Electroweak measurements at the LHC and HL-LHC with ATLAS and CMS

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Abstract. This contribution aims at giving an overview of ATLAS and CMS results in the electroweak sector of the standard model. First, the latest precision measurements for a selection of standard model parameters of the electroweak sector will be reviewed. Then, measurements related to the electroweak production of vector bosons with two jets, and inclusive diboson production, both class of processes sensitive to anomalous triple gauge couplings, will be summarised. A review of the measurements available for vector boson scattering and triboson processes will follow, both class of processes sensitive to anomalous quartic gauge couplings. Finally, the limits on anomalous couplings will be summarised. The review covers both LHC and HL-LHC (ATLAS and CMS) results.

1 Introduction

The ATLAS [1, 2] and CMS [3, 4] collaborations have a large physics program at the CERN LHC and HL-LHC [5]. The detectors have already recorded numerous proton-proton collisions at various centre-of-mass energies between 7 and 13.6 TeV. The largest dataset analysed by both collaborations to date corresponds to the so-called LHC Run-2 dataset, with an integrated luminosity of 140 (138) $\text{fb}^{-1}$of p-p collisions at $\sqrt{s}$ =13 TeV collected by ATLAS (CMS) in 2015–2018.

No new physics has been spotted yet. The experimental systematic uncertainties dominate already over the statistical uncertainty for a number of measurements and searches, and sometimes the experimental uncertainties become also similar to the theory uncertainties. However, the devil hides in the details, and new physics could still hide around the corner. Precision standard model (SM) measurements may hold the key to new physics discoveries at the LHC or HL-LHC.

In particular, the electroweak (EW) sector of the SM is particularly well-suited to test for deviations. With 5 parameters which are not independent from each others - namely α_{EM}, G_F, m_W, m_Z, $sin^2\theta_\text{W}$ - the model is over-constrained and gives very precise estimates of these quantities. It however needs experimental inputs. Global EW fits making use of the relations between the parameters then allow to test the self-consistency of the model, and in particular one can confront direct and indirect measurements and look for deviations (see section 2).

Concerning the production of single bosons (V), inclusive and through vector boson fusion (VBF), dibosons (VV), inclusive or through vector boson scattering (VBS) and tribosons

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(VVV), the SM also gives precise predictions of the cross sections and triple and quartic couplings between bosons. Any deviation in such measurements would be a sign of new physics (see sections 3, 4, 5).

Summary reviews have been released by CMS (ATLAS) in Ref. [6] ([7]) including results released up to 2023. This contribution will concentrate mainly on reviewing the results that became available since and as of July 2024.

2 Standard model parameters

2.1 W and Z production cross sections

Since their discovery at UA1, the cross section measurements for the production of inclusive W and Z bosons show excellent agreement between data and MC predictions, from 0.63 TeV up to 13.6 TeV hadron collisions [6, 8, 9]. At the LHC, special datasets with a small number of multiple proton interactions (pileup) are used for best accuracy.

2.2 W boson mass and width measurement

The ATLAS collaboration released a re-analysis of the data taken in 2010 at $\sqrt{s}$ =7 TeV in order to fully optimise the analysis and extract the best possible measurement of the W mass at the LHC [10]. Furthermore, the measurement was extended to also measure the W boson width Γ_W, leading to the first measurement of this quantity at the LHC and the best single-experiment measurement to date. The leptonic (e,μ) decays of the W boson are used, with profile maximum likelihood fits to the transverse momentum p_T^ℓ and transverse mass m_T^W. A number of signal MC templates are built for a range of m_W values, reweighted to the Breit-Wigner parametrisation of the W mass. Not unsurprisingly for such a challenging measurement at a hadron collider, the final uncertainty is dominated by theoretical uncertainties on the parton distribution functions (PDFs). The results are summarised in table 1 for independent fits of the mass and width parameters, or combined fits. The combined fit results in lower values for both the mass (12 MeV) and the width (4 MeV) with only a small price on the uncertainties.

