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Production of multiple electroweak bosons at CMS

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We present studies of diboson production in pp collisions at 7 TeV and 8 TeV center-of-mass energy based on data recorded by the CMS detector at the LHC in 2011 and 2012. These include precise measurements of W and Z production in association with a photon, as well as WW, WZ, and ZZ production at the LHC. The results are interpreted in terms of constraints on anomalous triple and quadruple gauge couplings.

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1. Introduction

The measurement of electroweak diboson production is a fundamental test of the validity of the standard model (SM), since the vector boson self-interaction probes the non-abelian structure of the electroweak Lagrangian. A precise measurement of diboson cross sections is also important in Higgs boson searches, as dibosons represent an irreducible background for many Higgs processes. Moreover, the measurement of diboson production cross section and kinematics provides direct information on trilinear and quartic gauge couplings (TGC and QGC). The SM predicts precisely the possible self-interactions of gauge bosons, and any deviation would be attributable to *anomalous* couplings (ATGC, AQGC), indicating the presence of new physics.

During 2011 and 2012, the Large Hadron Collider (LHC) delivered proton-proton collisions at center-of-mass energies of 7 and 8 TeV, allowing the measurement of diboson processes and tests of the SM up to energy scales never reached before. These proceedings present the measurement of diboson processes with the CMS detector [1]. The same measurements are also used to set upper limits on ATGC and AQGC parameters.

ZZ + X and $W^+W^- + X$ [2] processes are measured in fully-leptonic final states, both at 7 and 8 TeV, with data sets of about 5 fb^{-1} at each energy. All other processes are measured at 7 TeV, using the full CMS data set available at this energy, 5 fb^{-1}. $W\gamma$ +X and $Z\gamma$ +X [3, 4] are studied in leptonic channels, and WW + WZ + X [5] processes are measured inclusively in semileptonic channels, with a W decaying leptonically and the other boson decaying into two jets. A measurement of exclusive and quasi-exclusive W^+W^- production by two-photon exchange is also performed in $e\mu$ final state [6].

2. Selection, Backgrounds and Cross Sections

This section describes the selection strategy, background estimation, and cross section measurement of the main diboson processes.

$W\gamma$ and $Z\gamma$ processes are measured, respectively, in $\ell\nu\gamma + X$ and $\ell^+\ell^-\gamma + X$ final states, where the charged leptons ℓ are electrons or muons. Events are selected requiring exactly one (or two) isolated, high-transverse momentum (p_T) lepton(s) — also used to trigger the events — and one isolated photon with $p_T > 15$ GeV$/c$. In the $W\gamma$ measurement, additionally, the transverse mass of the lepton and missing transverse energy $\not{E}_T$ is required to be greater than 70 GeV$/c^2$. In the $Z\gamma$ case, instead, the dilepton invariant mass must be greater than 50 GeV$/c^2$. The main background is represented by W/Z + jets events with a jet misidentified as a photon. This contamination is measured in data by means of a two-component fit to the shape of the electromagnetic shower with signal and background templates. Other important backgrounds are Drell–Yan (DY) and diboson events, where an electron is misidentifed as a photon. These backgrounds are also estimated from data, using the e-γ misidentification rate measured in $Z \to ee$ events.

The measurement of $Z\gamma$ production is also performed in the $\nu\nu\gamma$ channel, characterized by an isolated, high-p_T photon and large $\not{E}_T$. The use of single-photon triggers imposes a minimum p_T threshold of 145 GeV$/c$ because of the prescale settings at lower momenta. The $\not{E}_T$ is required to be greater than 130 GeV. The largest backgrounds are multijet and $W \to e\nu$ events, where either a jet or an electron is misidentified as a photon. In order to reduce these backgrounds, events are required to have no jets, no tracker activity in the proximity of the photon candidate, and pass constraints on the shape of the electromagnetic shower. In addition, this channel suffers from abundant non-collision backgrounds, such as *bremsstrahlung* photons from beam-halo or cosmic muons. For this reason, the photon candidate is required to be synchronised with the time of the beam crossing, and a veto is imposed on muons identified as cosmic rays or beam-halo particles.

