PROCEEDINGS OF SCIENCE

Vector Boson Scattering results in CMS

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Vector Boson Scattering (VBS) is a key production process to probe the electroweak symmetry breaking (EWSB) of the Standard Model (SM), since it involves both self-couplings of vector bosons and coupling with the Higgs boson. If the Higgs mechanism is not the sole source of electroweak symmetry breaking, the scattering amplitude deviates from the SM prediction at high scattering energy. Moreover, deviations may be detectable even if a new physics scale is higher than the reach of direct searches. Latest measurements of production cross sections of vector boson pairs in association with two jets in proton-proton (pp) collisions at $\sqrt{s}$ = 13 TeV at the LHC are reported using a data set recorded by the CMS detector.

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1. Introduction

Interactions between vector bosons, giving either one or two vector bosons in the final state, are among the rarest processes measured at the LHC. VBS processes fall into this category and serve as essential probes for studying the EWSB mechanism. The discovery of a Higgs boson with a mass of 125 GeV plays a critical role in ensuring unitarity in VBS processes by introducing new exchange diagrams that mitigate divergences in theoretical calculations involving massive gauge bosons. Consequently, precise measurements of VBS cross sections in proton-proton (pp) collisions are fundamental for the validation of the Higgs sector of the SM and for the investigation of potential effects of new physics beyond the Standard Model (BSM). In addition, VBS processes are an ideal probe for the non-abelian structure of the SM symmetry group $SU(2)_L \otimes SU(1)_Y$, since they exhibit both triple and quartic gauge interactions, and can therefore well constrain possibile deviation from SM predictions, the so-called anomalous gauge couplings (aTGC and aQGC respectively).
VBS contributes to electroweak (EW) induced diboson production at tree level $O(\alpha^4)$. From an experimental point of view, in pp collisions VBS processes exhibit a very clear signature, characterized by the presence of decay products of two vector bosons in the central region of the detector, and two forward-backward jets with high invariant mass (m_{jj}) and large pseudorapidity separation ($|\Delta\eta_{jj}|$), called tagging jets. Typical observables in VBS measurements at LHC are cross sections in detector fiducial regions.
Recent analyses from the CMS experiment have produced a wealth of results on VBS, which cover the observation of new processes and the measurement of both differential and total cross-sections. There has also been growing interest in interpreting possible deviations from the SM predictions in an Effective Field Theory (EFT) context using dimension-6 and dimension-8 operators.
This article reports the results of the three most recent analyses [1–3].

2. Opposite sign WW production in fully leptonic final state

This analysis [1] reports the first observation of EW production of a pair of W bosons with opposite sign (OS) in association with two jets, where the Ws decay leptonically. The full 2016–2018 dataset recorded by the CMS experiment is used. Events are selected requiring typical VBS signature, as described in the introduction, two OS leptons (e,μ) with invariant mass $m_{ll} > 50$ GeV and $p_T > 30$ GeV, and $p_T^{\text{miss}} > 20$ GeV.
This channel is quite challenging with respect to other VBS processes, mainly due to the large background coming from QCD-induced and top pair ($\bar{t}t$) production, which lead to a lower experimental sensitivity. $\bar{t}t$ background is suppressed by applying a veto on jets originating from b quarks, resulting in a ≈ 95% pure $\bar{t}t$ sample. A dedicated control region (CR) is defined for $\bar{t}t$ validation. QCD-induced production is reduced by requirements on m_{jj} and $|\Delta\eta_{jj}|$.
Two other CRs are dedicated to the Drell Yan background. Since the same-flavor final states exhibit a higher contamination from DY processes, combined ee+$\mu\mu$ and $e\mu$ channels are studied in different CRs to enhance the sensitivity. This background is suppressed by vetoing events compatible with the decay of a Z boson and by also requiring large p_T^{miss}.

Two Signal Regions (SRs) are defined to optimize the signal significance. This categorization is based on the centrality of dilepton system with respect to the tagging jets, quantified by Zeppenfeld variable $Z_{ll} = \frac{1}{2}|\eta_{l_1} + \eta_{l_2} - (\eta_{j_1} + \eta_{j_2})|$. All categories are fit to data using a maximun likelihood fit including all SRs and SRs, based on different discriminating variables depending on the final state: a feed-forward deep neural network (DNN) is used for $e\mu$ channel, while number of events or m_{jj} are used in same-flavor case. The observed (expected) significance is 5.6 (5.2) σ.

