

Electroweak physics at the LHC

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Abstract. The Large Hadron Collider (LHC) has completed in 2012 its first running phase and the experiments have collected data sets of pp collisions at center-of-mass energies of 7 and 8 TeV with an integrated luminosity of about 5 fb^{-1} 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 and CMS experiments at the LHC and discusses phenomenological developments in the electroweak sector.

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1. Introduction

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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 [1]. 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 [2, 3]. 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 [4]. 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 [5]. CMS has limits with similar sensitivity estimated for LL contact interactions [6].

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 and 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 also 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 QCD backgrounds. The four lepton final state provides an almost background free signature, at the expense of a relatively small branching ratio $BR(ZZ) \rightarrow \ell^+\ell^-\ell^+\ell^- = 0.101^2 \cdot \frac{4}{9} = 0.0045$ [?]. The di-lepton and missing energy channel can exploit the one order of magnitude higher branching ratio of $BR(ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}) = 0.101 \cdot 0.20 \cdot 2 \cdot \frac{2}{3} = 0.0269$, at the expense of high background levels.

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 [20], and at 13 TeV in the $\ell^+\ell^-\ell^+\ell^-$ final state [21]. The CMS collaboration has analysed the full 7 and 8 TeV data sets in both the $\ell^+\ell^-\ell^+\ell^-$ [22, ?] and $\ell^+\ell^-\nu\bar{\nu}$ final state [23].

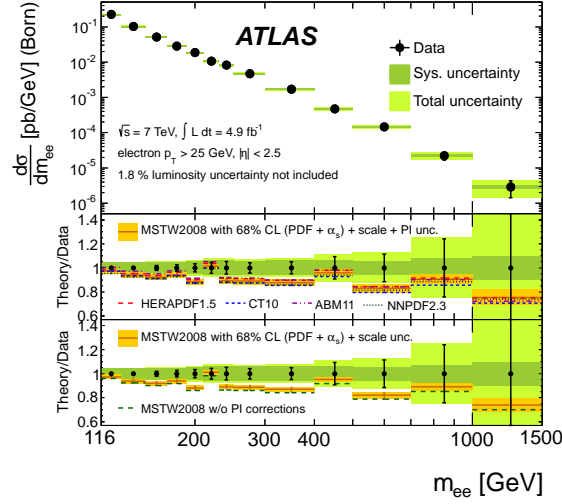


Figure 1. Measured differential cross-section at the Born level within the fiducial region (electron $p_T > 25$ GeV and $|\eta| < 2.5$) with statistical, systematic, and combined statistical and systematic (total) uncertainties, excluding the 1.8% uncertainty on the luminosity. On the left, in the upper 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 factorisation 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.

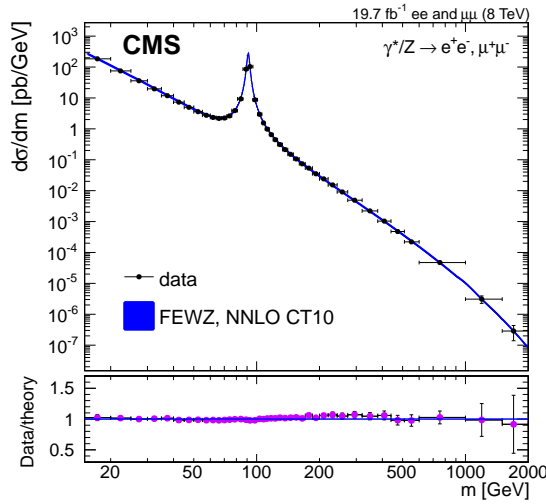


Figure 2. The DY differential cross section as measured in the combined dilepton channel and as predicted by NNLO FEWZ 3.1 with CT10 PDF calculations, for the full phase space.

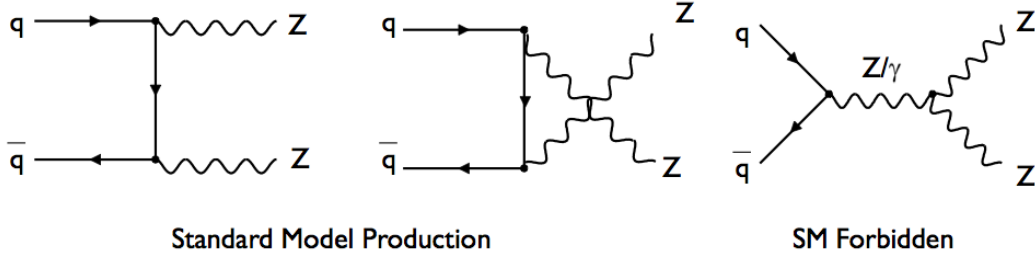


Figure 3. Leading order Feynman diagrams of ZZ production in the dominant $q\bar{q}$ channel. The ZZ production via the s -channel is not allowed in the SM.

Theoretical predictions for ZZ production are available at NLO in α_s [?]. In addition, electroweak corrections at NLO have been calculated [?, ?].

The event selection for the $\ell^+\ell^-\ell^+\ell^-$ final state requires exactly four leptons fulfilling a set of cuts on kinematic quantities. ATLAS and CMS use similar criteria as listed in detail in Table ???. 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 $Z + jets$, , and di-boson events. The background is estimated from data by control regions with looser selection criteria.

Events in the $\ell^+\ell^-\nu\bar{\nu}$ final state are characterized by exactly two leptons and missing energy. The event selection requires a leptonic Z candidate and missing energy in the event. Both experiments used refined observables of missing energy with additional information to improve the rejection against instrumental background. The background level is in the same order as the signal and substantially higher then for $\ell^+\ell^-\ell^+\ell^-$. 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 Tabel 1. ATLAS and CMS use different definitions of the fiducial phase space which needs to be taken into account to make a direct comparison is possible. For the total cross section a slightly different mass range for the Z mass range is used, where CMS uses a wider range of $60 \text{ GeV} < m_Z < 120 \text{ GeV}$ then ATLAS with $66 \text{ GeV} < m_Z < 116 \text{ GeV}$, which contributes to the difference in the quoted predicted cross section. Good agreement of experimental and theoretical cross section values is observed.

Limits on 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). A comparison of the measured and predicted differential cross sections in the four-lepton invariant mass is shown from CMS in Figure 4. Also shown is

Experiment	decay channel	\sqrt{s}	measured σ_{total} [pb]	predicted σ_{total} [pb]	reference
ATLAS	$\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-\nu\bar{\nu}$	7 TeV	6.7 ± 0.7 (stat.) $^{+0.4}_{-0.3}$ (syst.) ± 0.3 (lumi.)	$6.18^{+0.25}_{-0.18}$	[20]
CMS	$\ell^+\ell^-\ell^+\ell^-$	7 TeV	$6.2 \pm ^{+0.9}_{-0.8}$ (stat.) $^{+0.4}_{-0.3}$ (syst.) ± 0.1 (lumi.)	6.3 ± 0.4	[22]
CMS	$\ell^+\ell^-\nu\bar{\nu}$	7 TeV	$5.2 \pm ^{+1.5}_{-1.4}$ (stat.) $^{+1.4}_{-1.1}$ (syst.) ± 0.2 (lumi.)	6.1 ± 0.3	[22]
CMS	$\ell^+\ell^-\ell^+\ell^-$	8 TeV	7.7 ± 0.5 (stat.) $^{+0.5}_{-0.4}$ (syst.) ± 0.2 (lumi.)	7.7 ± 0.6	[24]
CMS	$\ell^+\ell^-\nu\bar{\nu}$	8 TeV	6.9 ± 0.8 (stat.) $^{+1.8}_{-1.4}$ (syst.) ± 0.3 (lumi.)	7.6 ± 0.3	[22]
ATLAS	$\ell^+\ell^-\ell^+\ell^-$	13 TeV	$16.7 \pm ^{+2.2}_{-2.0}$ (stat.) $^{+0.9}_{-0.7}$ (syst.) $\pm ^{+1.0}_{-0.7}$ (lumi.)	$15.6^{+0.4}_{-0.4}$	[?]