The inclusive measurement of WW and WZ processes is performed in the $\ell\nu + 2\mathrm{jets}$ final states. The selection requires exactly one isolated electron (muon) with p_{T} greater than 30 (25) GeV/c, and which triggers the event; exactly two jets with p_{T} greater than 35 GeV/c; and $\not{E}_{\mathrm{T}}$ greater than 30 (25) GeV, with the transverse mass of the lepton-$\not{E}_{\mathrm{T}}$ system greater than 35 (30) GeV/c^2. This channel has a larger branching fraction than the fully-leptonic final states, gives access to higher boson p_{T}, and is thus more sensitive to the presence of TGCs. On the other hand, the energy resolution of jets does not allow resolving the masses of W and Z bosons, thus the two processes are studied inclusively. Moreover, the semileptonic channel is affected by very abundant backgrounds, in particular W + jets, top + jets, Z + jets, and multijet events. Signal and background contributions are determined by an unbinned maximum-likelihood fit to the dijet invariant mass distribution. The shape and initial normalization of all processes are obtained from simulated data and next-to-leading-order (NLO) or higher-order calculations, with the exception of the multijet background, for which normalization and shape are determined from control regions in data.

$\mathrm{W}^+\mathrm{W}^-$ production is measured in the leptonic channel, $\ell\nu\ell'\nu'$, and is thus characterized by the presence of two electrons, two muons, or an electron and a muon — also used to trigger the events — and significant $\not{E}_{\mathrm{T}}$. The leptons are required to have p_{T} greater than 20 GeV/c and be isolated. In the same-flavor channels, ee and $\mu\mu$, the dilepton invariant mass is required to lie outside the Z-mass window in order to suppress the DY background. Different $\not{E}_{\mathrm{T}}$ requirements are applied in same- and opposite-flavor events. In order to reduce top backgrounds, events with a high-p_{T} jet, or a b-tagged jet, are rejected. Other diboson processes, WZ and ZZ, are further suppressed by vetoing events with a third lepton. Most backgrounds are measured directly in data, from background-dominated control samples: top processes are estimated using the measured top-tagging rate, W + jets and multijets using the lepton-misidentification rate, and the DY normalization is measured inside the Z mass region. Other minor backgrounds are estimated from simulation. Among these, the contamination from a SM Higgs boson of mass 126 GeV/c^2 is estimated to be about 4%.

The ZZ process is studied in final states with four charged leptons, $2\ell 2\ell'$, where one pair must be formed by electrons or muons, while the other can be also a τ pair. The background is expected to be very small, especially in 4e, 4μ, and $2\mathrm{e}2\mu$ channels. Therefore the selection is tuned to maximize the lepton identification and isolation efficiencies. The two highest-p_{T} electrons or muons must have p_{T} greater than 20 and 10 GeV/c, respectively. The two remaining leptons must have p_{T} greater than 7 GeV/c if electrons, or 5 GeV/c if muons. All τ leptons are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$. Two on-shell Z candidates are selected in a mass region of 60 to 120 GeV/c^2. This mass region is shifted to 30–90 GeV/c^2 in the case of τ pairs, to account for the undetected neutrinos. The residual background is estimated from data, using the lepton-misidentification rate in jets. The results are dominated by statistical uncertainties.

The selections and strategies presented above are used to extract cross section measurements for all these processes, and compare them with the SM predictions. The results are summarized in Figure 1. Most of the theoretical reference values are obtained with the NLO generator MCFM [7].

NLO predictions for $\mathrm{pp} \to \nu\nu\gamma$ are obtained with WGRAD [8]. In general, the measured cross sections are in very good agreement with the SM expectations. In the case of $\mathrm{W^+W^-}$, the experimental result at 8 TeV is slightly above the prediction — which, on the other hand, does not include some minor contributions, such as that from the SM Higgs boson.

