PROCEEDINGS OF SCIENCE

Vector boson scattering in CMS

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Vector boson scattering is a key production process to probe the electroweak symmetry breaking of the standard model, 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 standard model 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 collisions at $\sqrt{s} = 13$ TeV at the LHC are reported using a data set recorded by the CMS detector. Differential fiducial cross sections as functions of several quantities are also measured.

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1. Introduction

The standard model (SM) has been well tested and becomes complete after the discovery of Higgs boson in the ATLAS [1, 2] and CMS [3–5] experiment. The properties of Higgs boson, e.g., its coupling with vector bosons and fermions and the mass of Higgs boson, are vital for us to have a better understanding of Higgs boson and the Higgs mechanism, the latter one is of great importance as it provides masses for those massive particles. We know that three of the Goldstone Higgs bosons are eaten by the massless gauge bosons and become the longitudinal polarized component of the gauge bosons during the spontaneous symmetry breaking (SSB), which make the gauge bosons become massive. Inspired by the procedure how massive bosons obtain mass, we could study the SSB through the vector boson scattering (VBS), in which the longitudinal polarized VBS is the most interesting and important.

The typical topology of VBS is shown in Fig. 1. Two vector bosons are radiated from the initial state quarks and directly interact via scattering to produce a final state of two scattered vector bosons and two jets (VBS jets) from the quarks. The VBS processes have unique topologies as listed below:

- the VBS jets tend to be back-to-back, thus have very large separation in pseudorapidity.
- the invariant mass of two VBS jets is large, could reach TeV scale
- low hadronic activities in the central region

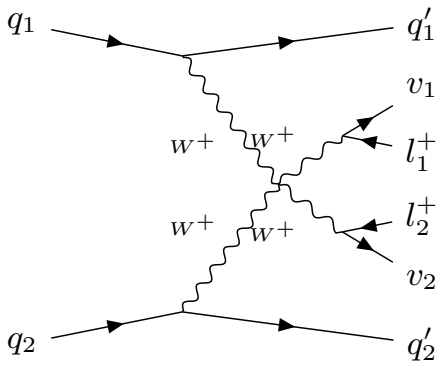

Figure 1: Scattering between two same sign charged W bosons with leptonic decays.

Besides the ability of SSB study, the VBS processes could also be used to search physics beyond SM (BSM) by introducing operators stands for anomalous couplings which are not allowed in SM, e.g., the coupling between four Z bosons. The extended lagrangian reads:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \frac{f_n}{\Lambda^{n-4}} O_{\text{n}} \tag{1}$$

where $\mathcal{L}_{\text{SM}}$ is the lagrangian of SM, and f_n, Λ^{n-4}, O_{n} are the coefficient, the energy scale and the anomalous operator with dimension n, respectively. The VBS processes are pure EW at leading order (LO) which are predicted by the SM precisely, thus they are sensitive to potential BSM which may promote the production of VBS events. The CMS collaboration has performed comprehensive measurements on the VBS processes, several recent measurements will be introduced in this article.

2. VBS WV

VBS WV [6] is a semi-leptonic channel, where "V" can be a Z boson or W boson which decay hadronically. This semi-leptonic decay channel has larger cross section than fully leptonic decay channel, and has smaller backgrounds than fully hadronic decay channel. The final states contain two VBS jets, two jets from vector boson (V-jets), one lepton and missing transverse momentum (MET). The separation between two V-jets depends on the energy of the hadronically decaying vector boson, thus the final states could be assigned to two categories, i.e., the boosted and the resolved. The two V-jets will be reconstructed as a single jet with large cone size (cone = 0.8), which refer to as AK8 jet. In the resolved case, two jet with small cone size 0.4 (AK4 jet) will be reconstructed. In both cases, the VBS jets are reconstructed with cone size 0.4. It's obvious that invariant mass of either the AK8 jets or of two AK4 V-jets should be close to the mass of W/Z boson. The definitions of signal region (SR) together with several other control regions (CR) are summarized in Fig. 2.

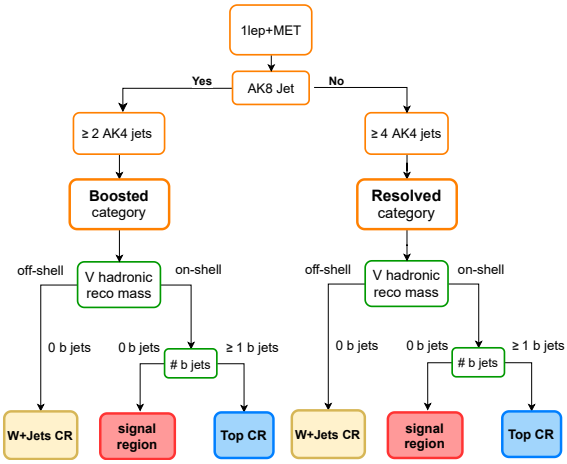

Figure 2: Analysis workflow: objects and categories selection followed by control regions (CR) and signal regions definition [6].