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

the prediction in the presence of a non-zero value of the anomalous coupling parameter $f_4^Z = 0.015$, which shows an enhancement over the SM value at high invariant masses.

Both experiment 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. [25]. The precision of the LHC results is driven by the steep increase of sensitivity with higher centre-of-mass energy and are about 2 orders of magnitude better compared to the combined LEP result [26].

3.2.2. WZ production At the LHC, $W^\pm Z$ diboson are produced from quark-antiquark initial states at leading order (LO) and quark-gluon initial states at next-to-leading order (NLO) [?]. The SM allowed s -channel diagram has a triple boson vertex and is sensitive to anomalous TGC of gauge bosons.

The ATLAS experiment measured the $W^\pm Z$ production cross section in the fully leptonic decay channel $\ell^+\ell^-\ell\nu$ [18] at $\sqrt{s} = 7$ TeV and set limits on anomalous charged TGC. In this analysis the final states involving electrons or muons are considered signal, whereas boson decays to tau's are considered as background. The dominant background sources are Z +jet and ZZ production, constituting about 40% of the background. The overall signal over background ratio is about 3.7. The dominant systematic uncertainty is from the data-driven estimate of the background, where the dominant Z + jets contributes with ($\pm 3.8\%$).

The fiducial cross section defined by $p_T^{\mu,e} > 15$ GeV for the leptons from the Z decay, $p_T^{\mu,e} > 15$ GeV for the lepton from the W , $|\eta^{\mu,e}| < 2.5$, $p_T^\nu > 25$ GeV, $|m_{l\bar{l}} - m_Z| < 10$ GeV, $M_T^W > 20$ GeV and $\Delta R > 0.3$ for the three possible $\ell\ell$ pairings. The fiducial and total cross sections are compared to the SM expectation at NLO in Table 3.2.2.

Experiment	cross section	\sqrt{s}	measured	predicted	reference
ATLAS	total	7 GeV	$19^{+1.4}_{-1.3}$ (stat.) $^{0.9}_{-0.9}$ (syst.) ± 0.4 (lumi.) pb	$17.6 \pm ^{+1.1}_{-1.0}$ pb	[18]
ATLAS	fiducial	7 GeV	$92 \pm ^{+7}_{-6}$ (stat.) $^4_{-4}$ (syst.) ± 2 (lumi.) fb	–	[18]

Table 2. Summary of measured fiducial and total $W^\pm Z$ production cross sections from ATLAS at 7 TeV centre-of-mass energies in the $\ell^+\ell^-\ell\nu$ final state.

In Figure 7 the differential cross section measured in bins of p_T^Z is shown, compared

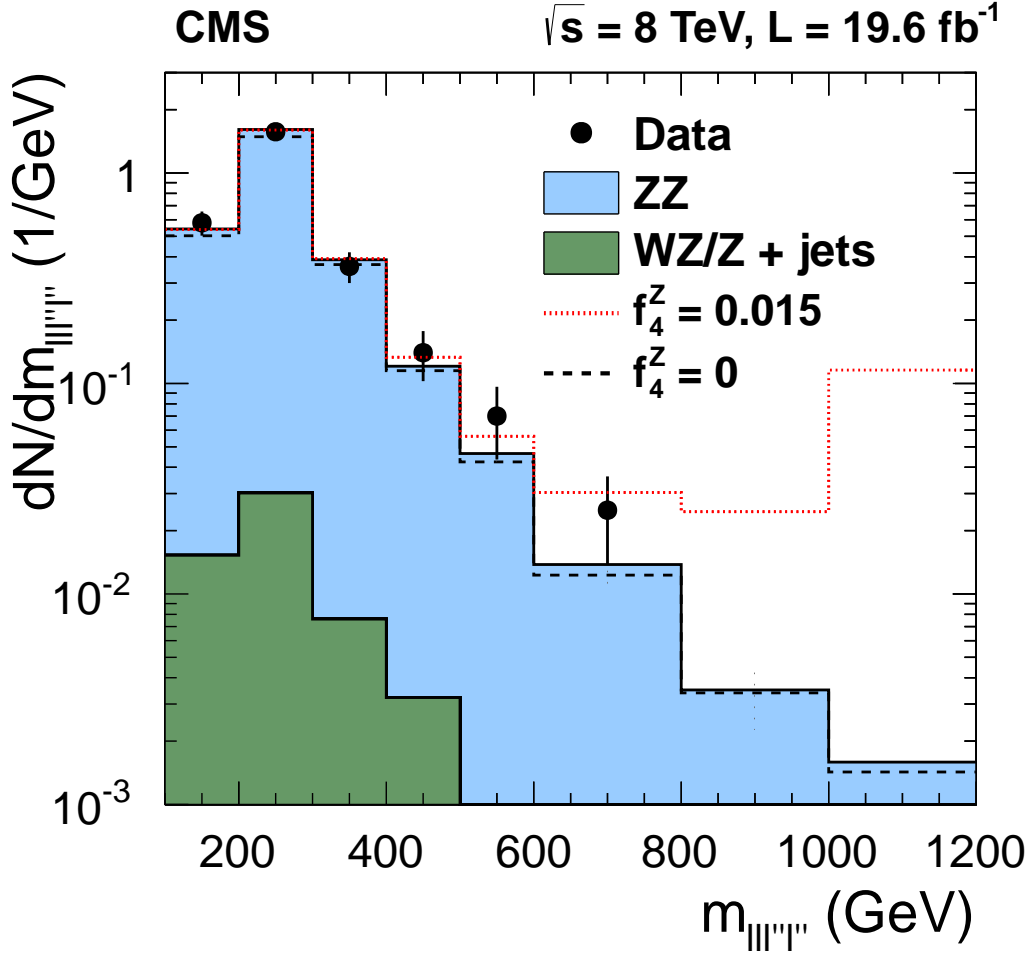


Figure 4. Distribution of the four-lepton reconstructed mass for the combined $4e$, 4μ , and $2e2\mu$ channels from CMS [?]. Points represent the data, the shaded histogram labeled ZZ represents the predictions for ZZ signal, the histograms labeled $W^\pm Z/Z+\text{jets}$ shows background estimated from 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.

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 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 . The ATGC parameter 95% CL limits are quoted using a form-factor of $\Lambda = 2$ TeV and without a form-factor, and summarized in Table 5.