The EW production cross section of OS WW VBS is measured in two distinct fiducial volumes. The first volume is more inclusive, with no tau-veto applied and less stringent cuts on outgoing partons ($m_{qq'} > 100$ GeV, $p_T > 10$ GeV), resulting in an observed (expected) cross section of 99 ± 20 fb (89 ± 5 (scale) fb). The second volume is obtained by applying the kinematic cuts defined at the preselection level, yielding an observed (expected) cross section of 10.2 ± 2.0 fb (9.1 ± 0.6 (scale) fb).

3. Wγ production with W decaying leptonically

The analysis [2] measures the electroweak Wγjj production cross section at $\sqrt{s} = 13$ TeV using the complete Run 2 dataset (2016-2018), improving previous CMS results. Constraints on aQGCs are also provided in terms of dimension-8 EFT operators.
Event selection requires an isolated e or μ with $p_T > 35$ GeV, large p_T^{miss} from neutrinos produced in the leptonic decay of the W boson, an isolated photon with $p_T > 25$ GeV and two tagging jets. This selection suppresses the contamination from the QCD-induced Wγjj production, as well as the non-VBS EW contribution. The main backgrounds arise from W+jets and top-quark processes where the jet constituents are misidentified as a photon. This background is estimated with a data-driven method. The fraction of non-prompt photons is extrapolated as functions of the photon p_T and η in a CR enriched with loose photons, defined by the selection $200 < m_{jj} < 500$ GeV, and are then applied in the SR. Discrimination relies on the photon $\sigma_{\eta\eta}$ observable, that quantifies the lateral extension of the shower, defined as the energy-weighted spread within the 5×5 crystal matrix centered on the crystal with the largest energy deposit in the supercluster. The region with small $\sigma_{\eta\eta}$ values is predominantly populated by prompt photons. The background from jets misidentified as leptons (nonprompt leptons) is estimated with a similar method. Smaller background contributions are estimated from MC simulation and normalized to the integrated luminosity of the dataset using their corresponding cross sections.
The SR is defined by the following criteria: $m_{jj} > 500\,\text{GeV}$, $|\Delta\eta_{jj}| > 2.4$, $m_{W\gamma} > 100\,\text{GeV}$, system centrality < 1.2, and an azimuthal separation between the Wγ system and the dijet system higher than 2 radians. The SR is further split based on detector subregions (barrel, endcap) and final-state lepton flavor (e,μ).
Measurement of EW Wγ production rate is extracted using a binned likelihood fit to the data of the 2D distribution in $m_{l\gamma}$ and m_{jj} including all SRs and CRs. The observed (expected) significance is 6.0 (6.8) σ. The purely EW ($\mu_{QCD} = 1$) and EW+QCD Wγ cross section is measured in a fiducial region as $\sigma^{\text{fid}} = \sigma_g \mu \hat{\alpha}$, where σ_g is the cross section calculated with MadGraph5 at LO in QCD, μ is the signal strength and $\hat{\alpha}$ is the acceptance of the detector. Results are reported in Table 1.

A BSM interpretation in terms of EFT is also provided in this analysis. Dimension-8 operators are the lowest-dimension operators that modify QGC without involving two or three weak gauge boson vertices. A base of independent charge-conjugate and parity-conserving dimension-8 effective operators have been proposed in [4], based on the $SU(2)_L \otimes U(1)_Y$ symmetry of the

Signal	$\mu = \sigma_{OBS}/\sigma_{SM}$	Cross Section [fb]
EWK Wγ	$0.88^{+0.19}_{-0.18}$	$23.5 \pm 2.8(\text{stat})^{+1.9}_{-1.7}(\text{th})^{+3.5}_{-3.4}(\text{syst})$
EWK+QCD Wγ	$0.98^{+0.12}_{-0.11}$	$113 \pm 2.0(\text{stat})^{+2.5}_{-2.3}(\text{th})^{+13}_{-13}(\text{syst})$

Table 1: Signal strength and cross section results for EW and EW+QCD signals in Wγ VBS.

SM Lagrangian. Associated EFT couplings are called Wilson coefficients (WCs) and are labelled with $f_{I,j}$. To simulate EFT signal including the effects of aQGCs, MadGraph5_aMC@NLO is used. Constraints on relevant WCs are extracted at a 95% confidence level using a likelihood scan approach, considering each operator individually, with other EFT couplings set to zero. A tighter cut on the $m_{W\gamma}$ distribution is applied to enhance sensitivity to aQGCs. The constraints obtained on aQGCs are the most stringent limits to date on $f_{M,2-5}/\Lambda^4$ and $f_{T,6-7}/\Lambda^4$ parameters [2].

