Recent results from the CMS experiment on the production of multiple vector bosons in proton-proton collisions at the CERN LHC are presented. Measurements of WZ and ZZ production with fully leptonic decays, Z(νν)γ, and WV (V = W,Z → q̅q) production at 8 and 13 TeV are discussed. Selected cross section measurements, unfolded differential measurements, and limits on anomalous triple gauge couplings are presented and compared with theoretical predictions.
1 Introduction

Measurements of the production of multiple vector bosons in proton-proton collisions at the CERN LHC is an important test of the electroweak sector of the Standard Model (SM). Such final states provide a natural probe of the vector boson self-couplings, which arise due to the non-Abelian nature of the electroweak gauge group and are exactly predicted by the SM. Deviations from these predictions could therefore be an indication of new physics. In addition, due to recent theoretical developments, the production cross sections of all processes producing vector boson pairs in proton-proton collisions are known at next-to-next-to-leading order (NNLO) in QCD – many differentially. When the perturbative QCD corrections are significant with respect to the experimental uncertainties, measurements can directly validate the higher-order perturbative QCD calculations.

This report summarizes recent measurements from the CMS collaboration using data collected by the CMS detector at $\sqrt{s} = 8$ and 13 TeV. A brief summary of measurements for a variety of vector boson pairs and decays is presented, each offering a unique probe of the SM and possible new physics. Full details of the analyses can be found in the references.

2 $Z(\nu\nu)\gamma$ Production at 13 TeV

In the SM, proton-proton collisions producing a Z boson in association with a photon, with the Z decaying to a pair of neutrinos, can only proceed through initial-state radiation of a photon from the incoming quarks. Other production mechanisms could arise through trilinear gauge boson self-interaction couplings (TGCs) which would be a sign of new physics. Measurements of this channel for high photon transverse energy are therefore sensitive to new physics, and are also important as background measurements to dark matter searches in the mono-photon channel.

The $pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma$ fiducial cross section has been measured for transverse energy $E_T^\gamma > 175$ GeV and photon pseudorapidity $|\eta^\gamma| < 1.44$ using $2.3 \text{ fb}^{-1}$ of data collected by the CMS experiment in 2015 [1]. The analysis selects events with a well-identified photon with transverse energy $E_T^\gamma > 175$ GeV and missing transverse momentum $p_T^{\text{miss}} > 170$ GeV. The two are required to have large angular separation and to be separated from all jets in the event, as the missing transverse momentum in $\gamma$+jet background events is typically aligned with mismeasured jets. The primary backgrounds to the signal process are experimental in nature, including spurious signals in the electromagnetic calorimeter (ECAL), beam halo, and cosmic rays. These contributions all give rise to signals mimicking photons in the detector, with missing transverse momentum arising due to the condition that the transverse momentum of the event sum to zero. The contribution of these backgrounds is estimated by exploiting their characteristic shape and timing in the ECAL. Other backgrounds enter the selection due to misidentification or objects escaping the detector acceptance, including $\gamma$+jets, $W \rightarrow \ell\nu$, $Z(\rightarrow \ell\ell)\gamma$ and $W(\rightarrow \ell\ell)\gamma$. They are estimated from simulated samples, with the exception of W decays to electrons and QCD multijet backgrounds which are estimated from data.

The measured fiducial cross section of

$$\sigma_{\text{fid}}(pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma) = 66.5 \pm 13.6 \text{ (stat)} \pm 14.3 \text{ (syst)} \pm 2.2 \text{ (lumi)} \text{ fb}$$

is found to be in agreement with the SM prediction of $65.5 \pm 3.3 \text{ fb}$, computed at NNLO with MATRIX. [2]

3 $W^{\pm}Z$ Production with Leptonic Decays at 8 and 13 TeV

Measurements of WZ production with fully leptonic decays probe the charged gauge interactions of the SM. The relatively clean three-lepton final state is balanced by a modestly high cross section, allowing a high statistics measurement with controlled systematics. The analysis selects events with three leptons and missing transverse momentum $p_T^{\text{miss}} > 30$ GeV. The condition on the mass of the three lepton system $m_{\ell\ell} > 100$ GeV is required to reject $Z\gamma$ events where a photon radiated from the leptonic Z decay is misidentified as an electron. Events with a b-tagged jet are rejected to reduce background yields from $t\bar{t}$. 