Table 1. Comparison of the results on the W boson mass and width when using independent or combined fits.

Parameter	1-param fits	2-param fit
m_W (MeV)	80366.5 ± 15.9	80354.8 ± 16.1
Γ_W (MeV)	2202 ± 47	2198 ± 49

It will not be possible to collect another dataset with low instantaneous luminosity until the start of the HL-LHC data taking. A study of the systematic uncertainties expected at HL-LHC was done [11], with the additional sensitivity expected from increased lepton acceptance for the upgraded detectors. The challenges lie in the size of the dataset that can be collected with low instantaneous luminosity, and the precision that can be achieved on PDFs.

2.3 Effective leptonic weak mixing angle

The effective leptonic weak mixing angle, $sin^2\theta^\ell_{\rm eff}$ is measured via $Z/\gamma^* \to ee, \mu\mu$ asymmetry in the lepton decay angle θ_{CS}. CMS released a new results with the full Run-2 dataset [12], and additional sensitivity was gained from using forward electrons. The final result gives:

$$sin^2\theta^\ell_{\rm eff} = 0.23157 \pm 0.00010\,({\rm stat}) \pm 0.00015\,({\rm exp}) \pm 0.00009\,({\rm theo}) \pm 0.00027\,({\rm PDF}).$$

The measurement sensitivity was also studied for HL-LHC, by ATLAS with the ee channel only, extending the electron acceptance to rapidity $|y| < 4.0$, and by CMS with the $\mu\mu$ channel only, extending the muon acceptance to $|y| < 2.8$ [11, 13].

2.4 Exclusive production of τ leptons

The exclusive production whereby two photons are emitted from the two incoming protons to give a pair of τ leptons is a pure QED process. In the SM, the anomalous magnetic moment of the τ is expected to be $a_\tau = 117721.10^{-8}$, and its electric dipole moment $d_\tau = -7.3.10^{-38} e$cm. CMS released a new analysis combining $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ channels [14]. The analysis relies on reduction of the backgrounds by requiring no track around the di-τ vertex, and low acoplanarity $A = 1 - |\Delta\phi(\ell, \ell')|/\pi$. It does not make use of tagging the outgoing protons. Corrections for the track multiplicity are extracted from a $\mu\mu$ control region. The measurement leads to the first-time observation of this process in p-p collisions, with an observed significance of 5.3 (expected 6.5) standard deviations.

2.5 Other measurements

Another important test of the SM is related to the number of ν families, and in particular through the measurement of the Z boson to $\nu\nu$ decay width, predicted to be $\Gamma(Z \to \text{inv}) = 501.445 \pm 0.047$ MeV in the SM [15]. The ATLAS analysis uses 37 fb^{-1} [16] and CMS 36.3 fb^{-1} [17] of data taken in 2016 at $\sqrt{s}$ =13 TeV.

The τ-lepton polarisation is measured by CMS using Z$\to \tau\tau$ decays with 35.9 fb^{-1}of data taken in 2016 at $\sqrt{s}$ =13 TeV [18], leading to the most precise measurement at hadron colliders, with a precision comparable to the SLD experiment.

3 Processes sensitive to triple gauge couplings

Only charged triple gauge couplings (TGC) are allowed in the SM, namely WWγ and WWZ. They are fully determined by the structure of the EW sector of the SM. As subtle cancellations happen, they are extremely sensitive to new physics through anomalous couplings. Experimentally, %-level precision is obtained for diboson measurements with clean multi-lepton final states. Diboson production makes use of state of the art MC predictions at next-to-next-to-leading order (NNLO) in perturbative QCD, with NLO EW corrections implemented in MATRIX [19].

TGC couplings are involved in the VBF production of single bosons and in inclusive diboson (WW, WZ, ZZ, Zγ) production. Inclusive and differential cross sections have been measured for these processes by both experiments. Table 2 summarises the references of measurements not covered by the previous reviews [6, 7].

