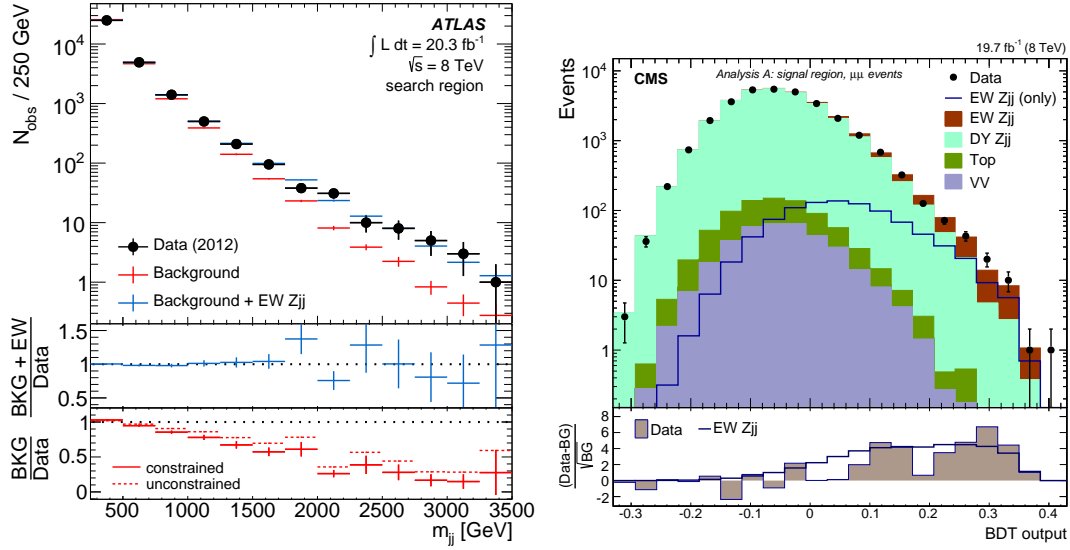


Figure 15. Evidence of observation of an electroweak amplitude in $Z + 2 \text{ jet}$ production. Left: The invariant mass distribution of di-jets in $Z + 2 \text{ jet}$ events selected from a signal region by ATLAS [59]. Right: The BDT distribution of $Z + 2 \text{ jet}$ events selected from a signal region by CMS in the di-muon channel [60].

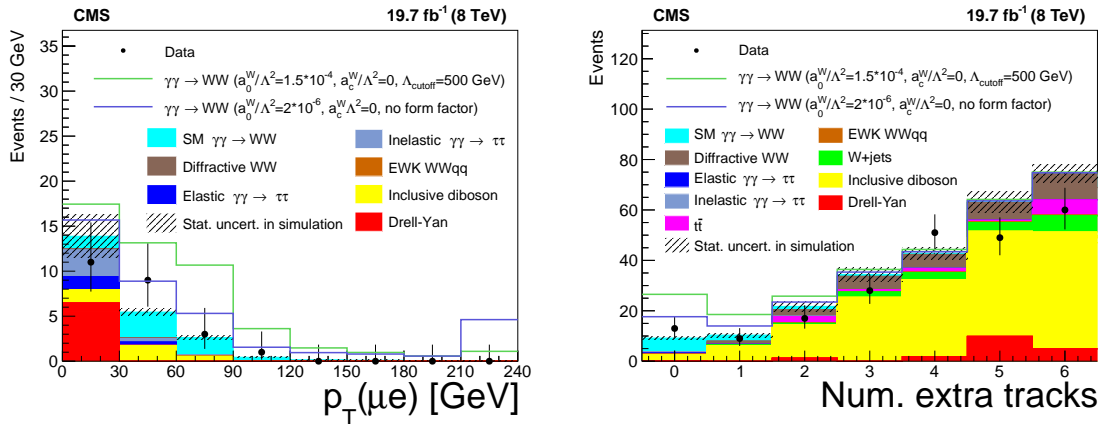


Figure 16. Evidence for exclusive diboson production via $pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}$ [61]. Distributions of muon-electron transverse momentum for events with zero associated tracks (left), and extra-tracks multiplicity for events with $p_T(\mu^{\pm}e^{\mp}) > 30 \text{ GeV}$ (right). The data are shown by the points with error bars; the histograms indicate the expected SM signal and backgrounds.