3.2.3. WW production The W^+W^- production process has the highest production cross section among the massive vector diboson processes. It is also an important

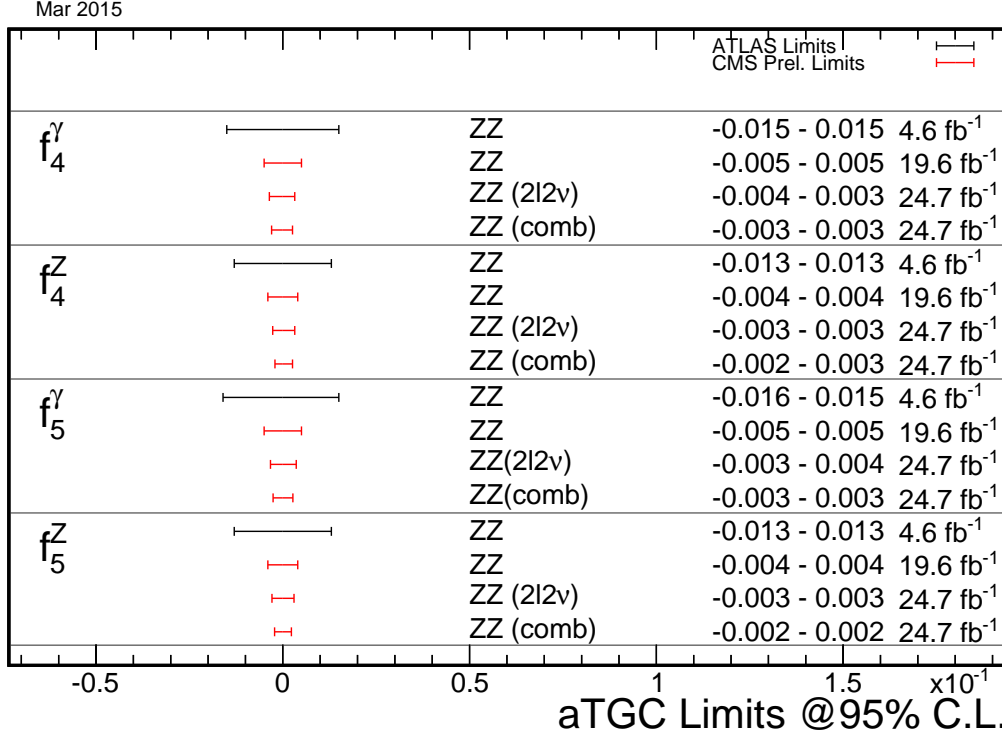


Figure 5. Comparison of the limits on f_{40}^V and f_{50}^V from ATLAS and CMS in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ channel at 7 and 8 TeV.

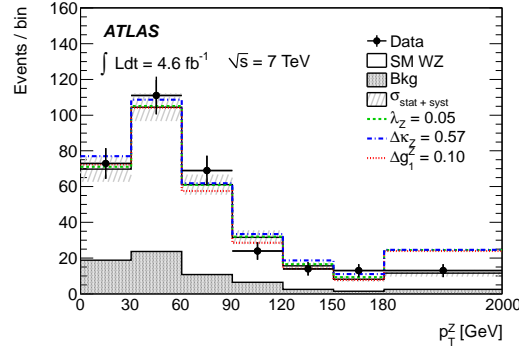


Figure 6. ATLAS measurement of the transverse momentum of the Z in $W^\pm Z$ events (p_T^Z) compared with the SM prediction at $\sqrt{s} = 7$ TeV. For illustration calculations for a set of anomalous couplings values are also shown. The full uncertainty contains statistical and systematic uncertainties.

Table 3. Expected and observed 95% CL on $\Delta\kappa_Z$, λ_Z and g_1^Z .

	Observed	Observed	Expected
	$\Lambda = 2$ TeV	no form factor	no form factor
g_1^Z	$[-0.074, 0.133]$	$[-0.057, 0.093]$	$[-0.046, 0.080]$
$\Delta\kappa_Z$	$[-0.42, 0.69]$	$[-0.37, 0.57]$	$[-0.33, 0.47]$
λ_Z	$[-0.064, 0.066]$	$[-0.046, 0.047]$	$[-0.041, 0.040]$

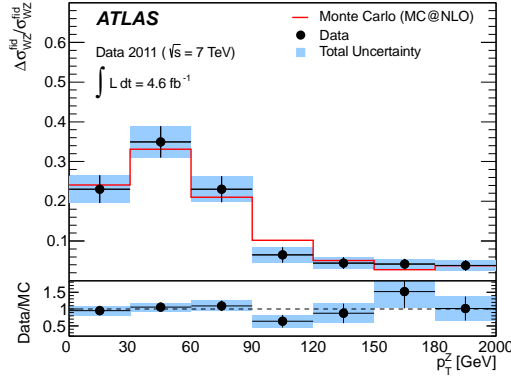


Figure 7. ATLAS measurement of the normalized fiducial cross-sections in bins of p_T^Z compared with the SM prediction at $\sqrt{s} = 7$ TeV. The full uncertainty contains statistical and systematic uncertainties.

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 published results for 7 TeV (ATLAS [12], CMS [15]) and 8 TeV (CMS [17]) centre-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, $W^\pm/\gamma^* + \text{jets}$, 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 about 5% for the W^+W^- production. The experiments quote a theoretical uncertainties on the signal acceptance due to variations of the parton distribution functions and renormalisation and factorization scale 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 summarised in Table 3.2.3. A good agreement of the experiments for the measured cross section as well as for the theoretical predictions is observed. A normalised 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. The

Experiment	cross section	\sqrt{s}	measured	predicted	reference
ATLAS	total	7 GeV	51.9 ± 2.0 (stat.) 3.9 (syst.) ± 2.0 (lumi.) pb	$44.7^{+2.1}_{-1.9}$ pb	[12]
CMS	total	7 GeV	52.4 ± 2.0 (stat.) 4.5 (syst.) ± 1.2 (lumi.) pb	47.0 ± 2.0 pb	[15]
CMS	total	8 GeV	69.9 ± 2.8 (stat.) 5.6 (syst.) ± 3.1 (lumi.) pb	$57.3^{+2.3}_{-1.6}$ pb	[15]

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

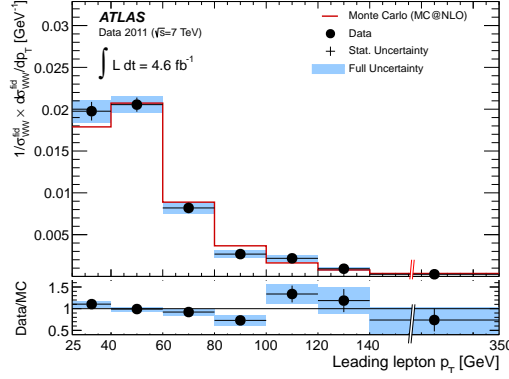


Figure 8. ATLAS measurement of the transverse momentum of the leading lepton in W^+W^- events compared with the SM prediction at $\sqrt{s} = 7$ TeV. The full uncertainty contains statistical and systematic uncertainties.

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 [12], CMS [15]). No form-factor is applied to the ATGC parameters.

	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	$[-0.048, 0.048]$	$[-0.062, 0.059]$	$[-0.060, 0.059]$

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 [27] 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 $W^\pm V \rightarrow \ell^\pm \nu q \bar{q}$ 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 centre 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 [13, 16].

Both analysis 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. [13] is shown. The largest systematic uncertainty is related to the modelling of the Z/W^\pm +jets background with about 20% on the cross section.

The measured and predicted cross sections are compared in Table 3.2.4.

Experiment	cross section	\sqrt{s}	measured	predicted	reference
ATLAS	total	7 GeV	68 ± 7 (stat.) ± 19 (syst.+lumi.) pb	61.1 ± 2.2 pb	[13]
CMS	total	7 GeV	$68.9 \pm \pm 8.7$ (stat.) ± 9.7 (syst.) ± 1.5 (lumi.) pb	65.6 ± 2.2 pb	[16]

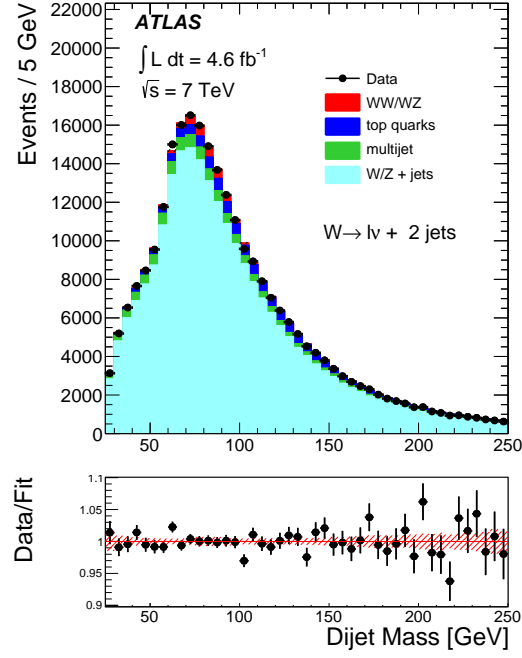
Table 6. Summary of measured total $W^\pm Z + W^+W^-$ production cross sections from ATLAS and CMS at 7 TeV centre-of-mass energies in the $W^\pm V \rightarrow \ell^\pm \nu q \bar{q}$ final state.

