Multiboson Production in CMS

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This review presents recent measurements of multiboson production using CMS data. Inclusive and differential cross sections are measured using several kinematic observables. Constraints on new physics using the effective field theory framework are reported.

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1. Introduction

The Compact Muon Solenoid (CMS) experiment [1] allows the study of multi-boson production processes, in previously unreachable regions of phase space. The study of multi-boson production processes is crucial to test the predictions of the Standard Model (SM) of particle physics in the electroweak sector. This review presents the most recent results achieved by the CMS Collaboration. It covers new studies of inclusive di-boson production processes, recent observations of central-exclusive production (CEP), double-parton scattering (DPS) processes, and the most recent results from tri-boson analyses. A discussion of the constraints extracted on new physics is also presented.

2. Di-boson production

The electroweak di-boson production includes the vector boson scattering (VBS), which is crucial for the study of triple and quartic gauge couplings predicted by the SM. Several VBS and inclusive di-boson observations and measurements have been performed by the CMS Collaboration in the past years with the data collected in the 2016-2018 LHC running periods [2–6] (the analyses targeting exclusive VBS processes were covered in a dedicated talk at the same conference). A new measurement of the inclusive opposite-sign WW (OS-WW) at a center-of-mass energy of 13.6 TeV has been presented [7]. It is the first multi-boson result obtained with an analysis of the 2022 CMS dataset (start of Run 3 data taking) corresponding to an integrated luminosity of L=34.8/fb. The final state considered for this analysis is eμ+2ν(+jets). The WW production process is sensitive to vector boson self-interactions and its study is fundamental to test perturbative-QCD and electroweak predictions. The production processes can occur via quark- and gluon-annihilation i.e. qq/gg$\rightarrow$WW. For the latter, a correction of a factor 1.4 was applied, corresponding to the ratio between the next-to-leading-order (NLO) and leading-order (LO) cross sections. Production via Higgs decay, H$\rightarrow$WW, gives a contribution about 10 times smaller than quark/gluon-annihilation, so it is considered a background for this analysis. Events were categorized by the flavour and charge of the leptons, the number of jets, and number of jets identified as originating from b-quarks. A maximum likelihood fit was performed in the designed event categories. An inclusive OS-WW production cross section of 125.7 ± 5.6 pb was measured. The cross sections were evaluated in a fiducial region bounded by the detector acceptance, both inclusively and differentially as a function of the jet multiplicity in the event. The results are in good agreement with standard model predictions.

Within CMS, multi-boson production processes associated with with final-state tagged protons can be studied thanks to the Precision Proton Spectrometer (PPS) [8]. This set of sub-detectors are located at a distance of about 200 meters from the central CMS detector, in the backward and forward directions, and provides the full kinematics of the events. PPS allows the study of Central Exclusive Production (CEP) processes of vector boson pairs with protons detected in the final state. It is a very special case of VBS, corresponding to photon scattering, p$\gamma\gamma$p$\rightarrow$ pVVp. A first analysis of the VV production [9] was performed in the inclusive hadronic final state, targeting the signature given by two large jets. The main background consists of the diffractive pileup, suppressed by selecting a fiducial region requiring $0.04 < \xi < 0.20$ and $m(\mathrm{VV}) > 1000$ GeV, where ξ is the proton fractional momentum loss, $\xi = \frac{p_{nom}-p}{p_{nom}}$. Constraints on the fiducial cross section for the WW/ZZ CEP were