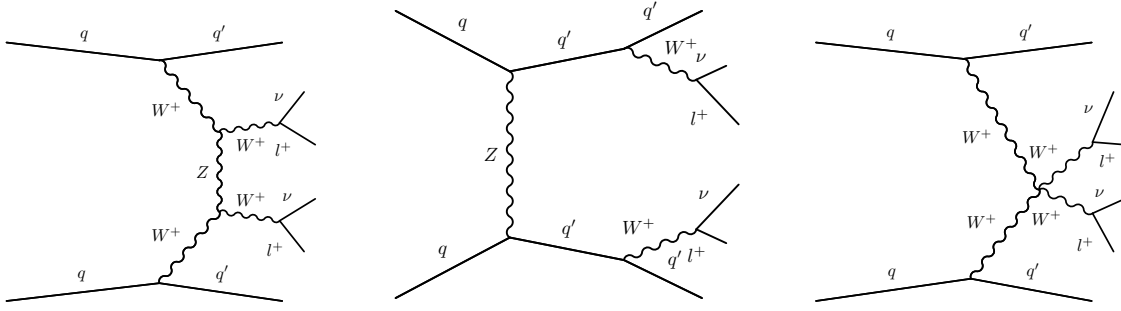


Figure 17. Representative Feynman diagrams for same-sign WW production in association with two jets from purely electroweak contributions: (left) vector boson fusion, (middle) bremsstrahlung-like, and (right) multiperipheral production [75].

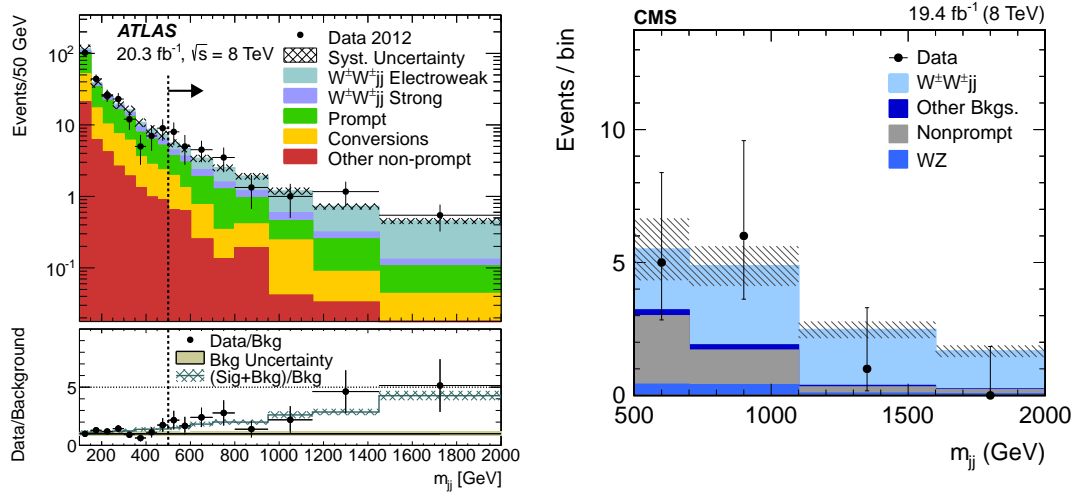


Figure 18. Left: Di-jet invariant mass distribution of $W^\pm W^\pm jj$ candidates selected by ATLAS [66]. The inclusive signal region is indicated by the arrow. Right: Di-jet invariant mass distribution of $W^\pm W^\pm jj$ candidates selected by CMS [75].