DNN method is used to separate signal and all the other backgrounds. Different DNNs are used for resolved and boosted case. The signal extraction is performed in several different signal definitions. The measurement of the purely EW signal strength μ_{EW} keeping the QCD WV production contribution fixed to the SM prediction $\mu_{\mathrm{QCD}} = 1$, the measurement of the signal strength considering as signal the EW and QCD WV processes together, and finally a 2D simultaneous measurement of the signal strengths μ_{EW} and μ_{QCD}. The observed electroweak signal strength is:

$$\mu_{\mathrm{EW}} = \sigma^{\mathrm{obs}}/\sigma^{\mathrm{SM}} = 0.85^{+0.24}_{-0.20} = 0.85^{+0.21}_{-0.17}(\mathrm{syst})^{+0.12}_{-0.12}(\mathrm{stat}), \tag{2}$$

($1^{+0.24}_{-0.22}$ expected), where σ^{obs} and σ^{SM} are the observed and predicted cross section respectively, corresponding to an observed evidence for the SM signal at 4.4 standard deviations, 5.1 expected.

Considering instead the signal as the overall EW and QCD WV production, the signal strength $\mu = \sigma^{\mathrm{obs}}/\sigma^{\mathrm{SM}}$ is measured to be:

$$\mu_{\mathrm{EW+QCD}} = \sigma^{\mathrm{obs}}/\sigma^{\mathrm{SM}} = 0.98^{+0.20}_{-0.17} = 0.98^{+0.19}_{-0.16}(\mathrm{syst})\ ^{+0.07}_{-0.07}(\mathrm{stat}), \tag{3}$$

($1^{+0.19}_{-0.18}$ expected) corresponding to a cross section defined in the same fiducial phase space as the pure EW one of $16.6^{+3.4}_{-2.9}$ pb, $16.9^{+2.9}_{-2.1}(\text{scale})^{+0.5}_{-0.5}(\text{pdf})$ expected.

3. VBS same sign WW and WZ

This is a combined analysis including VBS same sign WW (ssWW) and WZ [7], in both channels the vector boson decay leptonically. With the knowledge from previous studies, we know that ssWW is a very clean channel that the EW component dominants over the QCD-induced component in the signal region. A sequential selection is used in ssWW channel to perform the signal extraction. A BDT method is used to separate signal and backgrounds for the VBS WZ channel. The significance of the EW WZ signal is quantified from the p value using a profile ratio test statistic and asymptotic results for the test statistic. The observed (expected) statistical significance of the EW WZ signal is 6.8 (5.3) standard deviations, while the statistical significance of the EW $W^{\pm}W^{\pm}$ signal is far above 5 standard deviations.

Inclusive fiducial cross section measurements for the EW $W^{\pm}W^{\pm}$, EW+QCD $W^{\pm}W^{\pm}$, EW WZ, QCD WZ, and EW+QCD WZ processes and the theoretical predictions are summarized in Tab. 1. The measurements are more consistent with theoretical predictions without next–to–LO (NLO) corrections. Besides the inclusive cross section measurements, differential cross sections are also performed with respect to the m_{jj} and $m_{\ell\ell}$ for both VBS ssWW and VBS WZ.

The events in the ssWW and WZ SRs are used to constrain anomalous quartic gauge boson coupling (aQGC) in the effective field theory (EFT) framework. The diboson transverse mass are used for this study and no obvious deviation is found, a set of limits are obtained on the anomalous operators.

Table 1: The measured inclusive fiducial cross sections for the EW $W^{\pm}W^{\pm}$, EW+QCD $W^{\pm}W^{\pm}$, EW WZ, EW+QCD WZ, and QCD WZ processes and the theory predictions with MadGraph5_aMC@NLO at LO. The EW processes include the corresponding interference contributions. The theoretical uncertainties include statistical, PDF, and scale uncertainties. Predictions with applying the $O(\alpha_S\alpha^6)$ and $O(\alpha^7)$ corrections to the MadGraph5_aMC@NLO LO cross sections, as described in the text, are also shown. The predictions of the QCD $W^{\pm}W^{\pm}$ and WZ processes do not include additional corrections. All reported values are in fb [7].

