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Diboson and electroweak physics at CMS

A. Calderon on behalf of the CMS Collaboration
Instituto de Fisica de Cantabria (IFCA), CSIC-UC - Santander, Spain

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Summary. — We present the most recent studies of diboson production and electroweak physics in proton-proton 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 $\gamma\gamma$, ZZ and WZ production. Results on triboson production of WWγ and WZγ are also presented. The results are interpreted in terms of constraints on anomalous triple or quartic gauge couplings. We also review some recent electroweak physics results, including the purely electroweak Z bosons production cross section and the muon charge asymmetry measurement. The results are compared with Standard Model prediction.

PACS 14.70.-e – Gauge bosons.
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1. – Introduction

The diboson production and electroweak processes are expected to take place at the LHC and their cross sections, as well as detailed kinematic differential distributions, are precisely predicted in the framework of the Standard Model (SM). The cross section measurement provide excellent tests of the Quantum Cromodynamics (QCD) and the Electroweak (EW) sectors. Furthermore the diboson and electroweak processes are themselves sources of background to the SM Higgs searches, as well as searches for new phenomena. 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. Therefore, it is mandatory to have precise diboson and electroweak production cross section measurements as well as reliable and accurate theoretical predictions of these processes.

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 and electroweak processes and tests of the SM up to energy scales never reached before.

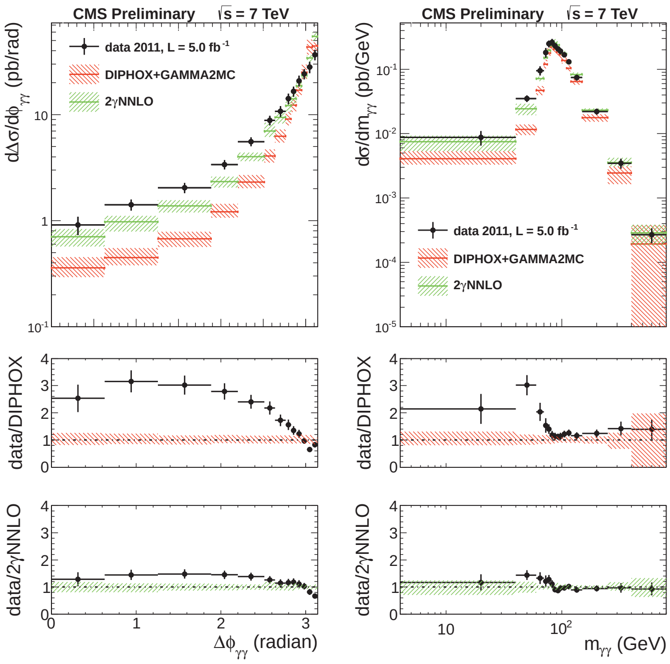

Fig. 1. – The comparisons of the differential cross section between data and the DIPHOX + GAMMA2MC NLO and the 2γNNLO NNLO predictions for $\Delta\phi_{\gamma\gamma}$ (left) and $m_{\gamma\gamma}$ (right). Black dots correspond to data with error bars including all statistical and systematic uncertainties.

These proceedings present precise measurements of $\gamma\gamma$, ZZ and WZ production, in association or not with a photon (ZZγ and WZγ) with the CMS detector [1]. The same measurements are also used to set upper limits on aTGC and aQGC parameters. We also review some recent electroweak physics results, including the purely electroweak production of Z bosons cross section and the muon charge asymmetry measurement.

2. – Measurement of diphoton production

The measurement of the isolated diphoton production cross section in pp collisions at center of mass energies of 7 TeV and 5.0 fb^{-1} integrated luminosity is presented [2].