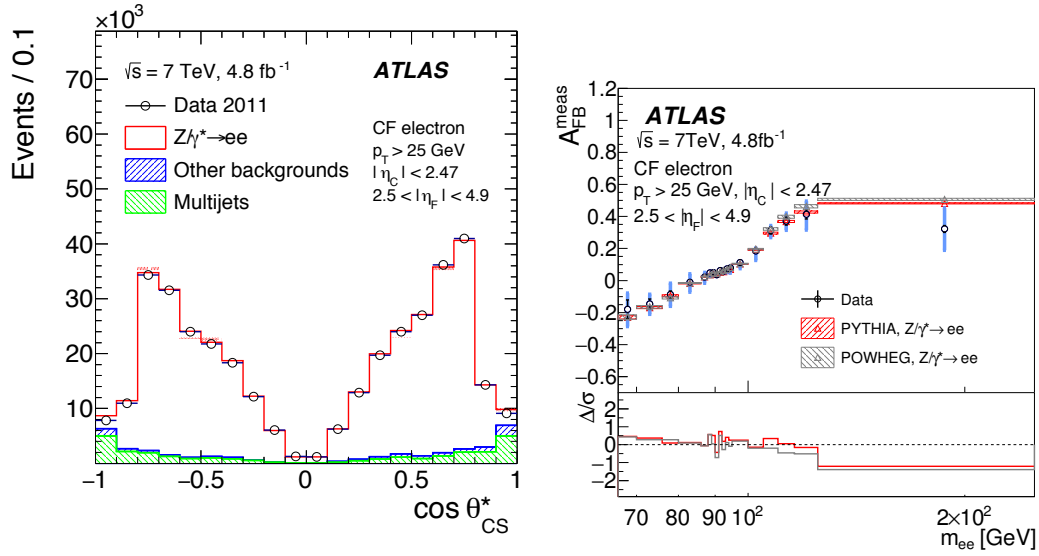


Figure 19. From the ATLAS analysis of the full 7 TeV dataset [85] on the left: The $\cos \theta^*$ distribution for selected central-forward electron pairs, compared with MC predictions. Right: $A_{FB}^{\text{meas}}(m)$ for central-forward electron pairs, compared with MC predictions using the best fit $\sin^2 \theta_W^{\text{eff}}$.

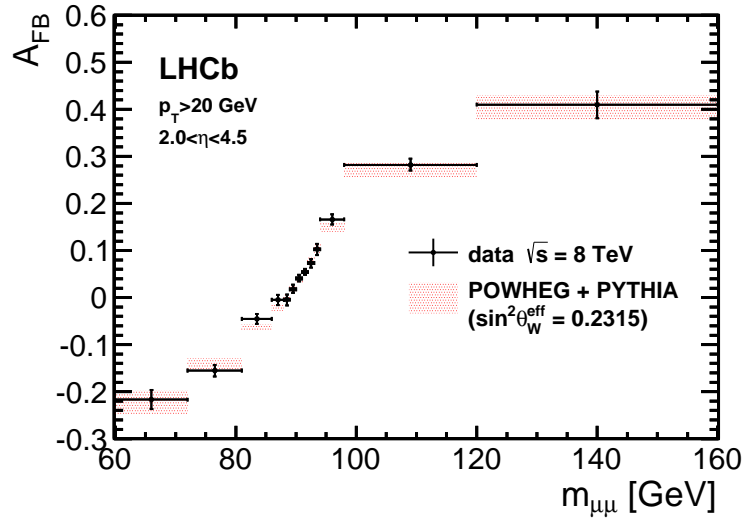


Figure 20. The unfolded A_{FB} distribution from LHCb 8 TeV data, as a function of di-muon mass, compared with NLO predictions from POWHEG-BOX [88].

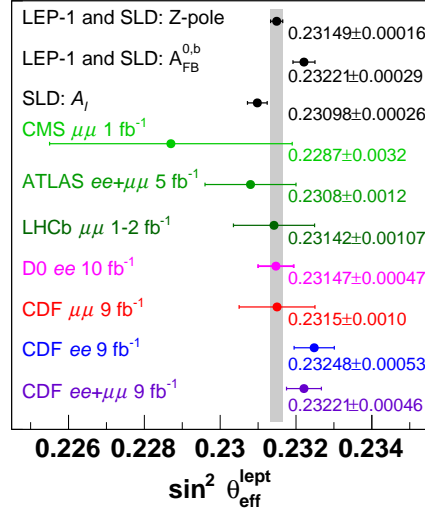


Figure 21. Comparison of experimental measurements of $\sin^2 \theta_W^{\text{lept}}$ [81].