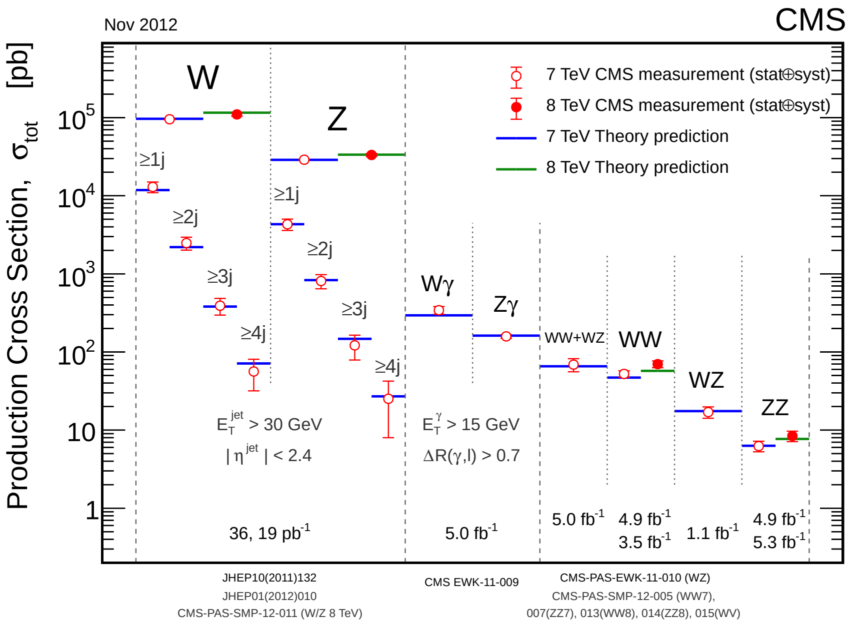

Figure 1: Summary of vector boson cross section measurements with the CMS.

Exclusive and quasi-exclusive $\mathrm{W^+W^-}$ production by photon-photon scattering are analyzed in $\mathrm{e}\mu + \mathrm{X}$ final states: $\mathrm{pp} \to \mathrm{p}^{(*)}\gamma\gamma\mathrm{p}^{(*)} \to \mathrm{p}^{(*)}\mathrm{W^+W^-p}^{(*)} \to \mathrm{p}^{(*)}\mathrm{e}\nu\mu\nu\mathrm{p}^{(*)}$. The signal includes both elastic and inelastic proton scattering. The choice of opposite-flavor leptons is driven by the background level, which is more than an order of magnitude larger in same-flavor final states, due to the contributions from $\gamma\gamma \to \ell^+\ell^-$ exclusive production and DY. Each lepton must be isolated and with $p_\mathrm{T} > 20\,\mathrm{GeV}/c$, and the $\mathrm{e}\mu$ system is required to have p_T greater than 30 GeV/c and invariant mass greater than 20 GeV/c^2. A peculiar signature of this channel is the lack of tracks associated with the $\mathrm{e}\mu$ vertex, due to the absence of hadronic activity in the interaction point. The main backgrounds, inclusive $\mathrm{W^+W^-}$ and $\tau^+\tau^-$ production, are measured in control regions with low dilepton p_T or low multeplicity of extra tracks in the $\mathrm{e}\mu$ vertex. After the full selection, two events are observed, compared to the standard model expectation of 2.2 ± 0.5 signal events (from CALCHEP [9]) with 0.84 ± 0.13 background events. An upper limit on the cross section of 8.4 fb at 95% confidence level (CL) is set.

3. Trilinear and Quartic Gauge Couplings

Anomalous TGC and QGC can be described using effective Lagrangians with several free parameters. The number of independent parameters can be reduced by imposing symmetry requirements. In CMS measurements the “LEP parametrization” is used [10, 11]. To prevent unitarity violation at high energies, the effective Lagrangian can be modified by including form-factors. Limits on ATGCs are presented here without form-factors in order to avoid biases from the particular choice of their energy dependence. Limits on AQGCs are provided with and without form-factors.

The presence of anomalous couplings modifies the diboson cross sections and kinematics, e.g. the boson p_T or the diboson invariant mass. In absence of deviations from the SM expectation, limits on ATGC and AQGC parameters are set. Profile-likelihood test statistics are built assuming Poisson distributions for signal and backgrounds and log-normal priors for each source of systematic uncertainty. Limits are set using the $\mathrm{CL_S}$ criteria, except for the inclusive $\mathrm{W^+W^-}$ channel.