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Figure 1: (Left) The total \( pp \rightarrow WZ \) cross section as a function of \( \sqrt{s} \) measured by the CMS and ATLAS experiments compared to the predictions of MCFM 7.0 and MATRIX v1.0.0_beta4. The CMS 13 TeV cross section are calculated for the Z boson mass window 60 – 120 GeV. The CMS 7 and 8 TeV cross sections are calculated for the Z boson mass window 71 – 111 GeV. ATLAS measurements are performed with the Z boson mass window 66 – 116 GeV. (Right) Differential cross section at \( \sqrt{s} = 8 \) TeV as a function of the Z boson transverse momentum, compared to the fixed-order prediction from MCFM 6.3 and the prediction from MadGraph5_aLHE+PYTHIA6.4, using MLM merging of tree-level contributions for up to two additional partons [3].

Backgrounds for this measurement are categorized into processes producing at least three prompt isolated leptons (\( \ell = e, \mu \)), including ZZ, triboson, and \( t\bar{t}\gamma \), and those processes where nonprompt leptons from hadrons decaying to leptons inside jets or jets misidentified as isolated leptons pass the signal selection, predominantly \( t\bar{t} \) and Drell-Yan. The nonprompt background is evaluated with a data-driven approach using control regions of events passing the full analysis selection, with the exception that one, two, or three leptons pass relaxed identification and isolation requirements but fail the more stringent requirements applied to signal events. These events are extrapolated into the signal region using per-lepton “tight to loose” transfer factors calculated from a sample of dijet events. Prompt backgrounds are evaluated using simulated samples. The Z\( \gamma \) process is also estimated with simulation.

The production cross section has been measured by the CMS experiment at 7, 8, [3] and 13 TeV [4]. These measurements and their agreement with the SM predictions, computed at NNLO in QCD with MATRIX [5] and next-to-leading order (NLO) in QCD with MCFM [6] are summarized in Fig. 1 which also presents ATLAS results for comparison. Good agreement with the SM predictions is observed. Some tension is seen in the 13 TeV measurement with 2.3 fb\(^{-1}\) and the NNLO prediction, but we note that this measurement is statistically limited and awaits a measurement with an increased 13 TeV dataset.

Differential measurements of WZ production, unfolded using the iterative d’Agostini method [7], are presented using 19.6 fb\(^{-1}\) collected by the CMS experiment in 2012 at 8 TeV. These measurements allow for comparisons of theoretical predictions in distributions sensitive to higher-order corrections, such as the Z boson transverse momentum, which is shown in Fig. 1. Limits on anomalous quartic gauge couplings are also calculated at 8 TeV, details of which can be found in the reference.

4 ZZ Production with Leptonic Decays at 8 and 13 TeV

In spite of its low cross section, the \( ZZ \rightarrow 4\ell \) process is favorable experimentally due to its clean and fully reconstructed four-lepton final state. It provides a probe of the neutral gauge sector of the SM, and its role as the primary background to the SM Higgs boson in the four-lepton channel makes it an important process to understand.
Measurements of the ZZ production cross section, inclusive differential distributions, and differential distributions of ZZ production associated with jets were performed using 35.9 fb\(^{-1}\) of 13 TeV data collected by the CMS experiment in 2016 \cite{8,9} and 19.7 fb\(^{-1}\) of data collected at 8 TeV in 2012 \cite{10}. The analysis selects four leptons forming two Z boson candidates with mass in the range 60 < \(m_{l^+l^-} < 120\) GeV. The very low background in this channel permits the use of loose identification and isolation criteria. Backgrounds with four prompt leptons such as triboson and \(t\bar{t}V\), which have very low production cross sections, are evaluated using simulated samples. The contribution from nonprompt leptons is estimated using the same technique described for WZ in the previous section. However, the “tight to loose” transfer factors are derived using a sample of Drell-Yan events, with associated jets as the loose and tight lepton probe.