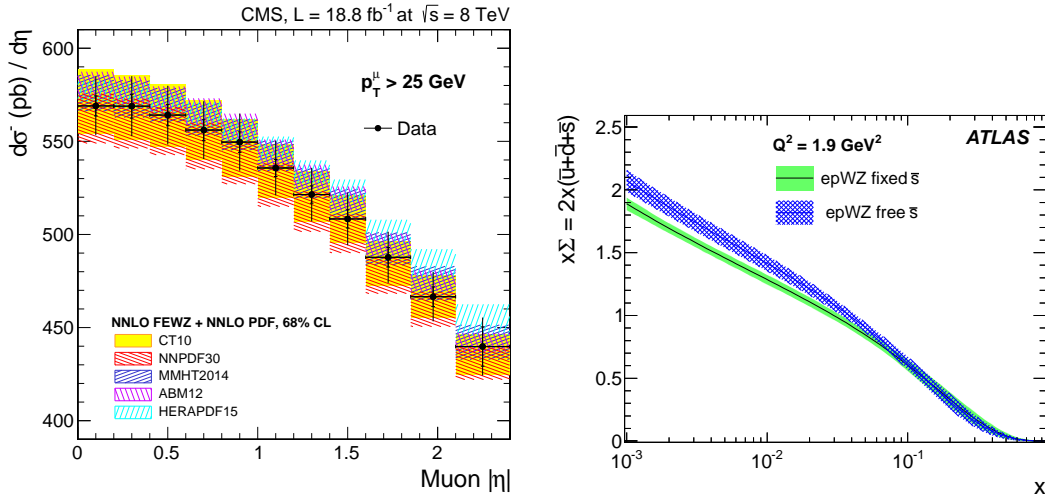


Figure 22. Left: CMS measurement of the W charge asymmetry at 8 TeV versus lepton rapidity, compared with predictions from various PDFs [94]. Right: ATLAS constraints on the strange quark PDF from W and Z boson lepton rapidity at 7 TeV [99].

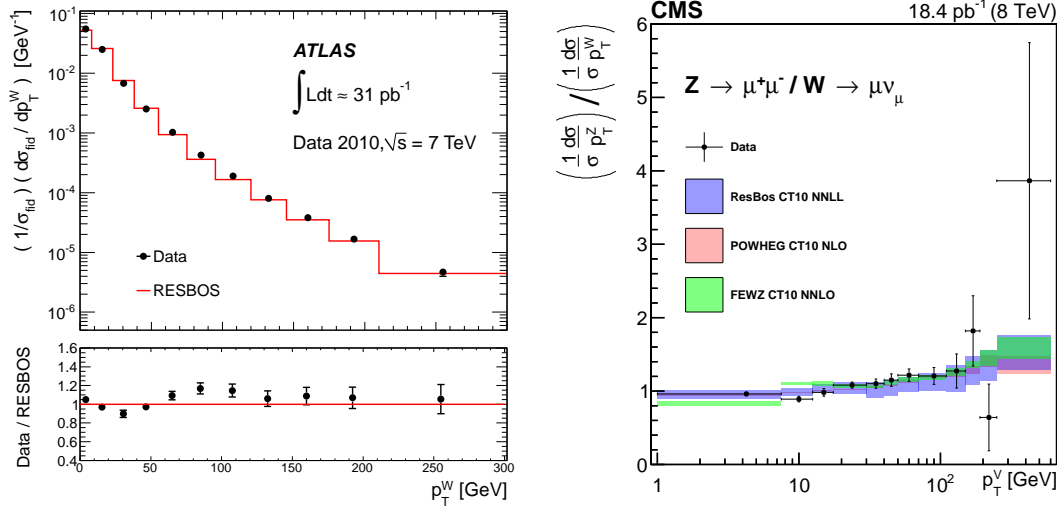


Figure 23. Left: W p_T distribution in 7 TeV ATLAS data, compared with predictions [106]. Right: Ratio of Z and W normalized differential cross sections with respect to boson transverse momentum in 8 TeV CMS data, compared with predictions [107].

6. Summary

The ATLAS and CMS experiments at the LHC have published a first set of electroweak measurements with the Run 1 data at a collision energy of 7 TeV and 8 TeV, probing the electroweak sector at the hitherto highest available scales. We started with the discussion of precision measurements of Drell-Yan production, a well understood electroweak process that in turn is used to validate theoretical calculations with higher order corrections in α_s and the PDF's of the proton. The total and differential cross section measurements help to reduce the theoretical cross section uncertainties of multi-boson processes, which are generally of the same order as the current experimental uncertainties. We reviewed the set of results available so far on inclusive di-boson production at the LHC. All inclusive di-boson final states (W^+W^- , $W^\pm Z$, ZZ , $W^\pm\gamma$, $Z\gamma$) have been observed and cross section measurements are available for collision energies of 7 TeV and 8 TeV. The complete set of measurements from both ATLAS and CMS including leptonic and semi-leptonic decay channels is expected to be published towards the end of 2016. A highlight of the electroweak physics program at the LHC is the observation of electroweak production channels that became accessible for the first time, namely processes with three vector bosons in the final state, and vector boson scattering processes that are characterized by two forward jets and two vector bosons in the final state.