Anomalous charged couplings WWγ and WWZ can be modeled with five parameters respecting $\mathrm{SU(2)}_L \times \mathrm{U(1)}_Y$ gauge invariance, and charge (C) and parity (P) symmetries: $\Delta\kappa_Z$, Δg_1^Z, $\Delta\kappa_\gamma$, λ_Z, and λ_γ. Because of gauge invariance, only three of them are independent. All of them vanish in the SM. These parameters are measured in WW, WZ, and Wγ channels using variables such as the leading-lepton p_T or boson p_T. No deviations from the SM expectations are found, and one- and two-dimensional 95% CL limits are set. Figure 2 shows that these limits are competitive with previous results from LEP [12] and Tevatron [13] experiments, and from ATLAS [14].

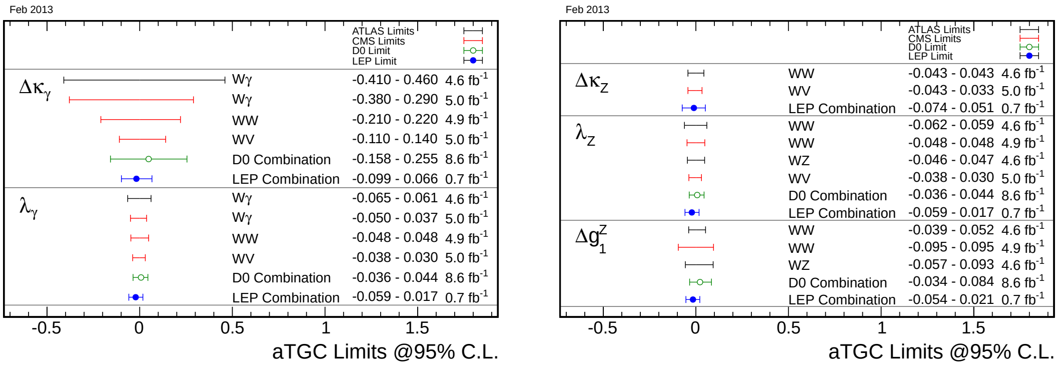

Figure 2: One-dimensional 95% CL limits on WWγ (*left*) and WWZ (*right*) ATGC parameters, compared with limits from ATLAS, Tevatron and LEP.

Neutral couplings are not permitted by the SM. Z$\gamma\gamma$ and ZZγ vertices contribute to Zγ production and are described with four parameters, $h_{3,4}^{\gamma,Z}$, all gauge-invariant and CP-conserving. Four more parameters, $f_{4,5}^{\gamma,Z}$, are associated with ZγZ and ZZZ couplings, which contribute to ZZ production. These couplings are Lorentz- and $\mathrm{U(1)}_{EM}$-invariant, and $f_5^{\gamma,Z}$ also conserve CP. No deviations from the SM are observed in the photon p_T and 4-lepton invariant mass spectra, and upper limits are set, as shown in Figure 3. These results are similar to or improve limits from other experiments.

The analysis of exclusive $\mathrm{W^+W^-}$ production provides the first measurement of $\gamma\gamma$WW quartic coupling at a hadron collider. This vertex can be described with two parameters, $a_0^{\mathrm{W}}/\Lambda^2$ and $a_{\mathrm{C}}^{\mathrm{W}}/\Lambda^2$, where Λ is the energy scale of new physics. From the observation of the high-$p_T(\mathrm{e}\mu)$ region, 95% CL upper limits are set: $a_0^{\mathrm{W}}/\Lambda^2$ is found within $[-1.7, 1.7] \times 10^{-4}\,\mathrm{GeV}^{-2}$ when using a form-factor with $\Lambda = 500\,\mathrm{GeV}$, and $[-2.8, 2.8] \times 10^{-6}\,\mathrm{GeV}^{-2}$ with no form-factor; $a_{\mathrm{C}}^{\mathrm{W}}/\Lambda^2$ is within $[-6, 6] \times 10^{-4}\,\mathrm{GeV}^{-2}$ with form-factor and $[-10.2, 10.2] \times 10^{-6}\,\mathrm{GeV}^{-2}$ with no form-factor. These limits improve LEP results by about two orders of magnitude.