Process	$\sigma\,\mathcal{B}$ (fb)	Theory prediction (fb)	Theory prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 0.37 (stat) ± 0.25 (syst)	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 0.39 (stat) ± 0.25 (syst)	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 0.39 (stat) ± 0.14 (syst)	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 0.40 (stat) ± 0.23 (syst)	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.4 0.45 (stat) ± 0.18 (syst)	3.12 ± 0.70	3.12 ± 0.70

4. Longitudinal polarized ssWW

As we have discussed in the introduction, the longitudinal polarized component of vector boson is related to the Higgs mechanism. Though the scattering between longitudinal polarized vector has been pursued for a long time, it is not possible until the ATLAS and CMS experiments collect large amount of data. CMS collaboration performed the first study on longitudinal polarized VBS through ssWW channel [8]. In the ssWW channel, each of the W bosons can be polarized either longitudinally (W_L) or transversely (W_T), leading to three distinct contributions $W_L^\pm W_L^\pm$, $W_L^\pm W_T^\pm$ and $W_T^\pm W_T^\pm$. But due to limited data sample size, two measurements are performed: one for $W_L^\pm W_L^\pm$ and $W_X^\pm W_T^\pm$; and another for $W_L^\pm W_X^\pm$ and $W_T^\pm W_T^\pm$. The index X indicates either of the two polarization states. Such study is very challenge due to the fact that the VBS processes have very small cross section, and the contribution of longitudinal component is only around 10 percent of the inclusive VBS process. The other challenge is due to kinematic similarity between different polarized VBS components. Trigger by this difficulty, a multi-variable analysis method is used to separate different polarized components, and to separate VBS and other backgrounds.

Since the definition of polarization depends on the choice of reference frame, the measurements are performed in two different reference frames, e.g., the WW center-of-mass and the initial-state parton-parton reference frames. The observed (expected) significance of $W_L^\pm W_L^\pm$ component in WW reference frame is 2.3 (3.1) standard deviations, while the observed (expected) significance in parton-parton reference frames is 2.6 (2.9) standard deviations. The cross section of different definition of signals are listed in Table. 2. In general, the measurements are consistent with the theoretical prediction within uncertainties.

Table 2: Measured fiducial cross sections for the $W_L^\pm W_L^\pm$ and $W_X^\pm W_T^\pm$ processes and for the $W_L^\pm W_X^\pm$ and $W_T^\pm W_T^\pm$ processes for the helicity eigenstates defined in the $W^\pm W^\pm$ center-of-mass frame. The theoretical predictions including the $O(\alpha_S\alpha^6)$ and $O(\alpha^7)$ corrections to the MadGraph5_aMC@NLO LO cross sections, as described in the text, are also shown. The theoretical uncertainties include statistical, PDF, and LO scale uncertainties. $\mathcal{B}$ is the branching fraction for $WW \to \ell\nu\ell'\nu$ [9].

Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

5. VBS Zγ

Different from the massive VBS process, the VBS Zγ [10] is not able to study the Higgs mechanism due to that photon does not directly couple to the Higgs boson. The interests of VBS Zγ is its sensitivity to pure neutral aQGCs, i.e., ZZZγ/ZZγγ/Zγγγ. This analysis focuses on the leptonic decay channel, thus the final state contains two electrons or two muons with invariant mass

within Z mass window, one photon and two VBS jets. The events are categorized to four channels, i.e., muon (electron) + photon in barrel (endcap) region.

The main backgrounds are the QCD-induced $Z\gamma$ and those processes with same final states but the photon are not prompt. The contribution of QCD-induced $Z\gamma$ is directly estimated using simulation. The contribution of nonprompt backgrounds are estimated using data-driven method, i.e., performing fit on the shape of σ_{ieie} of photon, while σ_{ieie} stands for the centrality of the photon energy deposit on the detector. The EW signal extraction is performed by a simultaneous fit between signal region and control region through a two dimensional distribution of m_{jj} and $\Delta\eta_{\mathrm{jj}}$. The observed significance of the EW signal is much higher than 5 standard deviations. The best fit value for the EW $Z\gamma$ signal strength and the measured fiducial cross section are

$$\begin{aligned}\mu_{\mathrm{EW}} &= 1.20^{+0.12}_{-0.12}(\mathrm{stat})^{+0.14}_{-0.12}(\mathrm{syst}) \\ &= 1.20^{+0.18}_{-0.17}\end{aligned} \tag{4}$$

$$\begin{aligned}\sigma^{\mathrm{fid}}_{\mathrm{EW}} &= 5.21 \pm 0.52(\mathrm{stat}) \pm 0.56(\mathrm{syst})\,\mathrm{fb} \\ &= 5.21 \pm 0.76\,\mathrm{fb}\end{aligned} \tag{5}$$