For most total and fiducial cross section measurements with the full Run 1 dataset the systematic uncertainties already limit the precision. The exceptions are processes with cross sections below a few fb, e.g. tri-boson production. To probe the validity of the standard model at high partonic center-of-mass energy the limits set in the framework of anomalous gauge couplings are surpassing legacy measurements at LEP and the Tevatron, and are expected to further improve with increased \sqrt{s} and integrated luminosity.

The set of Run 1 results, once completed, will present a unique legacy of electroweak precision results at \sqrt{s} values of 7 and 8 TeV. Run 2 analysis will extend the energy range to $\sqrt{s} = 13$ TeV and provide even more sensitivity to anomalous gauge couplings. Potentially, the combination of ATLAS and CMS results will allow for more stringent constraints. In addition, the combination with Higgs measurements in the framework of EFT with shared anomalous coupling operators is being actively pursued and will allow a further reduction of the allowed parameter space. Precision measurements or first observations of more tri-boson production and VBS processes will also become possible with the full Run 2 data set.

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- [1] Chatrchyan S *et al.* 2012 *Physics Letters B* **716** 30 – 61 ISSN 0370-2693 URL <http://www.sciencedirect.com/science/article/pii/S0370269312008581>
- [2] Aad G *et al.* 2012 *Physics Letters B* **716** 1 – 29 ISSN 0370-2693 URL <http://www.sciencedirect.com/science/article/pii/S037026931200857X>
- [3] Weinberg S 1979 *Physica* **A96** 327–340
- [4] Weinberg S 1980 *Phys. Lett.* **B91** 51–55
- [5] Georgi H 1993 *Ann. Rev. Nucl. Part. Sci.* **43** 209–252
- [6] Hagiwara K, Ishihara S, Szalapski R and Zeppenfeld D 1993 *Phys. Rev.* **D48** 2182–2203
- [7] Degrande C, Greiner N, Kilian W, Mattelaer O, Mebane H, Stelzer T, Willenbrock S and Zhang C 2013 *Annals Phys.* **335** 21–32 (*Preprint* 1205.4231)
- [8] Eboli O J P, Gonzalez-Garcia M C and Mizukoshi J K 2006 *Phys. Rev.* **D74** 073005 (*Preprint* hep-ph/0606118)
- [9] Degrande C 2014 *JHEP* **02** 101 (*Preprint* 1308.6323)
- [10] Alboteanu A, Kilian W and Reuter J 2008 *JHEP* **11** 010 (*Preprint* 0806.4145)
- [11] Chung S U, Brose J, Hackmann R, Klempt E, Spanier S and Strassburger C 1995 *Annalen Phys.* **4** 404–430
- [12] Falkowski A and Riva F 2015 *JHEP* **02** 039 (*Preprint* 1411.0669)
- [13] Baak M, Cth J, Haller J, Hoecker A, Kogler R, Mnig K, Schott M and Stelzer J (Gfitter Group) 2014 *Eur. Phys. J.* **C74** 3046 (*Preprint* 1407.3792)
