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Vector-boson fusion and scattering measurements

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Triple and quartic gauge self-couplings among the least known Standard Model structures and their interplay with the Higgs mechanism, giving rise to final states such as vector-boson scattering, probes the core of the Electro-weak Symmetry Breaking mechanism. Recent ATLAS and CMS measurements on the 13-TeV LHC dataset are reviewed concerning vector-boson fusion and scattering, which are electroweak processes with a large sensitivity on possible anomalies in gauge self-couplings. Results are presented in terms of measurements of fiducial and total cross-sections as well as polarization of outgoing vector bosons.

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1. Introduction

Massive gauge bosons (V = $W^{\pm}$, Z) were discovered decades before the Higgs boson. However, while the Higgs-gauge interactions are relatively well measured at the Large Hadron Collider (LHC), triple and quartic gauge self-couplings (TGC/QGC) are still among the least known Standard Model (SM) structures. Theoretical predictions in the SM are very precise, since their strengths are determined by non-abelian SU(2) structures, with no additional free parameters. However, they are experimentally difficult to investigate. At the LHC, final states whose diagrams contain TGCs and/or QGCs have typically very small cross-sections and could be subdominant with respect to competing processes with final states identical or very similar to the investigated signal. In addition, the interplay with the Higgs mechanism, giving rise to final states such as vector-boson scattering, probes the core of the Electro-weak Symmetry Breaking (EWSB) mechanism.

Vector-boson fusion (VBF) and scattering (VBS) are purely electroweak (EW) processes. Their experimental signature is a single vector boson (VBF) or a vector-boson pair (VBS) and 2 jets (jj) originating from scattered quarks of the colliding protons. The presence of TGC and/or QGC diagrams in such processes at the lowest perturbative order (LO) grants direct access to gauge self-couplings. In this purely electroweak component, next-to-leading-order (NLO) QCD corrections are of the order of ‰, unlike most LHC processes, ensuring very small theoretical uncertainties. Typical observables in VBF and VBS measurements at the LHC are cross-sections in detector fiducial regions. EW only and/or QCD+EW cross-section may be measured, the latter being theoretically cleaner, although interference terms are typically o(‰) of the signal. Fiducial region are usually EW-enriched by requiring large di-jet rapidity separation ($\Delta\eta_{\mathrm{jj}}$) and/or invariant mass (m_{jj}). In some cases, differential cross-section can be measured as a function of various event observables. Vector-boson polarization, which in the VBS case may be measured for both V or inclusively in one of the two, provides constraints on concrete Beyond-the-Standard-Model (BSM) predictions. A prominent example is [1], showing that alternative or additional sources of EWSB other than the Higgs boson modify significantly the VBS double-longitudinal component.

In the context of Effective Field Theories (EFT), VBF processes can establish competitive limits on dimension-6 operator coefficients, usually defined using the SILH or Warsaw bases. The VBS case is more complex, as VBS receives similar-size BSM contributions from both dimension-6 and dimension-8. Two alternative approaches are normally followed in literature: either neglect dimension-6, as they are powerfully constrained by many other LHC data (Higgs, dibosons, and so on) and set limits on dimension-8 coefficients using a gauge-boson specific basis [2], or to include VBS constraints on dimension-6 operators in combination with other data [3, 4].

There are challenges of several kinds in VBS and VBF measurements at the ATLAS [5] and CMS [6] experiments. Depending on the exact final state, VBF and VBS may have large SM backgrounds. Irreducible components of them are Vjj or VVjj where the jets result from diagrams containing at least one strong vertex. Top quark production may also contribute, for final states with many jets and/or W bosons. Experimentally, such large backgrounds must be separated by means of matrix-element or machine-learning techniques. Missing neutrino information in $W \to \ell\nu$ final states must be tackled with longitudinal-momentum extrapolation techniques. Jet systematic uncertainties in forward regions may be a limiting factor.