3.1 VBF production of single bosons

Reviews of recent CMS results can be found already in Ref. [6], and summary distributions for ATLAS in Ref. [7]. A good data/theory consistency is found for all measurements, which are measured to about 10% precision with the dominant uncertainty from systematic sources. With the 13 TeV data accumulated in Run-2, the statistical uncertainties become similar in size to the theory uncertainties. The MC predictions for these processes are still at leading order (LO).

Table 2. Overview of the newest results on inclusive diboson production.

Final state	ATLAS	CMS
W^+W^- $\sqrt{s}$ =13 TeV	[20] 140 fb^{-1}, inclusive & differential cross sections	-
W^+W^- $\sqrt{s}$ =13.6 TeV	-	[21] 34.8 fb^{-1}, inclusive & differential cross sections
WZ $\sqrt{s}$ =13 TeV	[22] 140 fb^{-1}, RAZ effect + polarisation studies	[23] 137 fb^{-1}, polarisations + inclusive & differential cross sections
ZZ $\sqrt{s}$ =13.6 TeV	[24] 29 fb^{-1}, inclusive & differential cross sections	-
ZZ $\sqrt{s}$ =13 TeV	[25] 140 fb^{-1}, polarisation + CP properties	[26] 138 fb^{-1}, ZZ+jets differential cross sections
$Z(\nu\nu)\gamma$ $\sqrt{s}$ =13 TeV	-	[27] 138 fb^{-1}

3.2 Inclusive production of dibosons

Reviews of recent CMS results can be found already in Ref. [6], and summary distributions for ATLAS in Ref. [7]. For all 13 TeV measurements performed to date, the dominant uncertainty arises from systematic sources. The theory uncertainties are of the same order as (exceed) the experimental uncertainties for WW, WZ and ZZ ($W\gamma$) production. Globally a good agreement with the MC predictions is observed, although NNLO QCD and NLO EW predictions are necessary to match the experimental precision.

The ZZ (WW) process was measured at $\sqrt{s}$ =13.6 TeV by ATLAS [24] (CMS [21]).

Differential cross sections are extracted as a function of a number of kinematical variables. These measurements allow to test the importance of higher order corrections. For example, the diboson invariant mass exhibits a large enhancement in the cross section from NNLO QCD corrections, but a reduction expected from NLO EW corrections. The CMS data for ZZ events [26] highlight the importance of higher-order QCD corrections to model the jet multiplicity. The ATLAS data for WW events [20] show excellent agreement with fixed-order MATRIX [19] predictions. The EW corrections improve the modelling at high diboson mass but overcorrect the p_T of the leading lepton, highlighting the limitation of the multiplicative treatment of the EW correction, missing the mixed EW/QCD contributions, in particular for hard QCD radiations. The central PDF choice is also shown to be important in predicting the overall cross section scale.

The size of the dataset available also allows to perform the first measurements of the polarisation of the bosons.

The vector boson polarisation gives direct access to the underlying physics of the interaction and the helicities of the other particles involved in the interaction [28]. The definition of the polarisation is frame dependent, measured via the angular distributions of the W or Z decay leptons. The fractions generally depend on the p_T of the vector boson or of the diboson object. As they are predicted by the SM, new physics would change the picture and measuring the fractions as precisely as possible is again a golden path to discoveries.

Several measurements are possible: either correlated-state $V_X V_Y$ production, with (X,Y)=(L,T) for the longitudinal (L) or transverse (T) states, or individual measurement of the polarisation of each boson independently of the other one, for WZ production. In the ATLAS and CMS literature, the longitudinal/transverve polarisations are referred by either "L/T" or "0/L/R" or "0/T", depending on the possibility to distinguish between the left and right transverse states.