- [14] Ciuchini M, Franco E, Mishima S and Silvestrini L 2013 *JHEP* **08** 106 (*Preprint* 1306.4644)
- [15] Andersen J R *et al.* 2016 Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report *9th Les Houches Workshop on Physics at TeV Colliders (PhysTeV 2015) Les Houches, France, June 1-19, 2015* (*Preprint* 1605.04692) URL <http://lss.fnal.gov/archive/2016/conf/fermilab-conf-16-175-ppd-t.pdf>
- [16] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Lett.* **B725** 223–242 (*Preprint* 1305.4192)
- [17] Melnikov K and Petriello F 2006 *Phys. Rev.* **D74** 114017 (*Preprint* hep-ph/0609070)
- [18] Gavin R, Li Y, Petriello F and Quackenbush S 2011 *Comput. Phys. Commun.* **182** 2388–2403 (*Preprint* 1011.3540)
- [19] Li Y and Petriello F 2012 *Phys. Rev.* **D86** 094034 (*Preprint* 1208.5967)
- [20] Khachatryan V *et al.* (CMS Collaboration) 2015 *Eur.Phys.J.* **C75** 147 (*Preprint* 1412.1115)
- [21] Aad G *et al.* (ATLAS) 2014 *Eur. Phys. J.* **C74** 3134 (*Preprint* 1407.2410)
- [22] Khachatryan V *et al.* (CMS) 2015 *JHEP* **04** 025 (*Preprint* 1412.6302)
- [23] 2012 Measurement of the total ZZ production cross section in the four-lepton channel with 4.7 fb-1 of ATLAS data Tech. Rep. ATLAS-CONF-2012-026 CERN Geneva URL <http://cds.cern.ch/record/1430735>
- [24] Olive K A *et al.* (Particle Data Group) 2014 *Chin. Phys.* **C38** 090001
- [25] Aad G *et al.* (ATLAS Collaboration) 2013 *JHEP* **1303** 128 (*Preprint* 1211.6096)
- [26] Aad G *et al.* (ATLAS) 2016 *Phys. Rev. Lett.* **116** 101801 (*Preprint* 1512.05314)
- [27] Chatrchyan S *et al.* (CMS Collaboration) 2013 *JHEP* **1301** 063 (*Preprint* 1211.4890)
- [28] Khachatryan V *et al.* (CMS) 2015 *Phys. Lett.* **B740** 250–272 (*Preprint* 1406.0113)
- [29] Khachatryan V *et al.* (CMS Collaboration) 2015 (*Preprint* 1503.05467)
- [30] Campbell J M, Ellis R K and Williams C 2011 *JHEP* **07** 018 (*Preprint* 1105.0020)
- [31] Cascioli F, Gehrmann T, Grazzini M, Kallweit S, Maierhofer P, von Manteuffel A, Pozzorini S, Rathlev D, Tancredi L and Weihs E 2014 *Phys. Lett.* **B735** 311–313 (*Preprint* 1405.2219)
- [32] Bierweiler A, Kasprzik T and Kohn J H 2013 *JHEP* **12** 071 (*Preprint* 1305.5402)
- [33] Baglio J, Ninh L D and Weber M M 2013 *Phys. Rev.* **D88** 113005 (*Preprint* 1307.4331)
- [34] Baur U and Rainwater D L 2001 *Int. J. Mod. Phys.* **A16S1A** 315–317 (*Preprint* hep-ph/0011016)
- [35] Herndon M 2015 Limits on anomalous triple and quartic gauge couplings URL

- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC>
- [36] LEP Electroweak Gauge-Couplings Group 2002 A combination of preliminary results on gauge boson couplings measured by the lep experiments URL <http://lepewwg.web.cern.ch/lepww/tgc/summer02>
 - [37] Aad G *et al.* (ATLAS Collaboration) 2012 *Eur.Phys.J.* **C72** 2173 (*Preprint* 1208.1390)
 - [38] Aad G *et al.* (ATLAS) 2016 (*Preprint* 1603.02151)
 - [39] Frixione S and Webber B R 2002 *JHEP* **06** 029 (*Preprint* hep-ph/0204244)
 - [40] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Rev.* **D87** 112001 (*Preprint* 1210.2979)
 - [41] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Eur.Phys.J.* **C73** 2610 (*Preprint* 1306.1126)
 - [42] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Phys.Lett.* **B721** 190–211 (*Preprint* 1301.4698)
 - [43] Gounaris G *et al.* 1996 Triple gauge boson couplings *AGS / RHIC Users Annual Meeting Upton, New York, June 15-16, 1995* (*Preprint* hep-ph/9601233) URL <http://alice.cern.ch/format/showfull?sysnb=0215385>
 - [44] Aad G *et al.* (ATLAS Collaboration) 2015 *JHEP* **1501** 049 (*Preprint* 1410.7238)
 - [45] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Eur.Phys.J.* **C73** 2283 (*Preprint* 1210.7544)
 - [46] Hagiwara K, Ishihara S, Szalapski R and Zeppenfeld D 1992 *Physics Letters B* **283** 353 – 359 ISSN 0370-2693 URL <http://www.sciencedirect.com/science/article/pii/037026939290031X>
 - [47] Hagiwara K, Ishihara S, Szalapski R and Zeppenfeld D 1993 *Phys. Rev. D* **48**(5) 2182–2203 URL <http://link.aps.org/doi/10.1103/PhysRevD.48.2182>
 - [48] Chatrchyan S *et al.* (CMS Collaboration) 2014 *Eur.Phys.J.* **C74** 2973 (*Preprint* 1403.3047)
 - [49] Chatrchyan S *et al.* (CMS Collaboration) 2013 *JHEP* **1310** 164 (*Preprint* 1309.1117)
 - [50] Aad G *et al.* (ATLAS) 2016 *Phys. Rev. D* (*Preprint* 1604.05232)
 - [51] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Rev.* **D87** 112003 (*Preprint* 1302.1283)
 - [52] Chatrchyan S *et al.* (CMS Collaboration) 2014 *Phys.Rev.* **D89** 092005 (*Preprint* 1308.6832)
 - [53] Khachatryan V *et al.* (CMS Collaboration) 2015 *JHEP* **1504** 164 (*Preprint* 1502.05664)
 - [54] Khachatryan V *et al.* (CMS) 2016 (*Preprint* 1602.07152)
 - [55] Baur U and Berger E L 1993 *Phys. Rev. D* **47**(11) 4889–4904 URL <http://link.aps.org/doi/10.1103/PhysRevD.47.4889>
 - [56] Aad G *et al.* (ATLAS) 2015 *Phys. Rev. Lett.* **115** 031802 (*Preprint* 1503.03243)
 - [57] Chatrchyan S *et al.* (CMS) 2014 *Phys. Rev.* **D90** 032008 (*Preprint* 1404.4619)
 - [58] Alwall J, Frederix R, Frixione S, Hirschi V, Maltoni F, Mattelaer O, Shao H S, Stelzer T, Torrielli P and Zaro M 2014 *JHEP* **07** 079 (*Preprint* 1405.0301)
 - [59] Aad G *et al.* (ATLAS Collaboration) 2014 *JHEP* **1404** 031 (*Preprint* 1401.7610)
 - [60] Khachatryan V *et al.* (CMS Collaboration) 2015 *Eur.Phys.J.* **C75** 66 (*Preprint* 1410.3153)
 - [61] Khachatryan V *et al.* (CMS) 2016 (*Preprint* 1604.04464)
 - [62] Vermaseren J A M 1983 *Nucl. Phys.* **B229** 347–371
 - [63] Baranov S P, Duenger O, Shooshtari H and Vermaseren J A M 1991 LPAIR: A generator for lepton pair production *In *Hamburg 1991, Proceedings, Physics at HERA, vol. 3* 1478-1482. (see HIGH ENERGY PHYSICS INDEX 30 (1992) No. 12988)*
 - [64] Alwall J, Herquet M, Maltoni F, Mattelaer O and Stelzer T 2011 *JHEP* **06** 128 (*Preprint* 1106.0522)
 - [65] Chatrchyan S *et al.* (CMS Collaboration) 2013 *JHEP* **1307** 116 (*Preprint* 1305.5596)
 - [66] Aad G *et al.* (ATLAS Collaboration) 2014 *Phys.Rev.Lett.* **113** 141803 (*Preprint* 1405.6241)
 - [67] Nason P 2004 *JHEP* **11** 040 (*Preprint* hep-ph/0409146)
 - [68] Frixione S, Nason P and Oleari C 2007 *JHEP* **11** 070 (*Preprint* 0709.2092)
 - [69] Alioli S, Nason P, Oleari C and Re E 2010 *JHEP* **06** 043 (*Preprint* 1002.2581)
 - [70] Jager B, Oleari C and Zeppenfeld D 2009 *Phys. Rev.* **D80** 034022 (*Preprint* 0907.0580)
 - [71] Melia T, Melnikov K, Rontsch R and Zanderighi G 2010 *JHEP* **12** 053 (*Preprint* 1007.5313)
 - [72] Melia T, Nason P, Rontsch R and Zanderighi G 2011 *Eur. Phys. J.* **C71** 1670 (*Preprint* 1102.4846)
 - [73] Kilian W, Ohl T and Reuter J 2011 *Eur. Phys. J.* **C71** 1742 (*Preprint* 0708.4233)