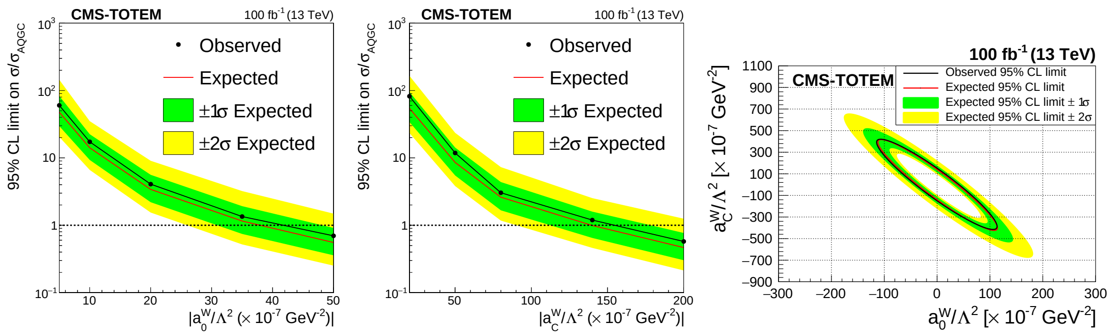

Figure 1: The two plots on the left show the expected and observed limits on two operators associated with the anomalous quartic gauge couplings, a_0^W/Λ^2 and a_C^W/Λ^2, respectively. The right plot illustrates the limits in the two-dimensional plane with unitarization imposed by clipping the signal model at 1.4 TeV.

extracted, yielding stringent upper bounds, $\sigma_{pWWp} < 67(53^{+34}_{-19})$ fb and $\sigma_{pZZp} < 43(62^{+33}_{-20})$ fb, at the 95% C.L.. The dataset considered for this analysis corresponds to an integrated luminosity of 100 fb^{-1}. The VBS $\gamma\gamma \to$ VV occurring in the studied CEP process are potentially very sensitive to anomalous gauge couplings. Therefore, constraints on them are extracted for the analyses of the fully hadronic pVVp channels. Some of them are shown in figure 1.

Other di-boson processes of great interest are those that occur via double-parton-scattering (DPS). The precise measurement of DPS processes allows the exploration of the internal structure of colliding protons, since they are very sensitive to multi-parton interactions. The analysis of the same-sign WW boson production from DPS in proton-proton collisions [10] was presented. It was performed with the data collected by the CMS experiment in proton-proton collisions at $\sqrt{s}$=13 TeV during the 2016-2018 LHC running periods (Run 2 of data taking, L=137/fb). The channels considered for this analysis are both eμ and $\mu\mu$. The inter-parton correlation with a double PDF approach is introduced in the most recent DPS generators used in the study presented. Boosted decision trees were deployed for the signal discrimination, and a binned maximum-likelihood fit was performed. The study claims the first observation of the $W^{\pm}W^{\pm}$ production in the fully leptonic channel. The measured cross section is 80.7±11.2(stat)$^{+9.5}_{-8.6}$(syst)±12.1(model) fb, and the observed significance corresponds to 6.2 standard deviations above the background-only hypothesis.

Another new CMS result was presented, obtained in the context of the inclusive Zγ production study, with Z$\to$ $\nu\nu$ [11]. The analysis was based on the data collected by the CMS experiment in proton-proton collisions at $\sqrt{s}$=13 TeV during the Run 2 of data taking (2016-2018). The clean final state signature, with a branching fraction about twice Z$\to$ $\ell\ell$, makes Z$(\nu\nu)\gamma$ one of the most suitable channels to detect anomalous Neutral Triple Gauge Coupling (aNTGCs) as an excess or a deficit relative to the Standard Model production. In particular, the photon transverse momentum was found to be the most sensitive variable yielding the most stringent limits on aNTGCs provided by the CMS experiment to date.

3. Tri-boson production

The observation of the production of three massive vector bosons, VVV, was first reported by the CMS Collaboration in 2020 [12], with an observed (expected) significance of 5.7(5.9) standard