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 [27], while the CMS limits are derived in the HISZ [28, 29] scenario. The achieved precision is comparable to the fully leptonic channel.

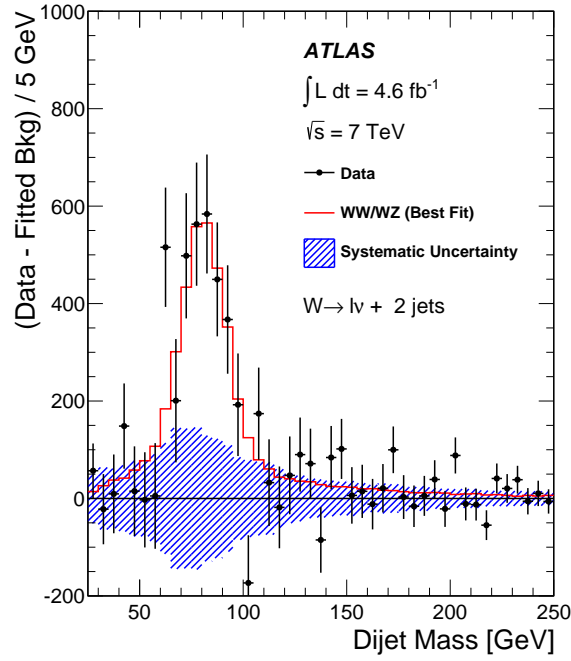
A measurement of the $W^\pm Z$ and ZZ production cross sections at $\sqrt{s} = 8$ TeV with a data set of 18.9fb^{-1} in the semileptonic final state with two b -quark jets from the Z and $\ell^+\ell^-$, $\nu\bar{\nu}$ or $\ell\nu$ has been published by CMS [19], so far the only published results at 8 TeV for these channels. The measured cross sections ($\sigma(pp \rightarrow$

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 [13] and CMS [16] collaborations.

	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	—	$[-0.055, 0.071]$	$[-0.072, 0.085]$



(a)



(b)

Figure 9. (a) The di-jet invariant mass spectrum for the sum of electron and muon channels, (b) the distribution of the background subtracted data. The lower panel shows that ratio of data and total fit result.

$W^\pm Z) = 30.7 \pm 9.3(\text{stat}) \pm 7.1(\text{syst}) \pm 4.1(\text{theo}) \pm 1.0(\text{lumi})\text{pb}$ and $\sigma(pp \rightarrow ZZ) = 6.5 \pm 1.7(\text{stat}) \pm 1.0(\text{syst}) \pm 0.9(\text{theo}) \pm 0.2(\text{lumi})\text{pb}$) are consistent with theoretical calculation at NLO in α_s ($\sigma(pp \rightarrow ZZ) = 22.3 \pm 1.1\text{pb}$ and $\sigma(pp \rightarrow ZZ) = 7.7 \pm 0.4\text{pb}$), 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 of photons 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 about two times 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 and making a direct comparison difficult. 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. For the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ process the cross section is defined as $E_T(\gamma) > 145(100)$ GeV, $|\eta(\gamma)| < 1.4(2.37)$, $p_T(\nu\nu) > 130(90)$ for CMS (ATLAS). A summary of the measurements is given in Table 3.2.5. Overall the agreement of the measured and NLO predicted cross sections is good.

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 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 for at 8 TeV measured by CMS in the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ channel [30] together with a hypotheticals 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.

Experiment	process	cross section	\sqrt{s}	measured	predicted	reference
ATLAS	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	inclusive	7 GeV	2.77 ± 0.03 (stat) ± 0.33 (syst) ± 0.14 (lumi) pb	1.96 ± 0.17 pb	[7]
ATLAS	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	exclusive	7 GeV	1.76 ± 0.03 (stat) ± 0.21 (syst) ± 0.08 (lumi) pb	1.39 ± 0.13 pb	[7]
ATLAS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	inclusive	7 GeV	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi) pb	1.18 ± 0.05 pb	[7]
ATLAS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	exclusive	7 GeV	1.05 ± 0.02 (stat) ± 0.10 (syst) ± 0.04 (lumi) pb	1.06 ± 0.05 pb	[7]
ATLAS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	inclusive	7 GeV	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi) pb	0.156 ± 0.012 pb	[9]
ATLAS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	exclusive	7 GeV	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi) pb	0.115 ± 0.009 pb	[9]
CMS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	inclusive	7 GeV	5.33 ± 0.08 (stat) ± 0.25 (syst) ± 0.12 (lumi) pb	5.45 ± 0.27 pb	[8]
CMS	$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	inclusive	7 GeV	37.0 ± 0.8 (stat) ± 4.0 (syst) ± 0.8 (lumi) pb	31.8 ± 1.8 pb	[8]
CMS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	inclusive	7 GeV	21.1 ± 4.2 (stat.) ± 4.3 (syst) ± 0.5 (lumi) fb	21.9 ± 1.1 fb	[9]
CMS	$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	inclusive	8 GeV	52.7 ± 2.1 (stat) ± 6.4 (syst) ± 1.4 (lumi) fb	40.7 ± 4.9 fb	[30]
CMS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	inclusive	8 GeV	2063 ± 19 (stat) ± 98 (syst) ± 54 (lumi) fb	2100 ± 120 fb	[10]
CMS	$Z\gamma \rightarrow \ell^+\ell^-\gamma$	exclusive	8 GeV	1770 ± 18 (stat) ± 115 (syst) ± 46 (lumi) fb	1800 ± 120 fb	[10]

Table 8. Summary of measured $V\gamma$ production cross sections from ATLAS and CMS at 7 and 8 TeV centre-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.

