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Studies of vector boson production at CMS

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Summary. — The most recent diboson production and electroweak physics results from CMS are presented. This overview is focused on the precise measurement of WW, WZ, ZZ and $\gamma\gamma$ production, as well as W or Z production in association with a photon. These results are interpreted in terms of constraints on anomalous triple gauge couplings, while the study of $WW\gamma$ and $WZ\gamma$ production is used to set limits on anomalous quartic gauge couplings. Selection of the latest electroweak results is also presented.

PACS 14.70.Fm – W bosons.
PACS 14.70.Hp – Z bosons.
PACS 14.70.Bh – Photons.

1. – Introduction

The measurement of the diboson production and studies of the electroweak processes represent a fundamental test of the Standard Model (SM). The self-interaction between the vector bosons is precisely predicted by the SM and results from the non-Abelian nature of the $SU(2) \times U(1)$. Any difference of the measured cross section from the SM prediction, or a deviation in the kinematic distribution of the diboson pair, would indicate a presence of new physics. Therefore, such studies are an excellent probe for the possible existence of the anomalous triple and quartic gauge couplings, aTGC and aQGC. Moreover, diboson and electroweak processes are often irreducible background for Higgs boson studies and various beyond SM searches.

The CMS experiment at CERN [1] has recorded data from the proton-proton collisions, delivered by the Large Hadron Collider (LHC) in 2011 and 2012 at center-of-mass energies of 7 and 8 TeV, that allowed the CMS Collaboration to measure the diboson production cross sections and study the electroweak physics at the energy scale never probed before.

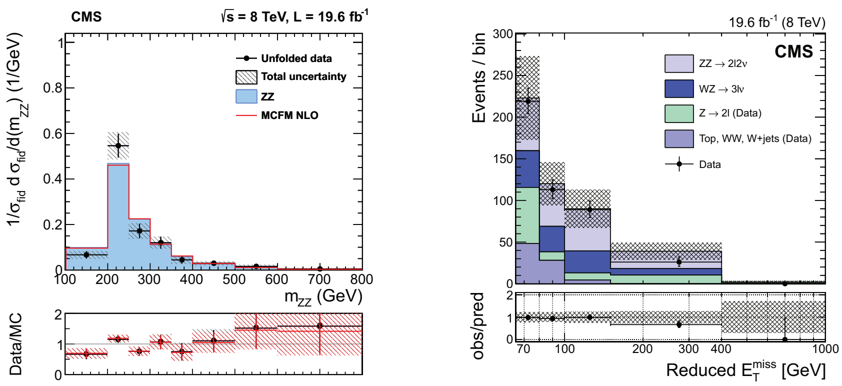

Fig. 1. – Differential cross section normalised to the fiducial cross section for the combination of $4e$, 4μ and $2e2\mu$ channels, shown for the $\mathrm{d}\sigma/\mathrm{d}M_{ZZ}$ distribution (left). Reduced MET distribution in the electron and muon channels combined, at the 8 TeV, after the full event selection (right).

2. – Measurement of ZZ production

The inclusive and differential cross section of the ZZ production in the four lepton final state were measured using $19.6\,\mathrm{fb}^{-1}$ of data recorded at the energy of 8 TeV [2]. The mutually exclusive sets of $4e$, 4μ, $2e2\mu$ and $ll\tau\tau$ were first studied individually and then combined using a simultaneous fit, to obtain the measured cross section of $\sigma_{\mathrm{data}} = 7.7 \pm 0.5(\mathrm{stat.})^{+0.5}_{-0.4}(\mathrm{syst.}) \pm 0.4(\mathrm{theo.}) \pm 0.2(\mathrm{lumi.})\,\mathrm{pb}$, found to be in a good agreement with the SM prediction of $7.7 \pm 0.6\,\mathrm{pb}$. Both Z bosons are required to be produced within the mass window of 60 to 120 GeV. The differential cross section normalised to the fiducial cross section is shown in fig. 1. A good agreement with respect to the NLO theory prediction from MCFM 6.0 [3] was found.