The measurement is probing a phase-space with asymmetric p_T selection to enhance sensitivity to higher order diagrams: two isolated photons with transverse momentum above 40 GeV and 25 GeV respectively, in the acceptance $\eta < 2.5$, $\eta \notin [1.44, 1.57]$ and with an angular separation $\Delta R > 0.45$. A new data-driven method is used to extract the prompt diphoton yield in data, based on the photon component of the particle-flow isolation, modified in such a way that the photon energy deposit leakage inside the isolation cone is subtracted event by event. The measured total cross section is: $\sigma_{\rm data} = 16.8 \pm 0.2({\rm stat.}) \pm 1.8({\rm syst.}) \pm 0.4({\rm lumi})$ pb in agreement with the NNLO prediction $\sigma(2\gamma{\rm NNLO}) = 16.2^{+1.5}_{-1.3}({\rm scale})$ pb.

The cross section is also measured differentially as a function of the diphoton invariant mass, the diphoton transverse momentum, the azimuthal angle difference between the two photons, and the cosine of the polar angle in the Collins-Soper frame of the diphoton pair. Figure 1 shows the comparisons of the differential cross section between data and the

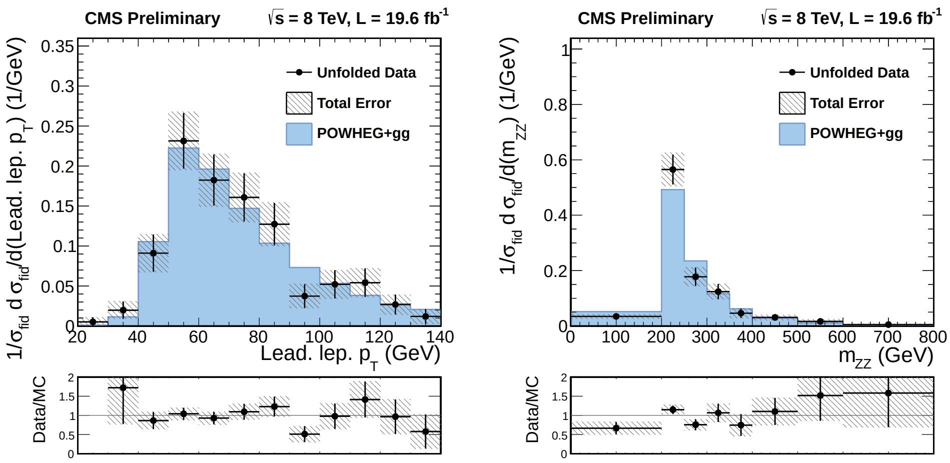

Fig. 2. – Differential cross section normalized to the fiducial cross section in the ZZ $\to$ 2l2l$'$ measurement at $\sqrt{s} = 8\,\text{TeV}$, for the leading lepton p_T (left) and the invariant mass of the 4 leptons (right).

DIPHOX + GAMMA2MC NLO and 2γNNLO predictions for the invariant mass and the $\Delta\phi_{\gamma\gamma}$ observables. NNLO predictions with 2γ NNLO show an improved agreement with the data for the kinematic distributions with respect to the DIPHOX + GAMMA2MC, especially in the low $\Delta\phi_{\gamma\gamma}$ region. It is the first time that a phase space defined by such an asymmetric p_T selection is probed at hadron colliders.

3. – Measurement of ZZ production

The ZZ production cross sections have been measured using the high-purity four-lepton (ZZ $\to$ 2l2l$'$) at center-of-mass energies of 8 TeV and 19.6 fb^{-1} integrated luminosity [3]. The branching ratio to four-lepton final state is small, however this process is really clean, with negligible amount of background. Events are selected by requiring two pairs of electrons or muons, with opposite charge and same flavour. The invariant mass of each pair is compatible with the Z boson mass. The challenge in the four-lepton analysis is the optimization for lepton efficiencies, especially for low-p_T leptons. Some leptons might fall outside the acceptance of the detector while some others may fail the criteria used to select a lepton. The measured cross section is $\sigma_{\text{data}} = 7.7^{+0.5}_{-0.5}(\text{stat.})^{+0.5}_{-0.4}(\text{syst.}) \pm 0.4(\text{theo.}) \pm 0.3(\text{lumi.})$ pb at $\sqrt{s} = 8\,\text{TeV}$ in the four lepton channel, for both Z bosons produced in the mass region of 60 to 120 GeV. Differential cross section distributions normalized to fiducial cross sections are also measured, as shown in fig. 2, and well described by the NLO theoretical predictions.