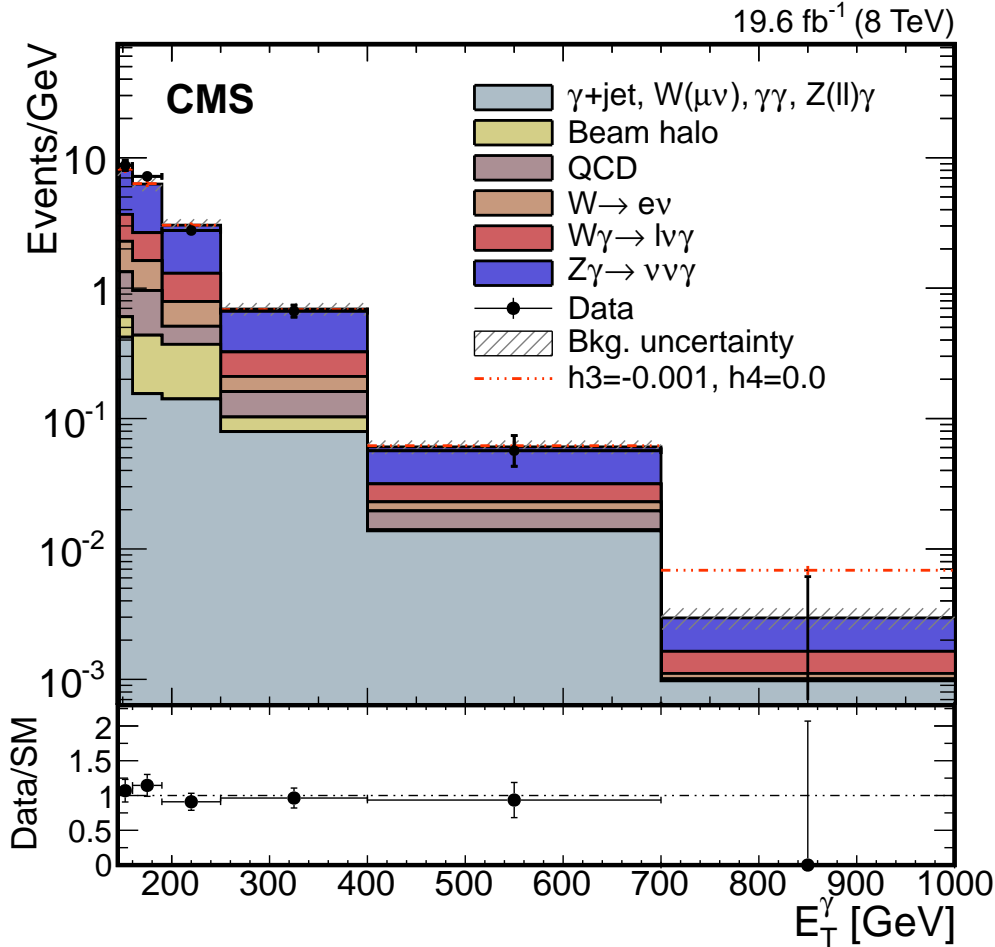


Figure 10. The $E_T(\gamma)$ distribution from CMS [30] in data (points) compared to signal and estimated background contributions (histogram). A aTGC signal with $h_{30}^V = -0.001$ is shown for comparison with the dot-dashed histogram. The background uncertainty includes statistical and systematic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

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.

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

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 triply heavy such channels (WWW, WWZ, WZZ, ZZZ) are not accessible anywhere near 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 problems, and sensitivity is at or near SM rates in Run 1.

An ATLAS analysis [31] 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, $E_T^{\text{miss}} > 25$ 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 diphoton invariant mass distributions of selected events, along with estimated backgrounds, are shown in Fig. 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 diphoton mass ($m_{\gamma\gamma} > 300$ GeV) is used to obtain 95% CL bounds on dimension 8 EFT couplings $f_{T,0}$ and $f_{M,(2,3)}$ [53]. 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 WVgamma 8 TeV [32]

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 [33, 34].

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 dijet phase space the electroweak amplitudes are dominant.

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 dijet 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 dilepton and dijet 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 dijet 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 dijet system. Additionally a multivariate discriminant is constructed which includes:

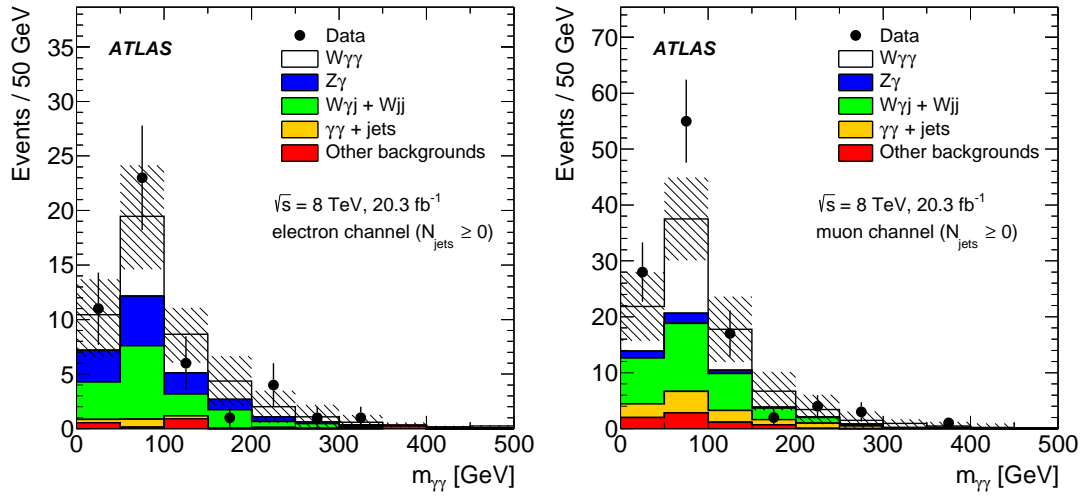


Figure 11. [31]

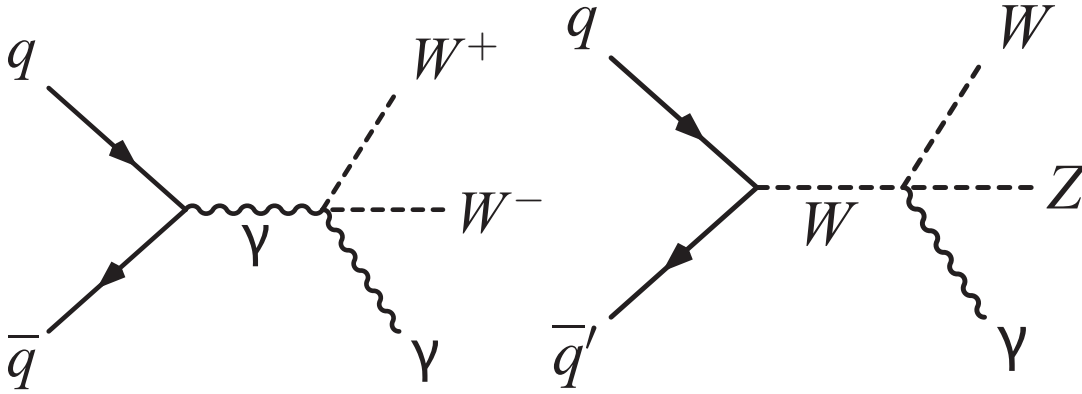


Figure 12. [32]

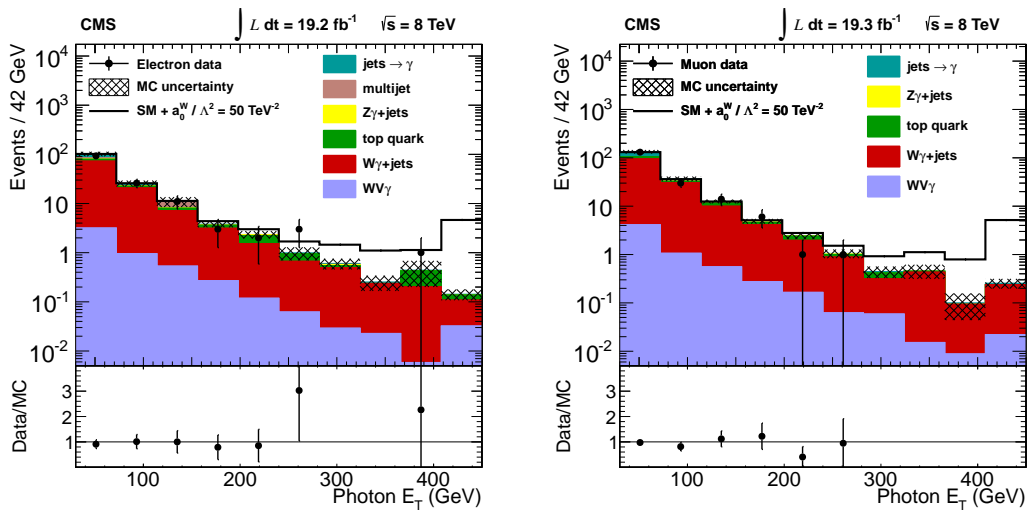


Figure 13. [32]