In the Monte Carlo (MC) modeling of EW signals, there has been a large theory-experimental

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efforts to cross-validate MC generators at the matrix-element level [7] and a proper choice of parton-shower scheme was also found to be essential [8]. Simulation of QCD samples with up to 2 extra jets is very CPU expensive and is performed at the NLO in QCD and/or with matched-and-merged samples using MadGraph5_aMC@NLO or Sherpa. In the case of EFT description of QGCs, unitarity violation at high scattering energies must be avoided by setting proper cut-offs on the scattering energy.

2. Vector boson fusion production of W $\rightarrow \ell\nu$ and Z $\rightarrow \ell^+\ell^-$

Vector-boson fusion analyses are particularly sensitive to dimension-6 BSM effects and to the hadronic activity in the di-jet rapidity gap. In general, the main backgrounds come from single-boson production processes which have much larger cross-sections. The signal selection in the VBF W $\rightarrow \ell\nu$ CMS analysis [9] is based on a Boosted-Decision-Tree (BDT) algorithm for the extraction of the EW component, with several input variables including: missing transverse momentum ($p_{\mathrm{T,miss}}$), W bosons transverse mass, $\Delta\eta_{\mathrm{jj}}$, m_{jj}, Zeppenfeld variables, and quark-gluon discrimination for jets. Results are an EW fiducial cross-section of 6.1 ± 0.6 pb, entirely dominated by systematic uncertainties, as well as dedicated studies of extra jet activity with different parton-shower programs are also performed. Both ATLAS and CMS [10, 11] performed detailed VBF Z $\rightarrow \ell\ell$ analyses. ATLAS uses a binned analysis in m_{jj}, in a signal and three control regions defined by the Z centrality and the number of extra jets. Fiducial and differential cross-sections (both EW and EW+QCD) are determined. Total cross-sections are in agreement with the SM NLO estimations, while the differential ones show better agreement with MadGraph5_aMC@NLO than with Sherpa simulations. CMS has a similar analysis to that of VBF W, which uses a BDT-based for EW extraction. Cross-sections are measured in fiducial regions which are much looser than their ATLAS definition. Constraints on dimension-6 EFT are considered in both analyses, CMS also performing a combination of VBF W and Z to maximize exclusion. ATLAS sets constraints on c_W/Λ^2 to be inside the interval [−0.19,0.41] TeV^{-2} and on c_{HWB}/Λ^2 to be inside the interval [−3.8,1.1] TeV^{-2}.

3. Scattering with massive bosons in the final state

The W$^\pm$W$^\pm$jj process is considered as the most important VBS channel, as the cross-section ratio of the EW component compared to the strong one is large. The W$^\pm$Zjj and ZZjj processes have much larger QCD contamination but receive contribution from different QGC structures and the possible BSM effects connected to those. ATLAS has reported the observation of electroweak W$^\pm$W$^\pm$jj and W$^\pm$Zjj production using a partial 13 TeV data set [12, 13]. CMS has already published the simultaneous observation and measurement of both final states on the full data set [14], including differential results and QGC studies.

For W$^\pm$W$^\pm$jj, both experiments fit the observed data after estimating backgrounds from either simulation (for irreducible components) or control regions (for sources of non-prompt leptons). Both analyses use fully selected events with low m_{jj} to constrain background-component normalizations. In the ATLAS analysis the signal-region data in four m_{jj} bins are fit together with the 3ℓ and the low-m_{jj} regions. In CMS a similar technique is used, but using two-dimensional distributions in bins of

$m_{\rm jj}$ and $m_{\ell\ell'}$ in the signal region and three control regions, leaving free in the fit the normalizations, in addition to the EW and strong cross sections. ATLAS reports a measured VBS fiducial cross-section of $\sigma_{\rm EW} = 2.89^{+0.59}_{-0.55}$ fb, where the total uncertainty is dominated by the statistical one. CMS similarly reports $\sigma_{\rm EW} = 3.98 \pm 0.45$ fb, as well as the total $W^{\pm}W^{\pm}$jj cross section including EW and strong components, $\sigma_{\rm tot} = 4.42 \pm 0.47$ fb. Differential cross-sections in four bins of $m_{\rm jj}$, $m_{\ell\ell'}$ and the leading lepton $p_{\rm T}$ are obtained by fitting simultaneously the corresponding regions of the phase space. All results are in agreement with SM expectations at the NLO, although the experimental uncertainties are of the order of 20% because of limited statistics.