- [74] Moretti M, Ohl T and Reuter J 2001 1981–2009 (*Preprint hep-ph/0102195*)
- [75] Khachatryan V *et al.* (CMS Collaboration) 2015 *Phys.Rev.Lett.* **114** 051801 (*Preprint 1410.6315*)
- [76] Baglio J *et al.* 2014 (*Preprint 1404.3940*)
- [77] Arnold K *et al.* 2011 (*Preprint 1107.4038*)
- [78] Arnold K *et al.* 2009 *Comput. Phys. Commun.* **180** 1661–1670 (*Preprint 0811.4559*)
- [79] Schael S *et al.* (SLD Electroweak Group, DELPHI, ALEPH, SLD, SLD Heavy Flavour Group, OPAL, LEP Electroweak Working Group, L3) 2006 *Phys. Rept.* **427** 257–454 (*Preprint hep-ex/0509008*)
- [80] Collins J C and Soper D E 1977 *Phys. Rev.* **D16** 2219
- [81] Aaltonen T A *et al.* (CDF) 2016 *Phys. Rev.* **D93** 112016 (*Preprint 1605.02719*)
- [82] Aaltonen T A *et al.* (CDF) 2014 *Phys. Rev.* **D89** 072005 (*Preprint 1402.2239*)
- [83] Abazov V M *et al.* (D0) 2015 *Phys. Rev. Lett.* **115** 041801 (*Preprint 1408.5016*)
- [84] Chatrchyan S *et al.* (CMS Collaboration) 2011 *Phys.Rev.* **D84** 112002 (*Preprint 1110.2682*)
- [85] Aad G *et al.* (ATLAS) 2015 *JHEP* **09** 049 (*Preprint 1503.03709*)
- [86] Alves A Augusto J *et al.* (LHCb Collaboration) 2008 *JINST* **3** S08005
- [87] Aaij R *et al.* (LHCb) 2015 *Int. J. Mod. Phys.* **A30** 1530022 (*Preprint 1412.6352*)
- [88] Aaij R *et al.* (LHCb) 2015 *JHEP* **11** 190 (*Preprint 1509.07645*)
- [89] Aad G *et al.* (ATLAS) 2012 *Phys. Rev.* **D85** 072004 (*Preprint 1109.5141*)
- [90] Ball R D, Bertone V, Carrazza S, Del Debbio L, Forte S, Guffanti A, Hartland N P and Rojo J (NNPDF) 2013 *Nucl. Phys.* **B877** 290–320 (*Preprint 1308.0598*)
- [91] Ball R D *et al.* 2013 *Nucl. Phys.* **B867** 244–289 (*Preprint 1207.1303*)
- [92] Aaltonen T A *et al.* (CDF Collaboration, D0 Collaboration) 2013 *Phys.Rev.* **D88** 052018 (*Preprint 1307.7627*)
- [93] Chatrchyan S *et al.* (CMS) 2014 *Phys. Rev.* **D90** 032004 (*Preprint 1312.6283*)
- [94] Khachatryan V *et al.* (CMS) 2016 (*Preprint 1603.01803*)
- [95] Aaltonen T *et al.* (CDF Collaboration) 2012 *Phys.Rev.Lett.* **108** 151803 (*Preprint 1203.0275*)
- [96] Abazov V M *et al.* (D0 Collaboration) 2012 *Phys.Rev.Lett.* **108** 151804 (*Preprint 1203.0293*)
- [97] Aaij R *et al.* (LHCb) 2014 *JHEP* **12** 079 (*Preprint 1408.4354*)
- [98] Chatrchyan S *et al.* (CMS Collaboration) 2012 *Phys.Rev.Lett.* **109** 111806 (*Preprint 1206.2598*)
- [99] Aad G *et al.* (ATLAS) 2012 *Phys. Rev. Lett.* **109** 012001 (*Preprint 1203.4051*)
- [100] Bozzi G, Citelli L and Vicini A 2015 *Phys. Rev.* **D91** 113005 (*Preprint 1501.05587*)
- [101] Bozzi G, Rojo J and Vicini A 2011 *Phys.Rev.* **D83** 113008 (*Preprint 1104.2056*)
- [102] Ladinsky G A and Yuan C P 1994 *Phys. Rev.* **D50** 4239 (*Preprint hep-ph/9311341*)
- [103] Landry F, Brock R, Nadolsky P M and Yuan C P 2003 *Phys. Rev.* **D67** 073016 (*Preprint hep-ph/0212159*)
- [104] Guzzi M, Nadolsky P M and Wang B 2014 *Phys. Rev.* **D90** 014030 (*Preprint 1309.1393*)
- [105] Gavin R, Li Y, Petriello F and Quackenbush S 2013 *Comput. Phys. Commun.* **184** 208–214 (*Preprint 1201.5896*)
- [106] Aad G *et al.* (ATLAS) 2012 *Phys. Rev.* **D85** 012005 (*Preprint 1108.6308*)
- [107] Khachatryan V *et al.* (CMS) 2016 (*Preprint 1606.05864*)