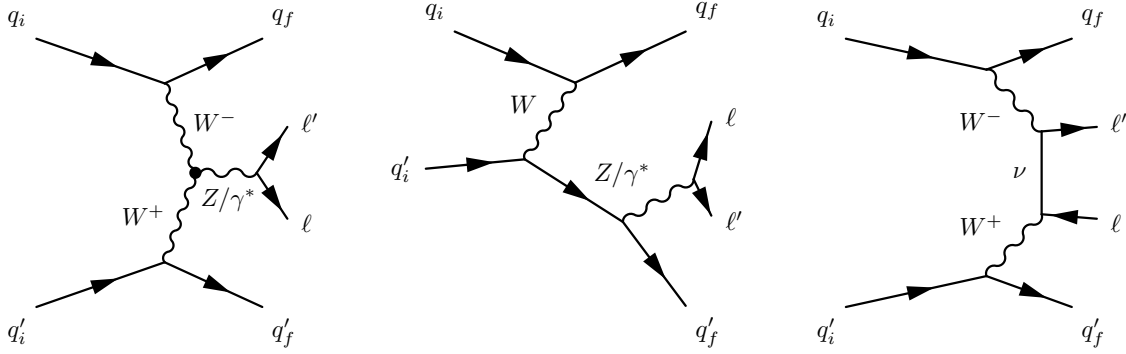


Figure 14. Representative Feynman diagrams for dilepton production in association with two jets from purely electroweak contributions: (left) vector boson fusion, (middle) bremsstrahlung-like, and (right) multiperipheral production.

- the dijet 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 dijet 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 dijet 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 dijet mass, increasing in significance for higher dijet 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 dijet 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 ± 18 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 diboson production, in two different channels. In one of them, CMS [35] has performed a search for exclusive diboson 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 dilepton 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 [36, 37]); proton dissociation is estimated to enhance the signal by a factor of 4.10 ± 0.43 with respect to an exclusive calculation from **MadGraph**.

Figure 16 shows the distributions of dilepton p_T and extra tracks in data compared with expectations from simulation. 13 events are observed with an expected background of 3.9 ± 0.6 in the 8 TeV data. In the 7 TeV [38] 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 diboson 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 Fig. 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 WZ) of a smaller relative QCD amplitude and smaller multi-lepton backgrounds from top quark, Drell-Yan, and WZ processes due to the same-sign dilepton requirement.

An ATLAS analysis [39] 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 dilepton mass less than 20 GeV or dielectrons 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 Fig. 18) and 34 for the VBS region. About half of selected events in either region are backgrounds from WZ , $W\gamma$ 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** [40, 41, 42, 43, 44, 45] 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 [46], calculated by **Whizard** [47, 48]: $0.14 < \alpha_4 < 0.16$ and $0.23 < \alpha_5 < 0.24$ limits are obtained at 95% CL.

A CMS analysis [49] 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 dilepton mass less than 50 GeV or dielectrons 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. The 12 events so selected are shown in Fig. 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 $4.0_{2.0}^{+2.4}(\text{stat})_{1.0}^{+1.1}(\text{syst})$ fb compared to an expected cross section estimated from **VBFNLO** [50, 51, 52] 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 $f_{T,(0,1,2)}$ [53]. 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 $-129\text{TeV}^{-4} < f_{S,1}/\Lambda^4 < 131\text{TeV}^{-4}$.

4.3. Z AFB and $\sin\theta_W$

4.4. W mass

5. Summary

Acknowledgments

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- [1] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Lett.* **B725** 223–242 (*Preprint* 1305.4192)
- [2] Melnikov K and Petriello F 2006 *Phys. Rev.* **D74** 114017 (*Preprint* hep-ph/0609070)
- [3] Li Y and Petriello F 2012 *Phys. Rev.* **D86** 094034 (*Preprint* 1208.5967)
- [4] Khachatryan V *et al.* (CMS Collaboration) 2015 *Eur.Phys.J.* **C75** 147 (*Preprint* 1412.1115)
- [5] Aad G *et al.* (ATLAS) 2014 *Eur. Phys. J.* **C74** 3134 (*Preprint* 1407.2410)
- [6] Khachatryan V *et al.* (CMS) 2015 *JHEP* **04** 025 (*Preprint* 1412.6302)
- [7] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Rev.* **D87** 112003 (*Preprint* 1302.1283)
- [8] Chatrchyan S *et al.* (CMS Collaboration) 2014 *Phys.Rev.* **D89** 092005 (*Preprint* 1308.6832)
- [9] Chatrchyan S *et al.* (CMS Collaboration) 2013 *JHEP* **1310** 164 (*Preprint* 1309.1117)
- [10] Khachatryan V *et al.* (CMS Collaboration) 2015 *JHEP* **1504** 164 (*Preprint* 1502.05664)
- [11] Aad G *et al.* (ATLAS Collaboration) 2015 *Phys.Rev.* **D91** 052005 (*Preprint* 1407.0573)
- [12] Aad G *et al.* (ATLAS Collaboration) 2013 *Phys.Rev.* **D87** 112001 (*Preprint* 1210.2979)
- [13] Aad G *et al.* (ATLAS Collaboration) 2015 *JHEP* **1501** 049 (*Preprint* 1410.7238)
- [14] 2014 Measurement of the W^+W^- production cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector Tech. Rep. ATLAS-CONF-2014-033 CERN Geneva
- [15] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Eur.Phys.J.* **C73** 2610 (*Preprint* 1306.1126)
- [16] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Eur.Phys.J.* **C73** 2283 (*Preprint* 1210.7544)
- [17] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Phys.Lett.* **B721** 190–211 (*Preprint* 1301.4698)
- [18] Aad G *et al.* (ATLAS Collaboration) 2012 *Eur.Phys.J.* **C72** 2173 (*Preprint* 1208.1390)
- [19] Chatrchyan S *et al.* (CMS Collaboration) 2014 *Eur.Phys.J.* **C74** 2973 (*Preprint* 1403.3047)
- [20] Aad G *et al.* (ATLAS Collaboration) 2013 *JHEP* **1303** 128 (*Preprint* 1211.6096)
- [21] Aad G *et al.* (ATLAS) 2016 *Phys. Rev. Lett.* **116** 101801 (*Preprint* 1512.05314)
- [22] Chatrchyan S *et al.* (CMS Collaboration) 2013 *JHEP* **1301** 063 (*Preprint* 1211.4890)
- [23] Khachatryan V *et al.* (CMS Collaboration) 2015 (*Preprint* 1503.05467)
- [24] Khachatryan V *et al.* (CMS) 2015 *Phys. Lett.* **B740** 250–272 (*Preprint* 1406.0113)
- [25] Herndon M 2015 Limits on anomalous triple and quartic gauge couplings URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC>
- [26] 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>
- [27] 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>
- [28] 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>