In a separate analysis, CMS [15] examines the same dataset in order to measure the polarization of W bosons in $W^{\pm}W^{\pm}$jj events. Two-dimensional fits use different variables than in the original analysis: both are output scores of BDT algorithms, an *inclusive* BDT optimized to select EW $W^{\pm}W^{\pm}$jj over backgrounds, and a *signal* BDT alternatively optimized to select purely longitudinal or longitudinal-unpolarised ($W^{\pm}_{\rm L}W^{\pm}_{X}$) signals over other polarization combinations. The resulting cross-sections are $\sigma_{\rm fid} = 1.2^{+0.6}_{-0.5}$ fb for the $W^{\pm}_{\rm L}W^{\pm}_{X}$ process and $\sigma_{\rm fid} < 1.17$ fb at the 95% Confidence Level (CL) for the $WL^{\pm}W^{\pm}_{\rm L}$ process. There is not yet an evidence for specific polarization states, the significance of the $W^{\pm}_{L}W^{\pm}_{X}$ background-hypothesis rejection being only 2.3σ.

For $W^{\pm}$Zjj, both ATLAS and CMS use BDT algorithms to isolate the EW signal over the large QCD background, combining several variables that are related to jet kinematics, vector-boson kinematics, or to correlated jets and leptons kinematics. Variables such as the $W^{\pm}$ rapidity or $m_{\rm T}$(WZ) are computed inferring the neutrino longitudinal momentum by a W-mass constraint. ATLAS reports a measured fiducial cross-section of $\sigma_{\rm EW} = 0.57^{+0.16}_{-0.14}$ fb, where the total uncertainty is dominated by the statistical one, finding a fairly large measured-to-SM ratio of 1.77. It corresponds to a background-only hypothesis rejection with a significance of 5.3σ, while only 3.2σ is expected. CMS similarly[3] reports $\sigma_{\rm EW} = 1.81 \pm 0.41$ fb in agreement with the NLO QCD+EW estimations in the respective fiducial region. It corresponds to a background-only hypothesis rejection with a significance of 6.8σ. The total cross section including EW and strong components is also measured to be $\sigma_{\rm tot} = 1.68 \pm 0.25$ fb in ATLAS and $\sigma_{\rm tot} = 4.97 \pm 0.46$ fb in CMS. Differential cross-sections are reported only as a function of $m_{\rm jj}$ in CMS and as a function of many variables in the ATLAS analysis.

The ZZjj VBS process has the smallest cross section among the final states containing VV, and is one of the rarest SM processes observed to date. ATLAS has reported observation of electroweak ZZjj production using the full Run-2 data set [16] and combining two ZZ decay channels. CMS only analyzed events with four charged leptons and has reported a strong evidence for the EW production [17]. ATLAS and CMS use multivariate analyses to isolate the EW signal over the large QCD background. ATLAS uses BDTs for both the 4ℓjj and $2\ell2\nu$jj channels where, in the latter, the quantities related to the undetected Z are replaced by $p_{\rm T,miss}$ and its significance. In CMS, a kinematic EW discriminant is instead built from analytical matrix elements of the EW and strong processes at LO. ATLAS reports a measured fiducial cross-section of $\sigma_{\rm EW} = 0.82 \pm 0.21$ fb, where the total uncertainty is dominated by the statistical one. It corresponds to a background-only hypothesis rejection with a significance of 5.5σ, while 4.3σ is expected, with the $4\ell jj$ channel

[3]The ATLAS cross-sections in the WZjj final state are quoted per lepton-flavor channel, while they are summed in CMS, so the two definitions differ by a factor of four.

exhibiting a larger sensitivity. CMS reports fiducial cross-sections in three fiducial regions with increasing EW purity, all in agreement with SM expectations at NLO in QCD. The background-only hypothesis is rejected with a significance of 4.0σ.