The ZZ production cross section is also measured in the 2-leptons and 2-neutrinos (ZZ $\to$ 2l2ν) decay channel, at center-of-mass energies of 7 and 8 TeV. The data sample corresponds to about 5.1 fb^{-1} and about 19.6 fb^{-1}, respectively, of integrated luminosity [4]. Events are selected by requiring a pair of oppositely charged, isolated electrons or muons, with invariant mass within a Z mass window and no additional leptons, other than the muon or electron pair from the Z decay. A large missing transverse energy is also required from the two neutrinos scaping the detection. The cross section is computed using

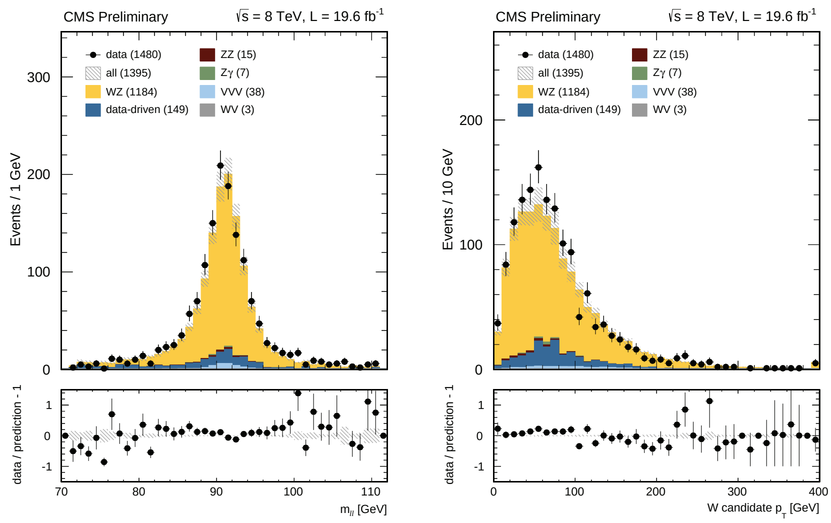

Fig. 3. – Z candidates invariant mass (left) and the p_T of the W candidates (right) at $\sqrt{s} = 8\,\text{TeV}$ for the WZ cross section analysis.

a profile likelihood fit to the reduced-E_T^{miss} distribution, which takes into account the expectations for the different background processes and the ZZ signal. Each systematic uncertainty is introduced in the fit as a nuisance parameter with log-normal prior. The measured cross sections are $\sigma_{\text{data}} = 5.0^{+1.5}_{-1.4}(\text{stat.})^{+1.3}_{-1.0}(\text{syst.}) \pm 0.2(\text{lumi.})$ pb at 7 TeV and $\sigma_{\text{data}} = 6.8^{+0.8}_{-0.8}(\text{stat.})^{+1.8}_{-1.4}(\text{syst.}) \pm 0.3(\text{lumi.})$ pb at 8 TeV. Results are in good agreement with the SM NLO predictions from [5].

4. – Measurement of WZ production

The WZ production cross sections have been measured in the WZ $\rightarrow$ lν2l$'$ decay channel at center-of-mass energies of 7 and 8 TeV. The data sample corresponds to about 4.9 fb^{-1} and about 19.6 fb^{-1}, respectively, of integrated luminosity [6]. This final state has very low background after requiring exactly three isolated leptons (electron or muon), a pair of which is of same flavor and has an invariant mass close to the mass of Z boson, in addition to significant missing transverse energy from W decay. Figure 3 shows the invariant mass of the Z dilepton system and the p_T of the W at 8 TeV.