- [29] 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>
- [30] Khachatryan V *et al.* (CMS) 2016 (*Preprint* 1602.07152)
- [31] Aad G *et al.* (ATLAS Collaboration) 2015 (*Preprint* 1503.03243)
- [32] Chatrchyan S *et al.* (CMS Collaboration) 2014 (*Preprint* 1404.4619)
- [33] Aad G *et al.* (ATLAS Collaboration) 2014 *JHEP* **1404** 031 (*Preprint* 1401.7610)
- [34] Khachatryan V *et al.* (CMS Collaboration) 2015 *Eur.Phys.J.* **C75** 66 (*Preprint* 1410.3153)
- [35] Khachatryan V *et al.* (CMS) 2016 (*Preprint* 1604.04464)
- [36] Vermaseren J A M 1983 *Nucl. Phys.* **B229** 347–371
- [37] Baranov S P, Duenger O, Shoostari 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)*
- [38] Chatrchyan S *et al.* (CMS Collaboration) 2013 *JHEP* **1307** 116 (*Preprint* 1305.5596)
- [39] Aad G *et al.* (ATLAS Collaboration) 2014 *Phys.Rev.Lett.* **113** 141803 (*Preprint* 1405.6241)
- [40] Nason P 2004 *JHEP* **11** 040 (*Preprint* hep-ph/0409146)
- [41] Frixione S, Nason P and Oleari C 2007 *JHEP* **11** 070 (*Preprint* 0709.2092)
- [42] Alioli S, Nason P, Oleari C and Re E 2010 *JHEP* **06** 043 (*Preprint* 1002.2581)
- [43] Jager B, Oleari C and Zeppenfeld D 2009 *Phys. Rev.* **D80** 034022 (*Preprint* 0907.0580)
- [44] Melia T, Melnikov K, Rontsch R and Zanderighi G 2010 *JHEP* **12** 053 (*Preprint* 1007.5313)
- [45] Melia T, Nason P, Rontsch R and Zanderighi G 2011 *Eur. Phys. J.* **C71** 1670 (*Preprint* 1102.4846)
- [46] Alboteanu A, Kilian W and Reuter J 2008 *JHEP* **11** 010 (*Preprint* 0806.4145)
- [47] Kilian W, Ohl T and Reuter J 2011 *Eur. Phys. J.* **C71** 1742 (*Preprint* 0708.4233)
- [48] Moretti M, Ohl T and Reuter J 2001 1981–2009 (*Preprint* hep-ph/0102195)
- [49] Khachatryan V *et al.* (CMS Collaboration) 2015 *Phys.Rev.Lett.* **114** 051801 (*Preprint* 1410.6315)
- [50] Baglio J *et al.* 2014 (*Preprint* 1404.3940)
- [51] Arnold K *et al.* 2011 (*Preprint* 1107.4038)
- [52] Arnold K *et al.* 2009 *Comput. Phys. Commun.* **180** 1661–1670 (*Preprint* 0811.4559)
- [53] Eboli O J P, Gonzalez-Garcia M C and Mizukoshi J K 2006 *Phys. Rev.* **D74** 073005 (*Preprint* hep-ph/0606118)
- [54] Aad G *et al.* (ATLAS Collaboration) 2015 (*Preprint* 1503.03709)
- [55] Chatrchyan S *et al.* (CMS Collaboration) 2011 *Phys.Rev.* **D84** 112002 (*Preprint* 1110.2682)
- [56] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Phys.Lett.* **B718** 752–772 (*Preprint* 1207.3973)
- [57] Aad G *et al.* (ATLAS Collaboration) 2008 *JINST* **3** S08003
- [58] Abulencia A *et al.* (CDF Collaboration) 2007 *J.Phys.* **G34** 2457–2544 (*Preprint* hep-ex/0508029)
- [59] Chatrchyan S *et al.* (CMS Collaboration) 2008 *JINST* **3** S08004
- [60] Abazov V *et al.* (D0 Collaboration) 2006 *Nucl.Instrum.Meth.* **A565** 463–537 (*Preprint* physics/0507191)
- [61] Alves A Augusto J *et al.* (LHCb Collaboration) 2008 *JINST* **3** S08005
- [62] Aaltonen T A *et al.* (CDF Collaboration) 2014 *Phys.Rev.* **D89** 072005 (*Preprint* 1402.2239)
- [63] Aaltonen T *et al.* (CDF Collaboration) 2013 *Phys.Rev.* **D88** 072002 (*Preprint* 1307.0770)
- [64] Aaltonen T A *et al.* (CDF Collaboration) 2014 *Phys.Rev.* **D89** 072003 (*Preprint* 1311.0894)
- [65] Aaltonen T *et al.* (CDF Collaboration) 2012 *Phys.Rev.Lett.* **108** 151803 (*Preprint* 1203.0275)
- [66] Abazov V M *et al.* (D0 Collaboration) 2014 *Phys.Rev.Lett.* **112** 151803 (*Preprint* 1312.2895)
- [67] Abazov V M *et al.* (D0 Collaboration) 2013 *Phys.Rev.* **D88** 091102 (*Preprint* 1309.2591)
- [68] Abazov V M *et al.* (D0 Collaboration) 2014 *Phys.Rev.* **D89** 012005 (*Preprint* 1310.8628)
- [69] Abazov V M *et al.* (D0 Collaboration) 2012 *Phys.Rev.Lett.* **108** 151804 (*Preprint* 1203.0293)
- [70] Aaltonen T A *et al.* (CDF Collaboration, D0 Collaboration) 2013 *Phys.Rev.* **D88** 052018 (*Preprint* 1307.7627)
- [71] Baak M, Blondel A, Bodek A, Caputo R, Corbett T *et al.* 2013 (*Preprint* 1310.6708)
- [72] Bozzi G, Rojo J and Vicini A 2011 *Phys.Rev.* **D83** 113008 (*Preprint* 1104.2056)

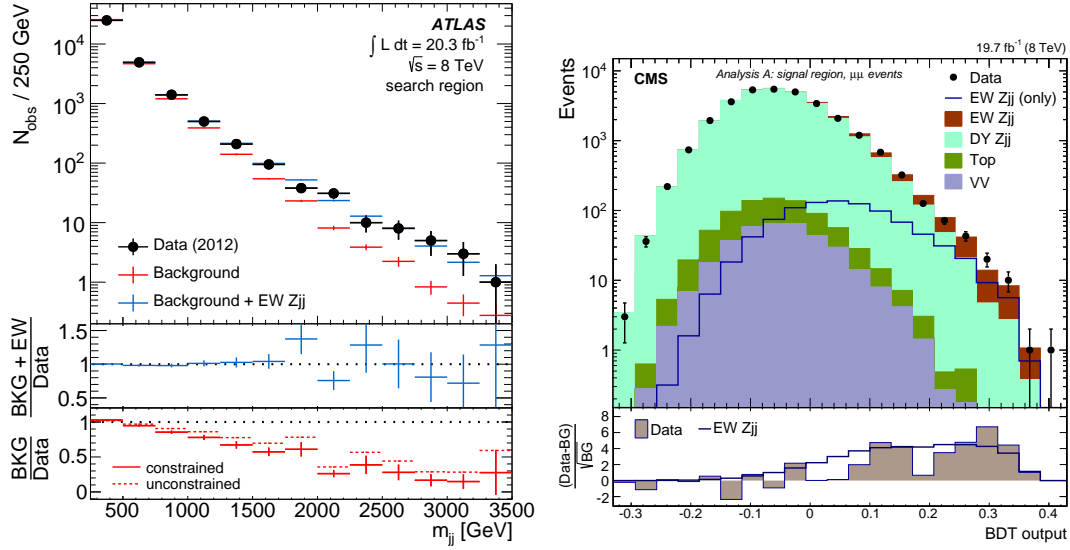


Figure 15. Evidence of observation of an electroweak amplitude in Z+2 jet production. Left: The invariant mass distribution of dijets in Z+2 jet events selected from a signal region by ATLAS. Right: The BDT distribution of Z+2 jet events selected from a signal region by CMS in the dimuon channel.