The best fit value for the combined $Z\gamma$jj signal strength and the measured fiducial cross section are

$$\begin{aligned}\mu_{\mathrm{EW+QCD}} &= 1.11^{+0.06}_{-0.06}(\mathrm{stat})^{+0.10}_{-0.09}(\mathrm{syst}) \\ &= 1.11^{+0.12}_{-0.11}\end{aligned} \tag{6}$$

$$\begin{aligned}\sigma^{\mathrm{fid}}_{\mathrm{EW+QCD}} &= 14.7 \pm 0.80(\mathrm{stat}) \pm 1.26(\mathrm{syst})\,\mathrm{fb} \\ &= 14.7 \pm 1.53\,\mathrm{fb}\end{aligned} \tag{7}$$

The theoretical fiducial cross section for the EW $Z\gamma$ signal at LO accuracy is $4.34 \pm 0.26(\mathrm{scale}) \pm 0.06(\mathrm{PDF})$ fb, and the expected fiducial cross section for the combined QCD and EW $Z\gamma$jj production is $13.3 \pm 1.72(\mathrm{scale}) \pm 0.10(\mathrm{PDF})$ fb. Besides the inclusive cross section measurements, differential cross section measurements are also derived on with respect to the p_{T} of leading lepton, leading jet and photon, as well as on the invariant mass of two jets. In general, good agreements are obtained between measurements and theoretical predictions. The invariant mass of Z boson and photon is used for aQGC study, no obvious deviation from SM is found thus a set of limits are obtained.

6. VBS Wγ

Similar with VBS $Z\gamma$, the main motivation of VBS Wγ [11] is its sensitivity to aQGCs. Different from the several analysis introduced above, this analysis use the data collected in 2016 which corresponds to a integrated luminosity 35.9 fb^{-1}. The main backgrounds of this channel are the QCD-induced Wγ, nonprompt photon and nonprompt lepton. The contribution of QCD-induced Wγ is estimated using simulation, and the contribution of nonprompt backgrounds are derived using the methods introduced above. The EW signal extraction uses the similar strategy with VBS $Z\gamma$, i.e., perform simultaneous fit between signal region and control region with respect to invariant mass of two jets m_{jj}, and invariant mass of lepton and photon $m_{\ell\gamma}$. The observed (expected) significance of EW signal is 4.9 (4.6) standard deviations using 2016 data, while 5.3

(4.8) standard deviations is obtained after combining with data collected in 2012 [12]. This is the first observation of VBS Wγ. The signal strength and corresponding fiducial cross section of EW signal are

$$\mu_{\mathrm{EW}} = 1.20^{+0.26}_{-0.24} \tag{8}$$

$$\sigma^{\mathrm{fid}}_{\mathrm{EW}} = 20.4 \pm 0.4(\mathrm{lumi}) \pm 2.8(\mathrm{stat}) \pm 3.5(\mathrm{syst})\,\mathrm{fb} = 20.4 \pm 4.5\,\mathrm{fb} \tag{9}$$

for the EW+QCD signal, the signal strength and corresponding fiducial cross section are

$$\mu_{\mathrm{EW+QCD}} = 1.21^{+0.17}_{-0.16} \tag{10}$$

$$\sigma^{\mathrm{fid}}_{\mathrm{EW+QCD}} = 108 \pm 2(\mathrm{lumi}) \pm 5(\mathrm{stat}) \pm 15(\mathrm{syst})\,\mathrm{fb} = 108 \pm 16\,\mathrm{fb} \tag{11}$$

The invariant mass of W boson and photon is used for aQGC study. No obvious deviation from SM is found and a set of limits are obtained. These are the most stringent limits to date on the aQGC parameters $f_{\mathrm{M},2-5}/\Lambda^4$ and $f_{\mathrm{T},6-7}/\Lambda^4$.

7. Summary

The CMS collaboration has performed comprehensive studies of the vector boson scattering process, containing massive vector boson scattering as well as those with photon, most of them are performed with data collected from 2016 to 2018, which corresponding to a integrated luminosity 137 fb^{-1}. The first measurement of longitudinal polarized vector boson scattering is performed through same sign WW channel. Vector boson scattering processes could be used to search physics beyond standard model by introducing anomalous couplings between vector bosons. Several works have implement such study and no obvious deviation from standard model is found, which lead to a set of limits on the anomalous couplings.

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