The cross sections are determined to be $\sigma_{\text{data}} = 20.76 \pm 1.32(\text{stat.}) \pm 1.13(\text{syst.}) \pm 0.46(\text{lumi.})$ pb at 7 TeV, and $\sigma_{\text{data}} = 24.761 \pm 0.76(\text{stat.}) \pm 1.13(\text{syst.}) \pm 1.08(\text{lumi.})$ pb at 8 TeV, for a Z bosons produced in the mass region of 71 to 110 GeV. Since the LHC is a pp collider, the W^+Z and W^-Z cross sections are not equal. The ratios of production cross sections for W^+Z and W^-Z have also been measured. They are $1.94 \pm 0.25(\text{stat.}) \pm 0.04(\text{syst.})$ and $1.81 \pm 0.12(\text{stat.}) \pm 0.03(\text{syst.})$ at 7 TeV and 8 TeV, respectively. Results are in agreement with the NLO SM prediction from [5].

5. – Measurement of VZ production cross sections in VZ → Vb$\bar{\text{b}}$ decay channels

The VZ (V = W, Z) production cross section in proton-proton collisions is also measured in the VZ $\rightarrow$ Vb$\bar{\text{b}}$ decay mode with the Z $\rightarrow \nu\nu$, W $\rightarrow$ lν and Z $\rightarrow$ ll, at $\sqrt{s} = 8\,\text{TeV}$

and an integrated luminosty of 18.9 fb^{-1} [7]. The event selection is based on the reconstruction of the vector bosons in their leptonic decay modes and of the Z boson decay into two b-tagged jets. The reconstruction of the $Z \to b\bar{b}$ decay proceeds by selecting the pair of central jets ($|\eta| < 2.5$) in the event (among all pairs of jets in the event), each with p_T above a minimum threshold, for which the value of the magnitude of the vectorial sum of their transverse momenta, p_T(jj), is the highest. One combination per event with the highest pair p_T(jj) is chosen and the m(jj) is required to be below 250 GeV. These jets are then also required to be tagged by the CSV algorithm as b-jets, with CSV discriminator [8] value above a minimum threshold. In the final stage of the analysis, to better separate signal from background, a BDT discriminant [9] is trained using simulated samples for signal and all background processes. The process is observed with a significance exceeding six standard deviations. The resulting cross section for WZ is measured to be $\sigma_{\mathrm{data}} = 30.7 \pm 9.3(\mathrm{stat.}) \pm 7.1(\mathrm{syst.}) \pm 4.1(\mathrm{theo.}) \pm 1.0(\mathrm{lumi.})$ pb to be compared to the theoretical value of 22.3 ± 1.1 pb calculated with MCFM. The ZZ cross section is measured to be $\sigma_{\mathrm{data}} = 6.5 \pm 1.7(\mathrm{stat.}) \pm 1.0(\mathrm{syst.}) \pm 0.9(\mathrm{theo.}) \pm 0.2(\mathrm{lumi.})$ pb compared to the theoretical value of 7.7 ± 0.4 pb calculated with MCFM. In both cass the Z boson is produced in the mass region $60 < M_Z < 120$ GeV.

6. – 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 CL_S criteria.

The ZZ production process provides a way to probe the existence of such anomalous neutral couplings at the ZZZ and ZZγ vertices. Figure 4 shows the limits at 95% confidence level on the aTGC set by ATLAS and CMS [3, 4]. No deviations from the SM expectations are found.

In addition limits on anomalous quartic gauge boson couplings are presented, based on WVγ processes. No evidence of anomalous WW$\gamma\gamma$ and WWZγ quartic gauge boson couplings is found. Figure 4 also shows the aQGC set by CMS as well as those set by LEP and Tevatron. These are the first ever limits on the pure dimension 8 WW$\gamma\gamma$ parameter $f_{T,0}$ and CP-conserving WWZγ parameters k_0^W and k_C^W [12].