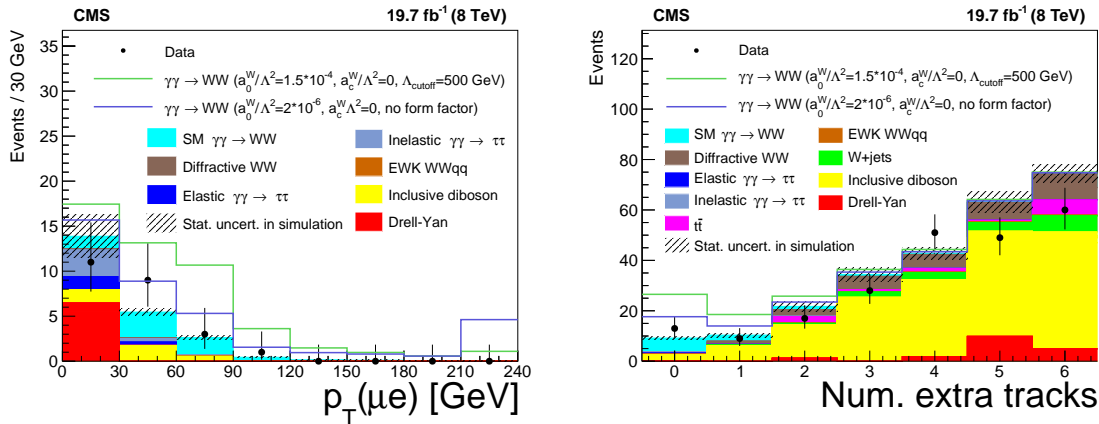


Figure 16. Evidence for exclusive diboson production via $pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}$ [35]. Distributions of muon-electron transverse momentum for events with zero associated tracks (left), and extra-tracks multiplicity for events with $p_T(\mu^{\pm}e^{\mp}) > 30 \text{ GeV}$ (right). The data are shown by the points with error bars; the histograms indicate the expected SM signal and backgrounds.

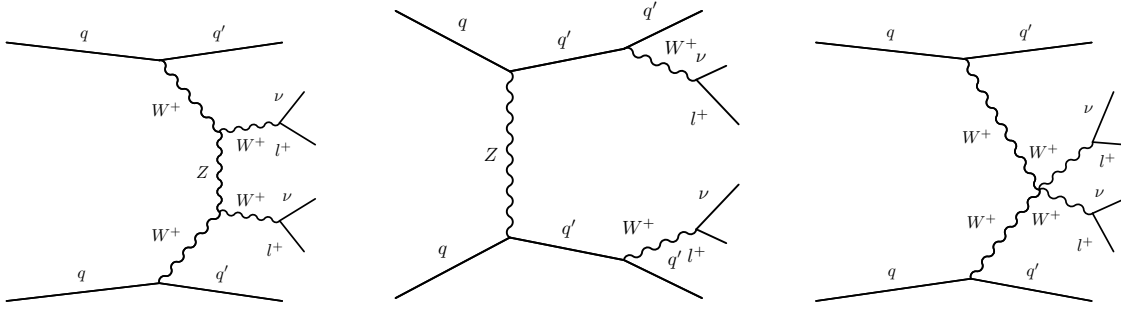


Figure 17. Representative Feynman diagrams for same-sign WW production in association with two jets from purely electroweak contributions: (left) vector boson fusion, (middle) bremsstrahlung-like, and (right) multiperipheral production [49].

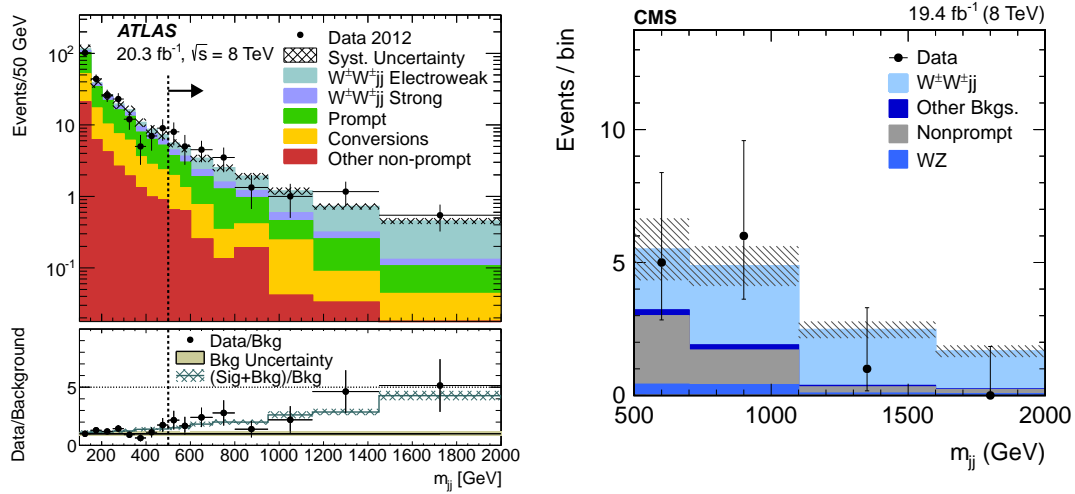


Figure 18. Left: Dijet invariant mass distribution of $W^\pm W^\pm jj$ candidates selected by ATLAS [39]. The inclusive signal region is indicated by the arrow. Right: Dijet invariant mass distribution of $W^\pm W^\pm jj$ candidates selected by CMS [49].

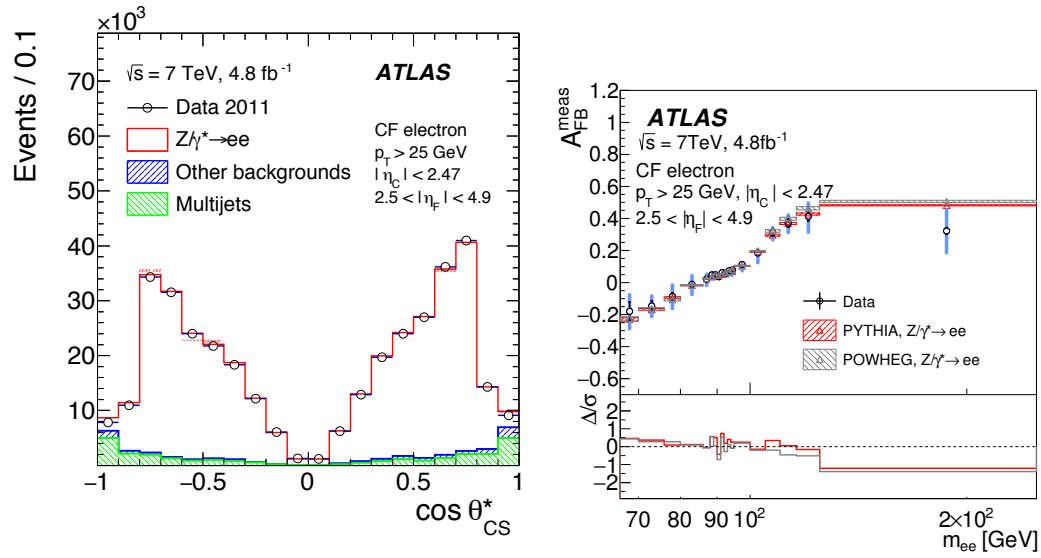


Figure 19. Left: a signal region by ATLAS. Right:

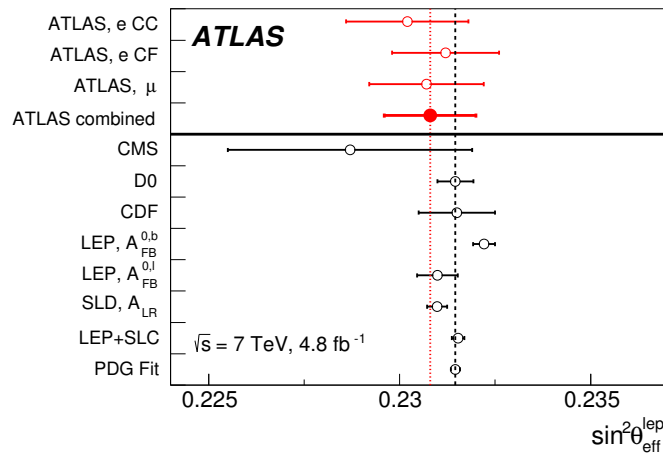


Figure 20.