4. Scattering with massive bosons and photons in the final state

ATLAS and CMS have reported evidence of electroweak $Z\gamma$ production using a partial Run-2 data set [18, 19]. Only CMS performed the search for the $W^{\pm}\gamma$ final state [20] in the same data set, leading to the observation of this process. The ATLAS $Z\gamma$ analysis uses a BDT algorithm to isolate the EW signal over the backgrounds, where the 13 input variables are related to the kinematic properties of the two tagging jets, the photon, and the reconstructed Z boson. CMS uses a two-dimensional fits using the most discriminating variables, which are (m_{jj}, Δy_{jj}) in the $Z\gamma$ case and (m_{jj}, $m(\ell\gamma)$) in the $W^{\pm}\gamma$ case. In both analyses, events are first separated by lepton flavor and central or forward rapidity regions, and control regions with small VBS yields are fit together with the signal regions to constrain background normalizations from data. Both ATLAS and CMS report EW and EW+QCD cross-sections in agreement with the SM. Both experiments have updated their results very recently to include differential results [21, 22].

The exclusive $\gamma\gamma \to W^+W^-$ is a particular production process of the VBS type and, as such, is sensitive to QGC. ATLAS and CMS studies so far employ techniques which does no require proton tagging. ATLAS recently reported observation of $\gamma\gamma \to W^+W^-$ in Run-2 data [23]. Background estimation in this analysis is quite complex because of the multiple sources that can feed additional charged particles in the event and therefore fail the requirement of zero charge tracks in the event, beyond the leptons. The fiducial cross-section is determined by fitting the signal region ($p_{T,e\mu} > 30$ GeV and $n_{trk} = 0$) after checking data/prediction agreement in control regions where either $p_{T,e\mu} < 30$ GeV or $1 \leq n_{trk} \leq 4$. The significance of the observation is 8.4σ and the corresponding result is: $\sigma_{fid} = 3.1 \pm 0.4$ fb.

5. Cross-sections and constraints on anomalous couplings

The summary of measured cross-sections in ATLAS and CMS are shown in Fig. 1. While a general agreement is found with the SM, a general trend of VBS cross-sections to be measured higher than their theoretical predictions. Since these analysis largely depend on simulation of the respective VVjj strong processes, a reduction of theory uncertainties and Monte Carlo tool comparison are essential for future precision analysis.

EFT constraints obtained in CMS VBS analyses use the parameterization in [2]. Unlike at dimension-6, where quartic and trilinear gauge couplings are intrinsically related, at dimension-8 one can assume the presence of anomalous QGC and no anomalous triple gauge couplings. There are 18 independent bosonic dimension-8 operators relevant for 2-to-2 scattering processes involving Higgs or gauge bosons at tree level, and conserving parity and charge conjugation. They can be classified as *scalar*, *mixed*, and *transverse* according to the number of gauge-boson strength fields contained in the operator (0, 2, and 4, respectively). EFT effects lead to modifications of the high-energy tail of differential distributions in the scattering process. Therefore, events are first selected in VBS enhanced phase-space regions and a distribution sensitive to this modification is used to set constraints on the couplings. Such distributions include the invariant mass of the diboson system (or approximations based on reconstruction of the missing neutrino flight directions), or the transverse momentum of either scattered gauge boson. Fig. 2 shows a compilation of the existing limits on dimension-8 mixed and trasverse operator couplings.