The measurement of the ZZ production cross section was also performed in the final state with two leptons (electrons or muons) and two neutrinos, at both 7 and 8 TeV, using $4.9\,\mathrm{fb}^{-1}$ and $19.6\,\mathrm{fb}^{-1}$, respectively [4]. This channel profits from the six times larger branching ratio than the four lepton, but is largely contaminated from the backgrounds, in particular from the Drell-Yan (DY) process. The crucial part here is the reconstruction of the missing transverse energy (MET), where the reduced-MET variable [5-7] was applied, shown to be effective in suppressing the instrumentally induced MET of the DY process. The cross section was extracted using a profile likelihood fit to the reduced MET and measured to be $\sigma_{\mathrm{data}} = 5.0^{+1.5}_{-1.4}(\mathrm{stat.})^{+1.3}_{-1.0}(\mathrm{syst.}) \pm 0.2(\mathrm{lumi.})\,\mathrm{pb}$ and $\sigma_{\mathrm{data}} = 6.8^{+0.8}_{-0.8}(\mathrm{stat.})^{+1.8}_{-1.4}(\mathrm{syst.}) \pm 0.3(\mathrm{lumi.})\,\mathrm{pb}$ at 7 and 8 TeV, respectively. Results are in a good agreement with the SM prediction at NLO. The reduced MET distribution is shown in fig. 1, after the final event selection.

3. – Measurement of WZ production

The measurement of the inclusive WZ production cross section in the three lepton (electron or muon) plus MET final state was performed using $4.9\,\mathrm{fb}^{-1}$ and $19.6\,\mathrm{fb}^{-1}$ of data recorded at 7 and 8 TeV, respectively [8]. The most important background to this very clean signature is the production of a Z boson associated to a fake or non isolated lepton from jets of photons, that was estimated from data, using a dedicated fake rate

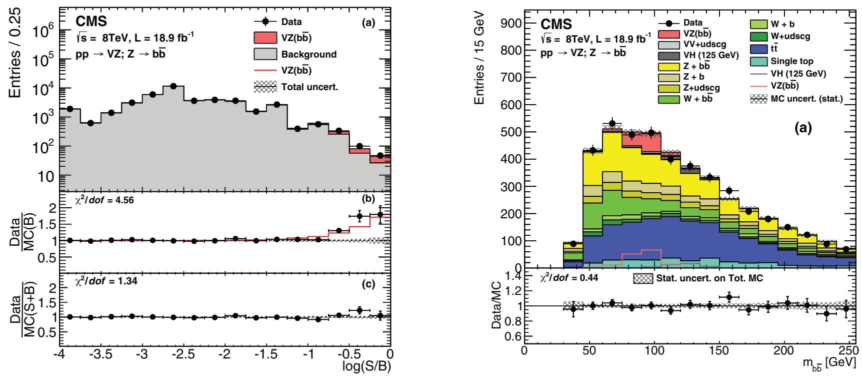

Fig. 2. – Distribution showing events sorted in bins of similar expected signal-to-background ratio, as given by the value of the BDT output, combining the events from all channels, with signal shown in red. (left). Dijet invariant mass distribution, combined for all channels (right).

method. The cross sections are calculated in the kinematical range corresponding to the Z boson mass within 71 and 111 GeV and measured to be $\sigma_{\text{data}} = 20.76 \pm 1.32(\text{stat.}) \pm 1.13(\text{syst.}) \pm 0.46(\text{lumi.})$ pb and $\sigma_{\text{data}} = 24.61 \pm 0.76(\text{stat.}) \pm 1.13(\text{syst.}) \pm 1.08(\text{lumi.})$ pb at 7 and 8 TeV, respectively, consistent with the expectation from the SM at the NLO. As proton-proton collider, the LHC favours the production of the W^+Z over the W^-Z process, which is demonstrated in measurement of the ratio of the two having the values of $1.94 \pm 0.25(\text{stat.}) \pm 0.04(\text{syst.})$ and $1.81 \pm 0.12(\text{stat.}) \pm 0.03(\text{syst.})$ at 7 and 8 TeV, respectively. The ratios are found to be consistent with the SM NLO prediction as well.

4. – Measurement of VZ production

The $VZ \to Vb\bar{b}$ production cross section, where V is either W or Z boson decaying leptonically, was measured using 18.9 fb^{-1} of CMS data [9]. Based on the particular decay of the V boson, the analysis was performed with the 0, 1 or 2 leptons in the final state. Two separate methods were applied to extract the signal. First method used a fit to the output of the multivariant discriminator, where the events were classified into different regions of the V boson transverse momentum and then sorted by the expected signal to background ratio, as shown in fig. 2. The second method was based on the invariant mass of the two b-tagged jets, shown in fig. 2, where a more restrictive selection was applied. The signal significance obtained with the MVA analysis was measured (expected) to be 6.3σ (5.9σ), while the more conservative two jet method yielded with 4.1σ (4.6σ). The cross section, restricted to the Z boson within the mass region of 60 to 120 GeV, was measured to be $\sigma(\text{pp} \to WZ) = 30.7 \pm 9.3(\text{stat.}) \pm 7.1(\text{syst.}) \pm 4.1(\text{theo.}) \pm 1.0(\text{lumi.})$ pb and $\sigma(\text{pp} \to ZZ) = 6.5 \pm 1.7(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.9(\text{theo.}) \pm 0.2(\text{lumi.})$ pb. The measured values are in a good agreement with the MCFM prediction at NLO of $\sigma(\text{pp} \to WZ) = 22.3 \pm 1.1$ pb and $\sigma(\text{pp} \to ZZ) = 7.7 \pm 0.4$ pb.