4. Same-sign WW with hadronic τ in the final state

This study [3] presents a measurement of the cross section for same-sign (SS) WW boson scattering. This is the first VBS investigation including a τ lepton in the final state. The analysis is performed with full Run 2 pp collision data collected by the CMS detector. The SS WW channel is considered the "golden channel" for VBS studies due to its clear distinction between EW and QCD contributions, as well as the full availability of next-to-leading order corrections.

SR is defined selecting events with a same-sign $l\tau_h$ pair, $p_T^{\text{miss}} > 50\,\text{GeV}$ and $m_{jj} > 500\,\text{GeV}$. Almost 95% of the background events are those that contain nonprompt leptons, which arise from misreconstruction of jets, produced mainly by QCD-mediated multijet processes, W+jets and hadronic or semi-leptonic $\bar{t}t$ production. Nonprompt leptons include also genuine leptons coming from the decays of hadrons within jets. This background is estimated in two dedicated CRs: a ”QCD-enriched” region, and the nonprompt CR. The QCD-enriched region is used to perform the first step of the nonprompt-lepton background estimate through a pass-fail method and is disjoint from the SR and other CRs. Events with only one loosely identified lepton, $p_T^{\text{miss}} < 50\,\text{GeV}$ and transverse mass $m_T(l, p_T^{\text{miss}}) < 50\,\text{GeV}$ are selected. The data and estimated background m_{jj} distributions are then compared in the nonprompt CRs for the $e\tau$ and $\mu\tau$ final states. This CR contains events with a same-sign $l\tau_h$ pair and $p_T^{\text{miss}} \leq 50\,\text{GeV}$.
Smaller sources of background comes from $Z/\gamma^* +$jets processes and dileptonic $\bar{t}t$ production. A $\bar{t}t$ and an OS CR are defined to constrain MC simulations of these backgrounds. Events with an OS $l\tau_h$ pair and no loose b-tagged jets are selected for the OS CR; events with an OS $l\tau_h$ pair, at least one medium b-tagged jet, and $p_T^{\text{miss}} > 50\,\text{GeV}$ are selected for the $\bar{t}t$ CR.
To discriminate signal from background, nine significant observables are combined in a single machine-learning discriminator (a DNN) and two dedicated transverse masses are defined to exploit the particular kinematical properties of the VBS SS WW. DNN distributions are given as input for a maximum likelihood fit, including both SRs and CRs. The extraction of the signal strength for both purely EW signal (assuming the amplitude for QCD-induced diboson production to be fixed at the SM value), and combined EW+QCD signal, is performed. Results are reported in Table 2.

Signal	$\mu = \sigma_{OBS}/\sigma_{SM}$	Significance [σ]
EWK ssWW	$1.44^{+0.63}_{-0.56}$	2.7 (1.9 exp)
EWK+QCD ssWW	$1.43^{+0.60}_{-0.54}$	2.9 (2.0 exp)

Table 2: Signal strength and significance results for EW and EW+QCD signals in SS WW VBS process with a hadronic tau in the final state.

Finally, constraints on bosonic dimension-6 and dimension-8 EFT Wilson coefficients are derived using a likelihood scan approach, providing both 1D and 2D limits. The 1D limits are obtained by considering one operator at a time, while the 2D limits involve pairs of operators that contribute similarly to the $W^{\pm}W^{\pm} \to W^{\pm}W^{\pm}$ scattering amplitude and have comparable ratios between quadratic and linear terms. This analysis is the first to consider pairs of different dimension operators in a 2D scan. Results are available in [3].

5. Summary

Many analyses have been performed in past years exploiting the full Run2 data collected by CMS at LHC. Recent results have been presented, showcasing that VBS processes benefit from a significant increase in precision and sensitivity, enabling the observation of processes that were previously inaccessible. As Run3 progresses, the larger dataset will allow for even more precise measurements due to the increased statistics. This heightened precision shifts the focus towards EFT measurements, since it facilitates the detection of potential deviations from Standard Model predictions. While good results have been achieved in constraining dimension-8 operators, recent studies have also demonstrated a high sensitivity to dimension-6 EFT operators, indicating that VBS processes can be effectively integrated into the broader framework of global EFT interpretations.

References

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