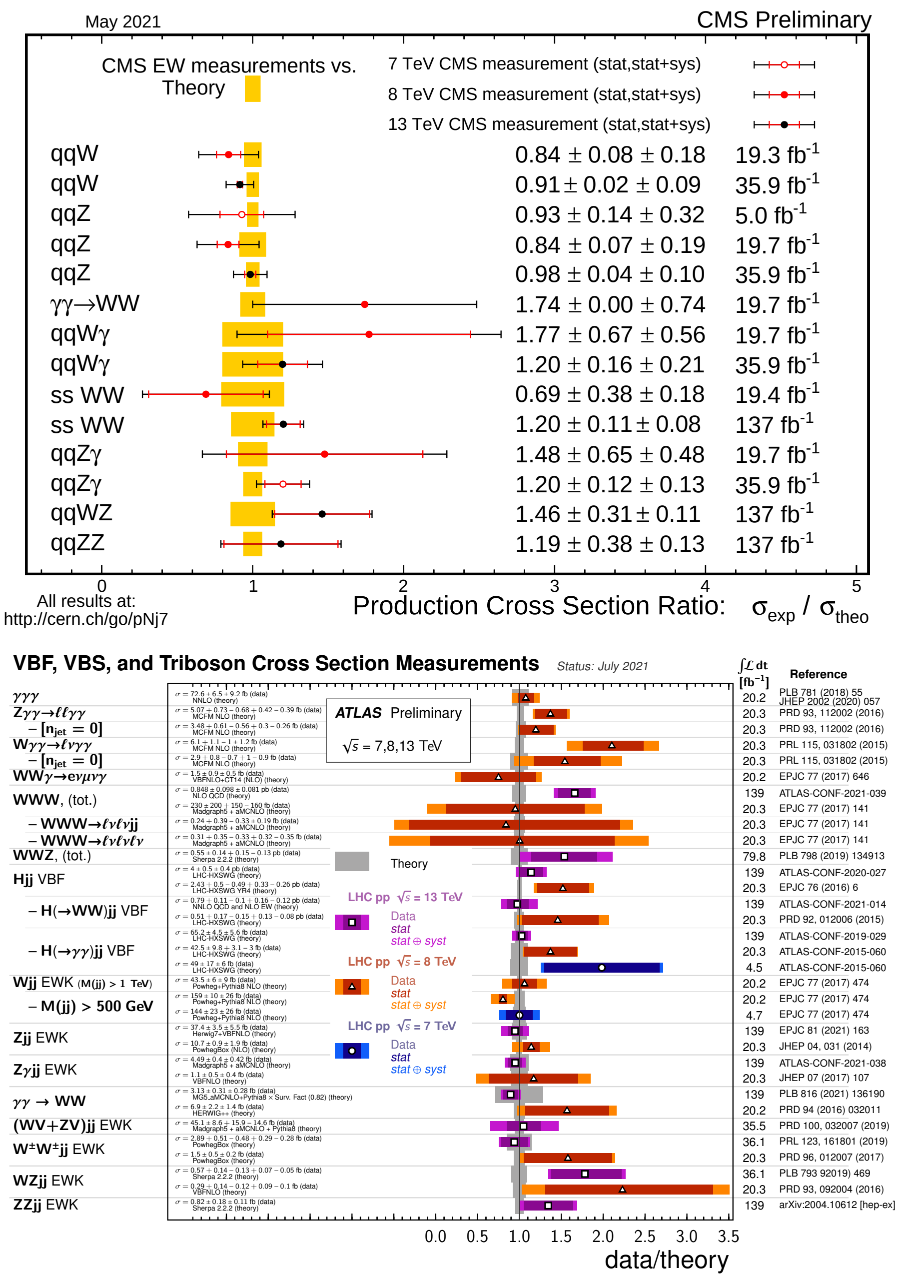

Figure 1: Summary of VBS and VBF fiducial cross-sections in CMS (top) [24] and ATLAS (bottom) [25] expressed as their ratio to the corresponding theoretical value.