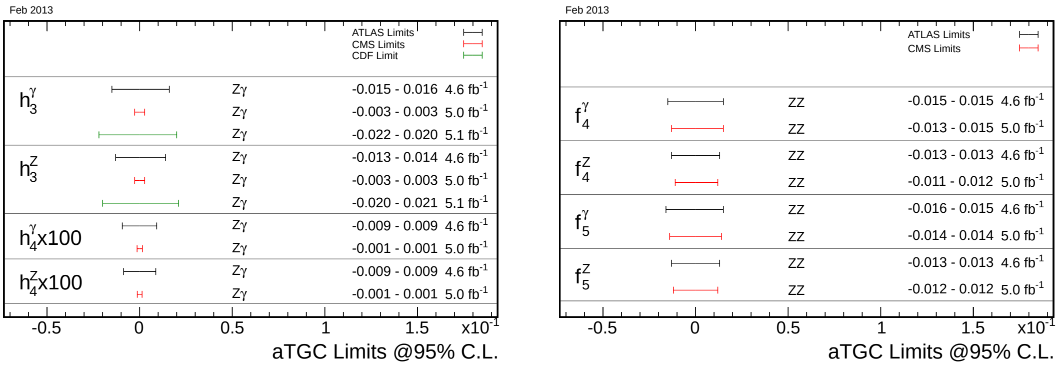

Figure 3: One-dimensional 95% CL limits on $Z\gamma\gamma$ and $ZZ\gamma$ (*left*), $Z\gamma Z$ and ZZZ (*right*) ATGC parameters, compared with limits from ATLAS and Tevatron.

References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[2] CMS Collaboration, *Measurement of W^+W^- and ZZ production cross sections in pp collisions at $\sqrt{s} = 8\,TeV$*, *Phys. Lett. B* **721** (2013) 190 [arXiv:1301.4698 [hep-ex]].

[3] CMS Collaboration, CMS-PAS-EWK-11-009.

[4] CMS Collaboration, CMS-PAS-SMP-12-020.

[5] CMS Collaboration, *Measurement of the sum of WW and WZ production with W+dijet events in pp collisions at $\sqrt{s} = 7\,TeV$*, *Eur. Phys. J. C* **73** (2013) 2283 [arXiv:1210.7544 [hep-ex]].

[6] CMS Collaboration, *Study of exclusive two-photon production of W^+W^- in pp collisions at $\sqrt{s}$ = 7 TeV and constraints on anomalous quartic gauge couplings*, arXiv:1305.5596 [hep-ex], sub. to *JHEP*

[7] J. M. Campbell, R. K. Ellis and C. Williams, *Vector boson pair production at the LHC*, *JHEP* **1107** (2011) 018 [arXiv:1105.0020 [hep-ph]].

[8] U. Baur, S. Keller and D. Wackeroth, *Electroweak radiative corrections to W boson production in hadronic collisions*, *Phys. Rev. D* **59** (1999) 013002 [hep-ph/9807417].

[9] A. Belyaev, N. D. Christensen and A. Pukhov, *CalcHEP 3.4 for collider physics within and beyond the Standard Model*, *Comput. Phys. Commun.* **184** (2013) 1729 [arXiv:1207.6082 [hep-ph]].

[10] K. Hagiwara, R. D. Peccei, D. Zeppenfeld and K. Hikasa, *Probing the Weak Boson Sector in $e^+e^- \to W^+W^-$*, *Nucl. Phys. B* **282** (1987) 253.

[11] G. Gounaris *et al.*, *Triple gauge boson couplings*, in *Geneva 1995, Physics at LEP2, vol. 1* 525-576, and Preprint - Gounaris, G. (rec.Jan.96) 52 p [hep-ph/9601233].

[12] ALEPH, DELPHI, L3, OPAL, LEP Electroweak W.G. Collaborations, *Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP*, arXiv:1302.3415 [hep-ex].

[13] A. Robson [CDF and D0 Collaborations], *Diboson Physics at the Tevatron*, *EPJ Web Conf.* **28** (2012) 06001 [arXiv:1201.4771 [hep-ex]].

[14] P. -F. Giraud [ATLAS Collaborations], *Di-boson results at ATLAS*, *EPJ Web Conf.* **28** (2012) 06003 [arXiv:1201.4868 [hep-ex]].