7. – EWK Z production

Pure electroweak productions of the lljj final state, of order $O(\alpha_{EW}^4)$, are more rare at the LHC, but are expected to carry a distinctive hallmark which can be explored experimentally: two jets of very high energy, well separated in pseudo-rapidity and with a large invariant mass, are expected to be produced in association with the dilepton

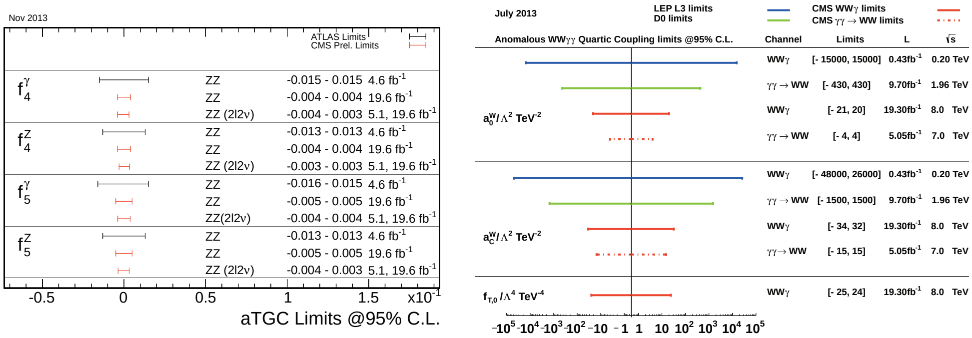

Fig. 4. – Limits on neutral aTGC ZZγ and ZZZ couplings (left) and on aQGC WW$\gamma\gamma$ dimension 6 and dimension 8 effective field theory operators couplings (right).

pair [13]. At the LHC the EWK Zjj process has been measured by CMS at 8 TeV, based on a data sample recorded with an integrated luminosity of 19.7 fb^{-1} [14].

Different methods are used to extract the signal, including a data-driven approach that models the QCD Zjj background based on γjj events. The cross section for this process is measured in di-electron and di-muon final states in the kinematic region $m_{ll} > 50\,\mathrm{GeV}$, $m_{jj} > 120\,\mathrm{GeV}$, transverse momenta $p_{Tj} > 25\,\mathrm{GeV}$ and pseudorapidity $|\eta_j| < 5$. The production cross section measurement, combining different methods and channels, yields $\sigma_{\mathrm{data}} = 226 \pm 26(\mathrm{stat.}) \pm 35(\mathrm{syst.})$ fb, in agreement with the theoretical cross section at NLO which is 239 fb.

8. – Muon asymetry from W decays measurement

At LHC in proton-proton collisions, in order to produce a W^+, most commonly a valence u quark is combined with a sea d quark, and for W^- it is a valence d quark combined and a sea u quark. Due to a larger number of u valence quarks in comparison to d valence quarks, there is an overall excess of W^+ *vs.* W^-. The overall ratio of $\mathrm{W}^+/\mathrm{W}^-$ measured by CMS in the past is in a good agreement with SM predictions. Taking it one step further, one can measure this asymmetry as a function of W rapidity, very sensitive to proton PDFs. The W asymmetry production is measured in the muon decay channel of the W, at $\sqrt{s} = 7\,\mathrm{TeV}$ and an integrated luminosity of 4.7 pb^{-1} [15]. Experimentally, the accessible quantity is the muon charge asymmetry as a function of the muon pseudorapidity:

$$\mathcal{A}(\eta) = \frac{\frac{\mathrm{d}\sigma}{\mathrm{d}\eta}(\mathrm{W}^+ \to \mathrm{l}^+\nu) - \frac{\mathrm{d}\sigma}{\mathrm{d}\eta}(\mathrm{W}^- \to \mathrm{l}^-\nu)}{\frac{\mathrm{d}\sigma}{\mathrm{d}\eta}(\mathrm{W}^+ \to \mathrm{l}^+\nu) + \frac{\mathrm{d}\sigma}{\mathrm{d}\eta}(\mathrm{W}^- \to \mathrm{l}^-\nu)}.$$