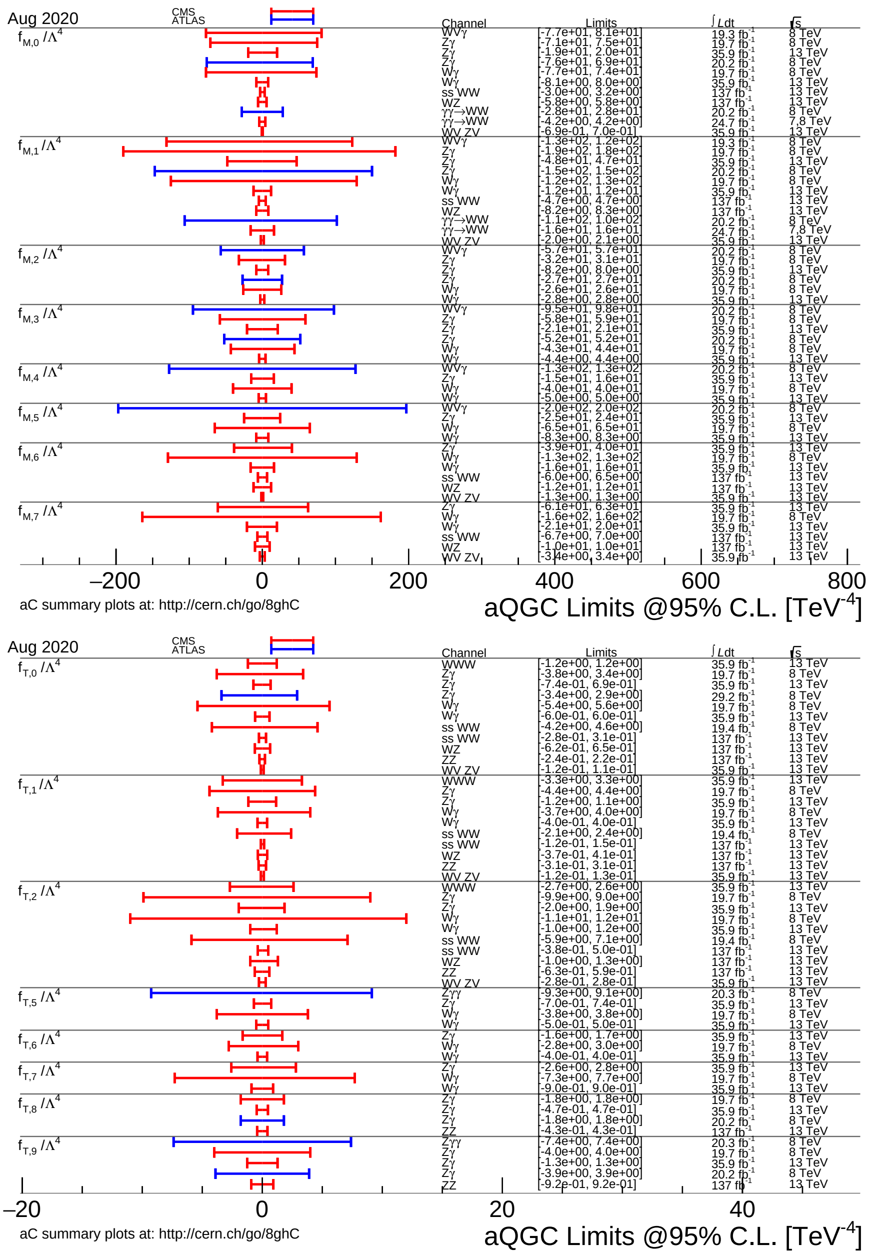

Figure 2: Current constraints on mixed (top) and transverse (bottom) dimension-8 operator couplings from various ATLAS (blue) and CMS (red) analyses at 7, 8, and 13 TeV, with corresponding integrated luminosities [26].

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