ATLAS was able to give evidence for $Z_L Z_L$ production with the full Run-2 dataset [25], using the $4\ell(\ell$ =e,$\mu)$ final state. A boosted decision tree (BDT) is used to enhance the LL contribution, using angular variables. The fractions are extracted using templates from MC. The challenge of this measurement lies in getting the higher-order QCD and EW corrections for the polarisation templates. The observed (expected) significance is 4.3σ (3.8σ). A good agreement is found with the predictions from NLO QCD × NLO EW $q\bar{q}$ →ZZ, LO gg→ZZ and LO EW qq→ZZ+2j. The measurement is limited by data statistics. The leading systematics comes from the theoretical modelling of the polarisation templates. The leading theoretical uncertainties on the predictions are from QCD scales and PDF.

The measurement is further exploited to test anomalous neutral TGC. Existing constraints on anomalous neutral TGC use high-p_T observables, which give very strong constraints but are insensitive to the CP properties of the interaction. By constructing CP-sensitive observables like $T_{yz,1(3)} = sin\phi_{1(3)} \times cos\theta_{1(3)}$ (see [25] for the definition of the angles), one can obtain a symmetric shape for the SM, and an asymmetric shape for a CP-odd neutral TGC. The constraints obtained on the relevant anomalous neutral TGC parameters are looser than those set using high-p_T kinematic observables, sensitive to quadratic terms, but they are sensitive to interference term and bring complementary information.

Polarisation fractions have also been measured by CMS in WZ production [23], using 3-lepton decays and $m_{WZ} > 100$ GeV. In this analysis, separate likelihood fits are performed to $\cos(\theta_W)$ and $\cos(\theta_Z)$. The polarisation templates are taken from MC: longitudinal "0", transverse "L"/"R". The fits each use three parameters: the total normalisation, f_0 and $f_{LR} = f_L - f_R$. A decorrelation is observed between the 0 and LR components for both W and Z. This measurement leads to the first observation of W_L in WZ events, with an observed (expected) significance of 5.6σ (4.3σ). The significance for Z_L is well above 5σ.

ATLAS made complementary measurements in WZ events, by measuring the so-called Radiation Amplitude Zero (RAZ), using 3-lepton decays [22]. At LO, one expects no events with two transversely-polarised (TT) bosons when $\Delta Y(WZ) \simeq 0$. The effect is enhanced for low jet activity, hence a selection is made on $p_T^{WZ} < 70$ GeV. The different background sources (accounting for $\simeq 10\%$ of the events selected) and the other polarisation states (00+0T+T0, accounting for $\simeq 27\%$ of the selected events) are subtracted, and the $\Delta Y(WZ)$ distribution is unfolded from detector-resolution effects. The RAZ effect is observed and a good agreement with simulation is obtained. The measurement is further exploited to enhance also the 00 contribution with a high p_T^Z selection. A BDT is constructed to separate 00 events from TT+0T+T0 events. A likelihood fit to the BDT discriminant distribution allows to extract three parameters: the fractions f_{00}, f_{0T+T0} and the total normalisation. The polarisation templates and predicted fractions are taken from MADGRAPH_aMC@NLO WZ + 0 jet, WZ + 1jet at LO with higher-order QCD corrections taken from data, and NLO EW corrections applied.

4 Processes sensitive to quartic gauge couplings

The quartic gauge couplings allowed in the SM are WWWW, WWZZ, WWZγ, and WW$\gamma\gamma$. They are involved in VBS production of a pair of vector bosons, and triboson production. Both type of processes are rare, and again crucial to test the EW symmetry breaking mechanism. The VV to VV scattering offers a unique possibility to measure the HVV coupling, by separating the longitudinal polarisation of the V boson and measure the cross section as a function of m_{VV}. Without the intervention of diagrams involving the exchange of the SM Higgs boson, the cross section diverges at high m_{VV} [29].

Different types of processes lead to the production of two vector bosons and two jets, at different orders in α_S and α. Representative diagrams are shown in figure 1. The VBS production (left) occurs with pure EW couplings at O(α^6), and leads to a specific topology with large dijet invariant mass m_{jj} (typically ≥ 500 GeV) and large dijet separation in pseudo-rapidity $\Delta\eta_{jj}$ (typically ≥ 2). Other processes are possible also at O(α^6) but non-VBS (middle), which constitute a background source that cannot be separated and is part of the signal. Background processes from strong production of jets occur at O($\alpha^4\alpha_s^2$) with interference terms at O($\alpha^5\alpha_s$). Those are theoretically well-defined and separable from the signal generated at O(α^6).