The observed asymmetry is plotted in fig. 5, compared with the NLO predictions calculated using the FEWZ 3.1 [16] tool interfaced with the NLO CT10, NNPDF2.3, HERAPDF1.5, MSTW2008, and MSTW2008CPdeut PDF sets. In this measurement, the selected candidates are required to have the transverse momentum of at least 25 GeV. A good agreement with HERAPDF is observed. However, the measured distributions is more flat at than the predictions produced using MSTW, CT10, and NNPDF.

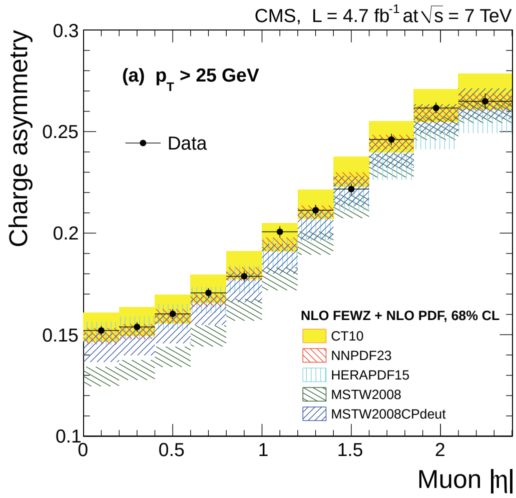

Fig. 5. – Comparison of the measured muon charge asymmetries to the NLO predictions. The vertical error bars on data points include both statistical and systematic uncertainties. The data points are shown at the center of each $|\eta|$ bin. The theoretical predictions are calculated using the FEWZ 3.1 [16] MC tool. The PDF uncertainty for each PDF set is shown by the shaded (or hatched) band and corresponds to 68% CL.

The muon charge asymmetry measurements, together with HERA DIS cross section data [17], improve the precision of the valence quarks over the entire x range in the fixed-s fit. This is illustrated in fig. 6, where the u and d valence quark distributions are shown at the scale relevant for the W boson production, $Q^2 = m_W^2$. A change in the shapes of the light-quark distributions within the total uncertainties is observed.

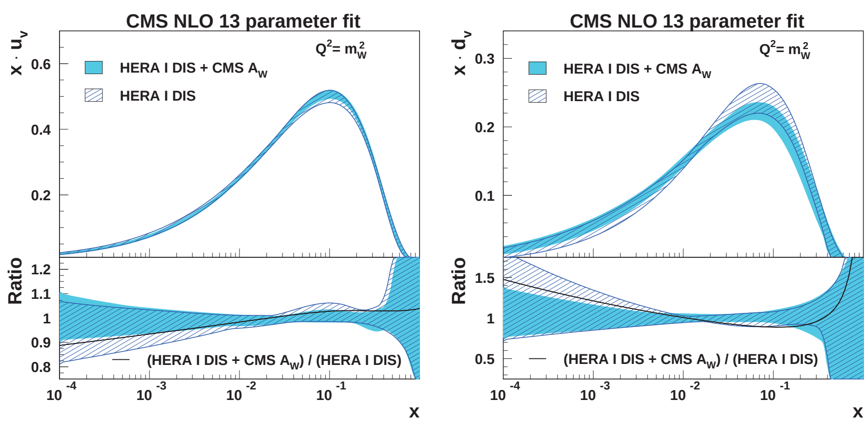

Fig. 6. – Distributions of u valence (left) and d valence (right) quarks as functions of x at the scale $Q^2 = m_W^2$. The results of the 13-parameter fixed-s fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The total PDF uncertainties are shown.

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