Multiboson measurements and limits on anomalous gauge couplings with the CMS experiment

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Abstract

Recent measurements of multiboson production from the CMS experiment will be presented, as well as limits on anomalous triple and quartic gauge couplings. Precision measurements of multiboson production allow a basic test of the Standard Model, where higher order QCD and electroweak corrections can be probed. In addition searches of physics beyond the Standard Model in multiboson final states rely on precise determination of the Standard Model multiboson processes. The presence of triple and quartic gauge couplings in multiboson production also allows for tests of modification of these vertices from new physics. Prospects for future measurements will also be shown. With the increased center of mass energy of the LHC and the integrated luminosity that will be collected in LHC Run 2, the limits on anomalous gauge couplings will improve significantly.

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Multibosons measurements and limits on Anomalous Gauge Couplings from the CMS Experiment

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1 Introduction

Measurements of multiboson processes are a stringent test of the Standard Model (SM) and have sensitivity to models of new physics. The LHC is a unique machine for studying multiboson processes because of its high center-of-mass energy and high luminosity. The CMS experiment has measured a suite of multiboson processes, which encompass signatures where two or more $W$ bosons, $Z$ bosons, or photons are produced. These processes have cross sections from a few hundred picobarns to extremely rare processes of a few femtobarns. A summary of CMS measurements of these processes as well as others can be found here\(^1\).

Many multiboson final states are produced through triple or quartic gauge couplings. These couplings arise naturally from the non-Abelian nature of the electroweak interaction. The presence of new physics may cause a modification of the these couplings which presents as an increase in the measured cross section. Such modifications are generally enhanced in collisions having large momentum transfer. Therefore collisions at the LHC are ideal for searching for new physics in the multiboson sector.

\(^1\)https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined
2 Parameterization of Anomalous Gauge Couplings

Anomalous modifications of gauge couplings are parameterized using an Effective Field Theory (EFT) which considers higher order modifications to the SM Lagrangian [1],

\[ \mathcal{L}^{NP} = \mathcal{L}^{4(SM)} + \frac{1}{\Lambda} \mathcal{L}^{5} + \frac{1}{\Lambda^{2}} \mathcal{L}^{6} + \frac{1}{\Lambda^{3}} \mathcal{L}^{7} + \frac{1}{\Lambda^{4}} \mathcal{L}^{8}. \]

The higher order terms are suppressed by a mass scale, \( \Lambda \), for each additional power beyond the SM the term. The terms of odd dimension are not considered as they do not effect multiboson measurements or cause significant anomalies such as lepton flavor violation that are ruled out. Therefore the dimension-6 and dimension-8 operators are considered. Dimension-6 operators lead primarily to anomalous triple gauge couplings (aTGC). Anomalous quartic gauge couplings (aQGC) arise from the dimension-8 operator. Generally, if some new physics exists, it is expected to be observed first as an aTGCs, but we also search for aQGC in the assumption that no aTGCs exist. In addition to the EFT parameterization, there are a number of other parameterizations that have been used in the past. For anomalous neutral gauge couplings, a separate parameterization is used as well.

3 Experimental Measurements

The CMS detector [2] is designed to efficiently identify electrons, muons, photons, and hadronic jets giving a high efficiency for selecting electroweak bosons. The CMS detector is highly symmetric and covers pseudorapidity ranges up to \( |\eta| < 4.5 \) so that escaping neutrinos can be identified from the missing transverse momentum \( (E_{T}^{\text{miss}}) \). The results in this note are from the 2012 data taking period where approximately 20 fb\(^{-1}\) of data were recorded. A summary of some results will be given below. More information can be found at the given references.
3.1 WW cross section measurements and limits on aTGC