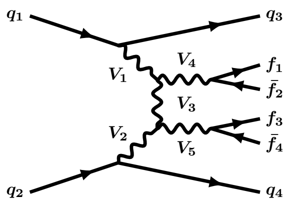

Figure 1. Representative Feynman diagrams for the production of two vector bosons and two jets. Left: VBS production at O(α^6). Middle: non-VBS production at O(α^6). Right: Non-VBS production at O($\alpha^4\alpha_s^2$) and interference term at O($\alpha^5\alpha_s$). Taken from Ref. [30].

When considering QCD and EW higher-order corrections, a mixing occurs that render the separation more difficult, as sketched in figure 2. For example, the NLO EW correction for the strong production leads to the same orders as the NLO QCD correction for the interference production, and the NLO EW correction for the interference terms are of same orders as the NLO QCD correction for the pure EW production. The complication incurred for the MC event generators is usually cured by using so-called VBS approximations which give a unique assignement as "EW" or "QCD" corrections.

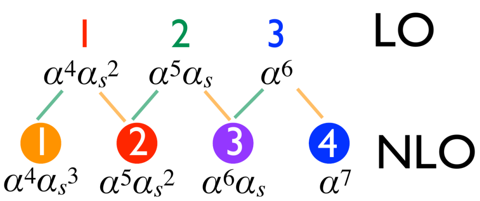

Figure 2. Sketch of the orders involved at LO and NLO for the different class of processes involved in the production of VV+2 jets [courtesy of Marco Zaro, LHCP2024]

4.1 VBS production of dibosons

Reviews of recent CMS results can be found already in Ref. [6], and summary distributions for ATLAS in Ref. [7].

The golden channel is the same-sign WW production, $W^\pm W^\pm$+2j, because it has the best EW/strong production ratio, ≃ 5 in the fiducial area of the measurement. The main background is WZ+2j. The strategy employed by CMS is to measure both processes together in Ref. [31]. ATLAS measured them independently, and extracted inclusive and differential cross section measurements for $W^\pm W^\pm$+2j using 139 $fb^{-1}$of data [30]. Some discrepancy with the MC are observed, with the MC predictions generally underestimating the data. The measurements are statistically limited.

CMS measured polarisation fractions in $W^{\pm}W^{\pm}$+2j events using 137 fb^{-1}of data [32]. Two independent measurements were made, attempting at separating $W^{\pm}_{L}W^{\pm}_{L}$ from $W^{\pm}_{X}W^{\pm}_{T}$ and $W^{\pm}_{T}W^{\pm}_{T}$ from $W^{\pm}_{X}W^{\pm}_{L}$ using BDTs. The fractions are extracted in two reference frames: that of the $W^{\pm}W^{\pm}$ and of the parton-parton centre-of-mass frames.

CMS also studied final states with a τ lepton to extend the sensitivity to BSM models [33]. A Deep Neural Network is used to enhance the signal. The measurement if very statistically limited, leading to an observed (expected) significance of 2.7σ (1.9σ).

This channel is also a flagship channel for the HL-LHC physics program and was studied by both ATLAS [34] and CMS [35] using 3000 fb^{-1} of integrated luminosity, 3 leptons (e,μ) + 2j $m_{jj} > 500$ GeV. The ATLAS analysis extended the lepton acceptance to $|\eta| < 4$. The CMS strategy is identical to the Run-2 one. The expected precision on the total cross section is summarised in table 3. For the measurement of $W^{\pm}_{L}W^{\pm}_{L}$ at HL-LHC, CMS extrapolated the Run-2 analysis [32]. The expected significance with 3 ab^{-1} of data is 4σ and the expected precision 30%.