5. – Measurement of $Z\gamma$ production

The measurement of the $Z\gamma$ production cross section in electron and muon channels was performed using 19.5 fb^{-1} of 8 TeV data, for the kinematical range of $p_T^l > 20$ GeV, $M_{ll} > 50$ GeV, $E_T^\gamma > 15$ GeV, $\Delta R(l,\gamma) > 0.7$ and lepton and photon in the fiducial area of the CMS detector [10]. The DY+jets background, where the non-prompt

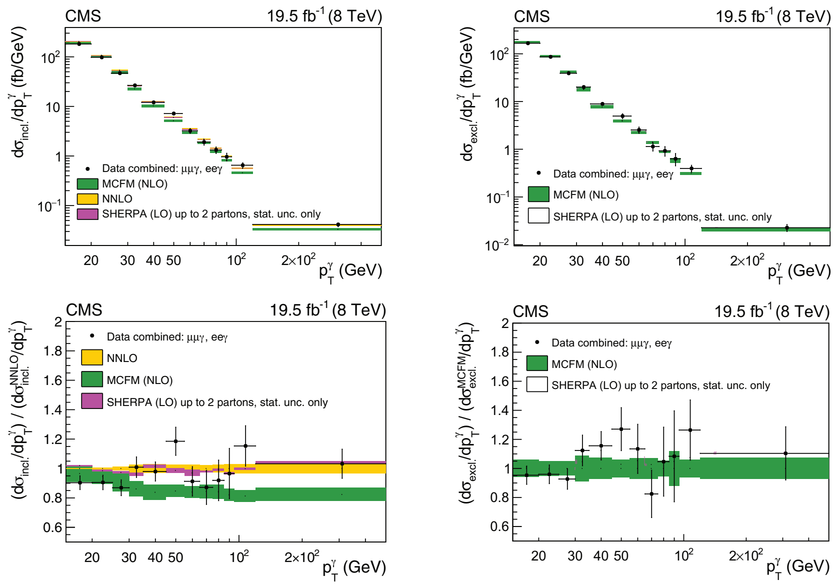

Fig. 3. – Combined inclusive differential cross section compared to the NNLO, MCFM (NLO) and SHERPA SM predictions (top left). The ratios of the data and other predictions to the NNLO calculation (bottom left). Combined exclusive differential cross section compared to the MCFM (NLO) and SHERPA SM predictions (top right). The ratios of the MCFM (NLO) prediction are shown for the exclusive measurement (bottom right).

leptons arise from π^0 or η decays or misidentified hadrons, was estimated from data using two independent template observables. The first one is $\sigma_{\eta\eta}$, where the separation between the two background photons, albeit small, leads to a larger value of this variable than for signal photons. The second variable is constructed as a sum of transverse momenta of all photon-like Particle Flow (PF) objects within a cone of $\Delta R < 0.4$ around the photon, while removing the "footprint" of the photon itself from the sum. The overall inclusive cross section, using a combination of the two template methods, was measured to be $\sigma(\text{incl}) = 2063 \pm 19(\text{stat.}) \pm 98(\text{syst.}) \pm 54(\text{lumi.})\,\text{fb}$, in agreement with the MCFM prediction at NLO of $2100 \pm 120\,\text{fb}$ and NNLO prediction [11] of $2241 \pm 22\,\text{fb}$, within the uncertainties. The differential cross section was also measured inclusively and exclusively, while the exclusive cross section was measured without any accompanying jet with $p_T > 30\,\text{GeV}$ and $|\eta| < 2.4$. The inclusive cross section shows a better agreement at high p_T^γ with the NNLO and SHERPA [12] generators than the prediction of MCFM at the NLO, as shown in fig. 3. In the exclusive differential cross section measurement the difference between the MCFM and SHERPA is less pronounced that in the inclusive one at high p_T^γ, as presented in fig. 3. This measurement already shows the importance of the NNLO prediction in modelling of the $Z\gamma$ process.