The production of opposite-sign W boson pairs is a high rate process at the LHC having a theoretical cross section of $59.8 \pm 2.2$ pb calculated at NNLO [3]. The WW process is identified from fully leptonic decays in the di-electron, di-muon, or electron-muon final state [4]. Large $E_T^{\text{miss}}$ is required to reduce backgrounds by identifying the escaping neutrinos. To further reduce backgrounds from Drell-Yan in the same-flavor channels an MVA-based discriminator is used, and to reduce backgrounds from $t\bar{t}$ and single top, events are rejected if a jet is tagged as originating from a b-hadron. Data-driven methods are used to estimate the W, Drell-Yan, and top quark backgrounds and other, smaller backgrounds are estimated using Monte Carlo simulation. Figure 1 (a) shows the dilepton $p_T$ spectrum for selected events having no reconstructed jets. The measured cross section is $60.1 \pm 0.9$ (stat) $\pm 3.2$ (exp) $\pm 3.2$ (theory) $\pm 1.6$ (lumi) pb, consistent with the NNLO theoretical prediction. Differential cross sections of a number of quantities are measured. The differential cross sections are unfolded to the parton level and are compared to a number of theoretical predictions as shown in Figure 2 (a). In addition, improved limits are placed on aTGC couplings.

3.2 Measurement of $Z\gamma$ in the $Z \to \nu\nu$ final state

The production of $Z\gamma$ is another high-rate process at the LHC. This measurement takes advantage of the relatively higher branching fraction of the $Z$ boson decay to neutrinos by selecting one photon with large transverse momentum and large $E_T^{\text{miss}}$ directed oppositely to the photon [5]. Backgrounds from, W events where the decay electron mimics a photon, $\gamma +$ jet, and instrumental sources are estimated using data-driven methods. The background from $W\gamma$ events where the decay lepton is lost is estimated using simulation. The photon $E_T$ spectrum with the signal and background predictions is shown in Figure 1 (b). The measured cross section in the fiducial region where the photon has transverse momentum greater than 145 GeV is $52.7 \pm 2.1$ (stat) $\pm 6.4$ (syst) $\pm 1.4$ (lumi) fb, consistent with the theoretical prediction of $50.0 \pm 2.4$ fb. In addition stringent limits are set on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ neutral gauge couplings.
3.3 Measurement of $WW$ photoproduction

This measurement identifies events where the incoming protons radiate photons, producing two opposite-sign $W$ bosons. The interaction can occur through triple or quartic gauge couplings. In these events the protons receive only a small transverse momentum and are lost out of the acceptance of the detector. Such events are identified from the leptonic decays of the $W$ bosons with no additional activity from the interaction vertex [6]. Backgrounds in the selection are estimated with Monte Carlo simulations with systematic uncertainties determined from dedicated control regions. Figure 2 (b) shows the dilepton mass spectrum for events passing the event selection and having one electron and one muon. The measured cross section is $12.3^{+5.5}_{-4.4}$ fb with a theoretical cross section of $6.9 \pm 0.6$ fb. The significance of the observed events over background is $3.6\sigma$. In addition, limits are placed on aTGCs and aQGCs.

3.4 Measurement of same-sign $WW$ production with forward jets

This measurement searches for the unique signature of two same-sign $W$ bosons in vector boson scattering (VBS) events. In these events both incoming protons radiate $W$ bosons which scatter in a quartic gauge vertex. The event signature is two leptons having the same charge, and two forward jets [7]. The signal is enhanced by requiring the jets to have large mass and large pseudorapidity separation. Figure 1 (c) shows the dijet mass distribution for signal events. Backgrounds from non-prompt leptons are estimated using a data-driven method and the remaining backgrounds are estimated using simulation. The signal is observed with a significance of $2.0\sigma$ and stringent limits are placed on aQGC.

3.5 Conclusions

The large integrated luminosity delivered by the LHC in the 2012 data set allows for the measurement of many multiboson processes. Precision measurements of multiboson processes test the electroweak gauge sector. With NNLO theoretical predictions available for many multiboson processes precision measurements become more powerful. An Effective Field Theory is used to test for the presence of possible new physics and limits are set on the
coupling parameters. Many multiboson measurements have been made with CMS; a selection of measurements that are representative of the SM physics program was given.

References


Figure 1: The dilepton $p_T$ spectrum for signal WW events having no reconstructed jets in the event (a). Photon $E_T$ spectrum for the $Z\gamma$ analysis (b). The predictions show the expectation from some models of anomalous gauge couplings. Dilepton mass spectrum for events that pass the exclusive vertex selection and have one electron and one muon (c). Dijet mass spectrum for events that have two same-sign leptons and two jets with large pseudorapidity separation (d).
Figure 2: Differential cross section as a function of the azimuthal separation of the leptons. The observed events are unfolded to the parton level and compared to a number of NLO theoretical predictions.