Table 3. Expected total (statistical-only) precision on the production cross section of $W^{\pm}W^{\pm}$+2j, at LHC (Run-2) and at the end of HL-LHC (3 ab^{-1}).

	Run-2	HL-LHC
ATLAS	10% (stat 8%)	6% (stat 2%)
CMS	11% (stat 9%)	3% (stat 2%)

The first observation of the EW production of ZZ(4ℓ)+2j was made by ATLAS [36] with an observed significance of 5.7σ, and a 26% precision on the cross section. Evidence was seen by CMS [37] with an observed significance of 4σ, and 36% precision on the cross section. The studies were recently extended to measure differential cross sections using three types of observables [38]: sensitive to the VBS process, to polarisation and CP properties of the bosons, or sensitive to higher-order QCD effects. At HL-LHC, $\simeq$ 10% precision is expected on the cross section with 3 ab^{-1} of integrated luminosity [38].

Other measurements for the EW production of WZ+2j, $W^{+}W^{-}$+2j, Wγ+2j, Zγ+2j are summarised in table 4.

The exclusive production $\gamma\gamma \rightarrow WW$ was studied by CMS [39] using forward proton tagging and hadronic W decays. The analysis targets high diboson mass m_{VV} region for new physics signals. ATLAS also studied this process but using the leptonic e+μ channel with track veto [40], and obtained an observed (expected) significance of 8.4σ (6.7σ) with a precision of $\simeq$ 13% on the cross section measurement. The analysis was projected to HL-LHC [41].

The relative uncertainties from the different ATLAS and CMS recent VBS results with the full Run-2 dataset (references given in table 4) are summarised in figure 3.

4.2 Inclusive production of tribosons

Reviews of recent CMS results can be found already in Ref. [6], and summary distributions for ATLAS in Ref. [7]. To be noted since, the first observation of WWγ in p-p collisions by CMS [50], with an observed (expected) significance of 5.6 (4.7) σ.

5 Anomalous gauge couplings and the effective field theory approach

The effective field theory approach allows to model new physics in a general way, with precise calculations of cross sections. Assuming the existence of a new high mass particle at an

Table 4. VBS results with the full Run-2 dataset.

Channel	Final state	ATLAS	CMS
$W^{\pm}W^{\pm}$+2j	2ℓ (e,μ)	[30]	[31]
ZZ+2j	4ℓ (e,μ)	[36, 38]	[37]
WZ+2j	3ℓ (e,μ)	[42]	[31]
$W^{+}W^{-}$+2j	e+μ	[43]	[44]
Wγ+2j	W$\rightarrow e, mu$	[45]	[46]
Zγ+2j	Z$\rightarrow \nu\nu$	[47]	-
Zγ+2j	Z$\rightarrow \ell\ell$ (e,μ)	[48]	[49]
Excl. $\gamma\gamma \rightarrow WW$	e+μ	[40]	[]
Excl. $\gamma\gamma \rightarrow WW$	fwd p-tagging, V$\rightarrow$had	-	[39]