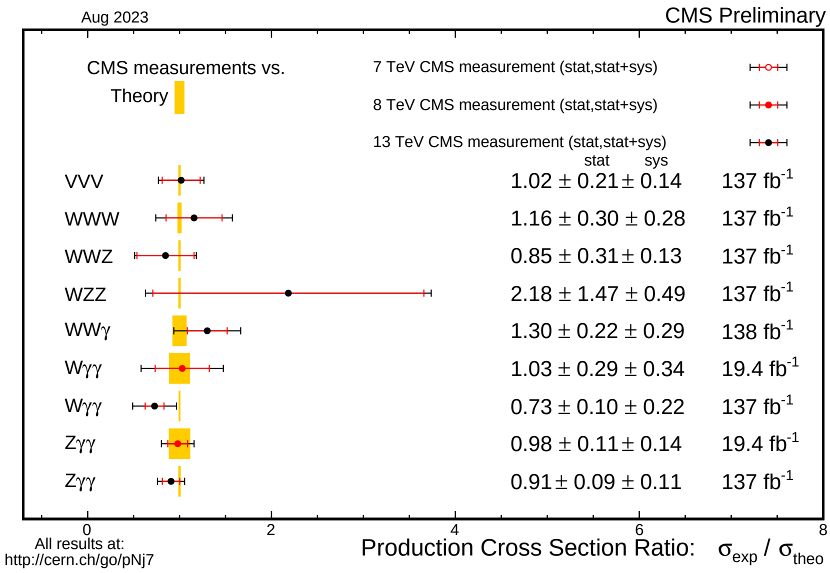

Figure 2: The figure shows the summary of the tri-boson production cross sections presented as a ratio compared to theory.

deviations, combining many different channels, and an reaching evidence for the the WWW and WWZ production. More recently, triboson studies of V$\gamma\gamma$ and VVγ production were performed in CMS, with the full Run 2 data set. In particular, the V$\gamma\gamma$ production in a fully leptonic channel includes both W$\gamma\gamma$ and Z$\gamma\gamma$, where the former triboson state can involve quartic gauge couplings, unlike the latter (according the SM predictions). The study [13] considered the photon production via initial and final state radiation. The main background contributions are induced by jets and electrons misidentified as photons, for which dedicated control regions were defined. In particular, the first case is treated by a data-driven method, with a control region for the Vγ component, where the photon is selected with a loose identification. The QCD-induced backgrounds (tγ, ttγ, tt$\gamma\gamma$, VVγ) are extracted from montecarlo simulations. The cross sections were extracted in fiducial region defined by electrons (muons) with transverse momentum larger than 35 (30) GeV and photons with transverse momentum larger than 20 GeV, resulting in σ(W$\gamma\gamma$)= 13.6±1.9(stat) ±4.0(syst) ±0.08(PDF+scale) fb, and σ(Z$\gamma\gamma$)= $5.41^{+0.58}_{0.55}$(stat)$^{+0.64}_{0.70}$ (syst) ±0.06(PDF+scale) fb. Since the V$\gamma\gamma$ production processes are potentially affected by anomalous quartic gauge couplings, constraints on effects of dimension-eight operators were extracted in the framework of effective field theory. In particular, the constraints set on f_{T5-9}/Λ^4 were found to be very stringent, compared to other analyses.

The most recent CMS result in the context of analyses, was reached for the WWγ fully leptonic channel [14]. The WWγ production involves triple and quartic gauge couplings, as well as Higgs couplings with gauge bosons and light quarks. The background estimation was performed with a data-driven method. The main background processes include prompt leptons and photons, characterized and validated in a set of dedicated control regions. The signal discrimination was optimized reaching an observed (expected) significance of 5.6(4.7) standard deviations. Considering H+γ intermediate states, with H$\rightarrow$WW, a dedicated study to the Higgs couplings with light quarks involved in the WWγ production process was made possible. The analysis presented provides constraints on the Yukawa couplings. A profile likelihood ratio test was built in bins of the Higgs transverse mass and the charged lepton pair distance in the $\eta - \phi$ space, ΔR_{ll}, observables found to have an excellent discrimination power.

The CMS results related to the triboson analyses are summarized in figure 2, which shows the signal strength extracted for each triboson channel studied. Overall, a good agreement with the SM predictions has been observed so far, but more measurements are expected to be achieved with the completion of the Run 2 and the ongoing Run 3 CMS physics program.

4. Summary and outlook

Most of the recent results from the CMS Collaboration on the di-boson, and tri-boson production processes have been presented. The di-boson results show a good agreement with the theoretical predictions, with a precision close to next-to-next-to-leading order. Many efforts are underway to measure all the processes predicted by the Standard Model and constrain new physics effects. The first di-boson results obtained with the Run-3 dataset were also presented. The CMS Run 3 physics program and the future high luminosity Phase 2 are expected to boost the studies in this direction, in particular for the analyses of rare tri-boson production processes.

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PoS(DIS2024)141

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