The total cross section measurements and their agreement with the SM prediction, computed at NNLO
in QCD with MATRIX [11] [12] and NLO in QCD with MCFM are summarized in Fig. 2 which also presents ATLAS results for comparison. Differential cross section measurements have also been performed for a variety of inclusive and jet-dependent distributions, unfolded using the iterative d’Agostini method. The four-lepton mass, which includes contributions from resonant ZZ production, Z → 4ℓ production, and H → 4ℓ production, is also presented in Fig. 2. For this differential measurement the mass constraint of the Z boson pairs is relaxed to 4 < m_{ℓ+ℓ−} < 120 GeV, 40 < m_{ℓ′+ℓ′−} < 120 GeV. Results are in good agreement with the SM predictions.

Differential measurements of ZZ boson production associated with jets are a direct test of higher-order calculations. The normalized differential ZZ production cross section by number of anti-k_T R = 0.5 jets at 8 TeV is shown in Fig. 3. Also shown is the differential cross section for the pseudorapidity separation of the two leading anti-k_T R = 0.4 jets at 13 TeV for events with at least two jets. Understanding this distribution is critical for extracting information about vector boson scattering and vector boson quartic interactions. Limits on anomalous quartic gauge couplings have also been calculated at 13 TeV, details of which can be found in the reference.

5 WV Production with Semileptonic Decays

The large branching fraction of vector bosons to quark anti-quark pairs offsets the challenge of reconstructing the vector boson from hadronic decay products. Diboson pairs with semileptonic decays are therefore attractive due to the balance of leptonic signature, distinguishable above the large QCD multijet background at the LHC, and the favorable branching fraction of the hadronic decay. In particular, the higher production cross section allows sensitivity to tails of distributions most sensitive to new physics effects. Boosted object techniques allow further discrimination of vector boson-like objects from background, and are particularly applicable in the new physics regime.

Figure 4: (Left) Transferse momentum of vector boson-tagged jet, used for aTGC limit extraction at 8 TeV [13]. (Right) Diboson mass, used for limit extraction in 13 TeV analysis [14].

Limits on charged aTGC parameters, using the effective Lagrangian formalism of [15], are calculated using 19.6 fb^{-1} of 8 TeV data [13] and 2.3 fb^{-1} of 13 TeV data collected in 2015 [14]. The analyses selects a high p_T lepton and large missing transverse momentum associated with the leptonically decaying W boson. An anti-k_T (Cambridge-Aachen) “fat jet” is selected at 13 (8) TeV with p_T > 200 GeV and tagged as a vector boson candidate using subtructure techniques including pruning [16] and N-subjettiness [17]. Events with additional b-tagged jets are rejected to reduce t睹 background contributions. The analysis uses event categorisations based on the jet mass to tag events as WZ-like or WW-like, but cannot fully distinguish the two states.

Limits are extracted via a fit to the WV invariant mass (transverse momentum of the vector boson-tagged jet) distribution at 13 (8) TeV. These distributions are shown in Fig. 4. The 95% CL limits from the 8 TeV
analysis,
\[-0.011 < \lambda_Z < 0.011, \quad -0.044 < \Delta \kappa_\gamma < 0.063, \quad -0.0087 < \Delta g^Z < 0.024, \tag{2}\]
are the most stringent to date on $\Delta \kappa_\gamma$ and $\Delta g^Z$.

6 Conclusions

![Figure 5: Summary of diboson total production cross sections measured by the CMS experiment.](image)

We have summarized recent diboson measurements from the CMS experiment using data collected at 8 TeV and 13 TeV. The current status of diboson cross sections measured by the CMS experiment is shown in Fig. 5. We note that almost all results are compared to theoretical predictions at NNLO, where theoretical errors are typically below experimental ones, which presents an exciting challenge for future measurements.

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