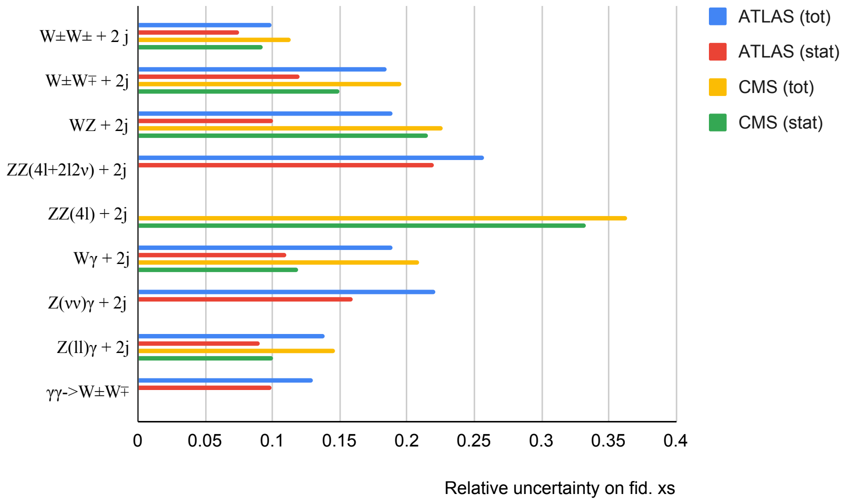

Figure 3. Relative uncertainties (total and statistical-only) obtained by ATLAS and CMS on fiducial cross sections measurements. Numerical values are taken from the references given in table 4.

energy scale Λ, the EFT models the impact on the cross section at lower energy scale E. It should be noted that the size of the new physics effect may be of the same order as the size of higher-order QCD/EW effects, hence the importance to model the latter as accurately as possible. Anomalous gauge couplings are hence introduced via new EFT operators of varying dimensions (dim).

The SM corresponds to dim-4 operators in the EFT. In the cross section of the process under consideration, interference terms between the SM and the dim-N appear, scaled by $1/\Lambda^{N-4}$, and pure BSM terms scale as $1/\Lambda^{N-2}$. Generally speaking, anomalous TGC (ATGC) are sensitive to dim-6 operators, whereas anomalous QGC (AQGC) are sensitive to dim-8. Quadratic terms are also important, in particular VBS processes give sensitivity to dim-8 and quadratic dim-6 operators.

Generally speaking, ATLAS and CMS analyses use the following procedure:

- generate events for each coupling independently;

- add events to the SM predictions, and perform likelihood fits using the most-sensitive variable(s), usually m_{VV} or a CP sensitive variable to test CP-odd operators;
- extract 95%CL limits on single / pair of operators;
- to test the impact of missing higher-order terms: remove quartic couplings for the dimension considered and study the impact on the limits;
- given the validity is limited to E<< Λ, an upper cut E_c is set on m_{VV} for the EFT components, to preserve unitarity at high energy scale, and the 95%CL interval is studied as a function of E_c. More conservative limits are obtained at the crossing between the observed limit and the unitarity bound.

Many new results were obtained by ATLAS and CMS with limits on anomalous EFT dim-6 and dim-8 operators with the full Run-2 dataset using the measurements detailed in the previous sections. Differential cross sections are now available to improve sensitivity: one observable can have several contributing operators, and one operator can affect several observables. Ultimately, a global analysis is required and efforts are already ongoing, by ATLAS in Ref. [51] which includes also LEP EW precision observables. All the new results available since are yet to be added, and a similar effort from CMS is ongoing.

6 Conclusion

Despite being hadron colliders, LHC and HL-LHC have much more to bring to the EW sector picture before the next generation of lepton collider comes into life. MC predictions and theory calculations are confronted to new highs every data-taking year [52]. If ILC or CLIC or FCC-ee/CEPC came into life tomorrow, we would be in deep trouble for comparing with theory! The years ahead are crucial to build the required accuracy. The ATLAS and CMS experiments are reaching a precision era for the measurements of SM parameters, some of which are already limited by PDF uncertainties. Percent-level precision is obtained on diboson production, and with the high statistics collected, cross sections can be measured differentially, including for VBS production. Many VBS processes are now measured with both ATLAS and CMS with $\mathcal{O}(10\%)$ precision for golden same-sign WW production and exclusive production, 20% for others. The most recent results include first polarisation measurements in inclusive ZZ, WZ and $W^{\pm}W^{\pm}$+2j productions. New constraints are set on EFT parameters and continued experimental/theory collaboration should be a priority for global fits. The HL-LHC data are expected to help reach 3-10%-level precision on the golden VBS channels. Assuming that the current projections are too conservative, $W^{\pm}_{L}W^{\pm}_{L}$ will be observed at HL-LHC! More work is needed on reducing theory modelling uncertainties, and on analysing all the LHC data available to date.

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