6. – Measurement of diphoton production

An important test of the Quantum-Chromo-Dynamics (QCD), the measurement of the diphoton production cross section is performed at $7\,\text{TeV}$, using $5\,\text{fb}^{-1}$ of CMS data [13]. This process represent a major background for the $\text{H} \rightarrow \gamma\gamma$ studies and various beyond SM searches. The dominant background arises from jets that are misiden-

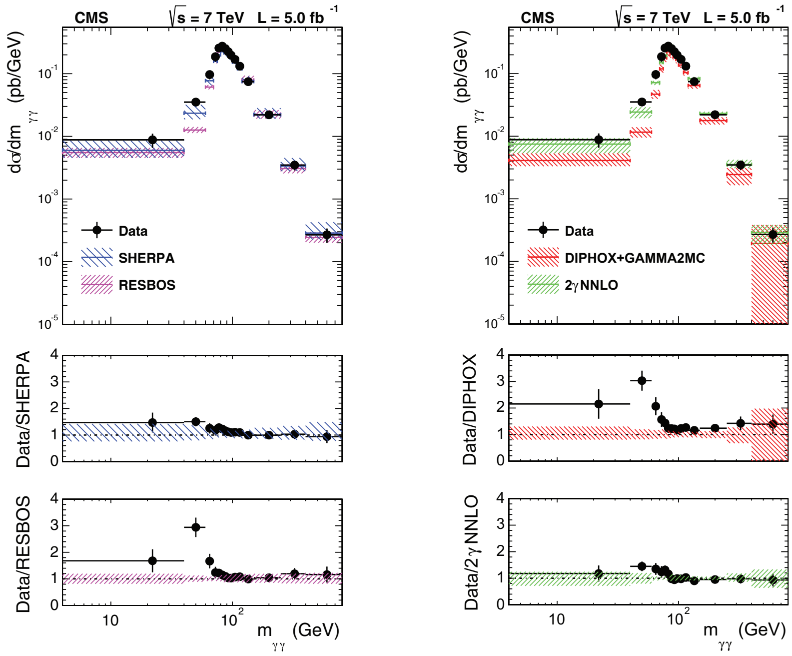

Fig. 4. – Differential cross section for $m_{\gamma\gamma}$, compared to the SM prediction of SHERPA LO, RESBOS NLO (left), DIPHOX+GAMMA2MC NLO and 2γNNLO generators (right).

tified as photons. The analysis was designed to select two isolated photons in a phase space with an asymmetric p_T selection: $p_T^\gamma > 40\,\text{GeV}$, $p_T^\gamma > 25\,\text{GeV}, |\eta_\gamma| < 1.44$ or $1.57 < |\eta_\gamma| < 2.5, \Delta R(\gamma_1, \gamma_2) > 0.45$, to enhance sensitivity to the higher order diagrams. The photon component of the PF isolation was used as a discriminator and template shapes for both signal and background were built from data. Signal was statistically separated using a binned maximum likelihood fit. The measured total cross section in the above mentioned phase space is $\sigma(\text{data}) = 16.8 \pm 0.2(\text{stat.}) \pm 1.8(\text{syst.}) \pm 0.4(\text{lumi.})\,\text{pb}$ which is in agreement with the SM prediction of $\sigma(\text{NNLO}) = 16.2^{+1.5}_{-1.3}(\text{scale})\,\text{pb}$ from the 2γNNLO generator. The production cross section was also measured differentially as a function of $m_{\gamma\gamma}, p_T^{\gamma\gamma}, \Delta\phi_{\gamma\gamma}$ and $\cos\Theta^*$ [14]. The prediction from 2γNNLO [15] shows an improved agreement with data in the distributions of these kinematical variables. There is a reasonable agreement from SHERPA at the LO, since it includes up to three extra jets at the matrix element level. The differential cross section for $m_{\gamma\gamma}$ is shown in fig. 4.

7. – Anomalous triple and quartic gauge couplings

The ZZZ and $ZZ\gamma$ aTGCs were searched for in the $ZZ \to 4l$ channel using the effective lagrangian approach. A presence of the aTGC events would be manifested as an increased yield of the events at the high four lepton invariant mass, as shown in fig. 5. The limits with respect to the aTGC parameters f_4^V and f_5^V (V $= Z/\gamma$), predicted to be zero in the SM, are derived without the use of the form factors, in order to avoid a possible bias. The one dimensional limits were extracted and have the values of $-0.004 < f_4^Z < 0.004$, $-0.004 < f_4^\gamma < 0.004$, $-0.005 < f_5^Z < 0.005$ and $-0.005 < f_5^\gamma < 0.005$, improving over the previously set limits by a factor of three to four [16].

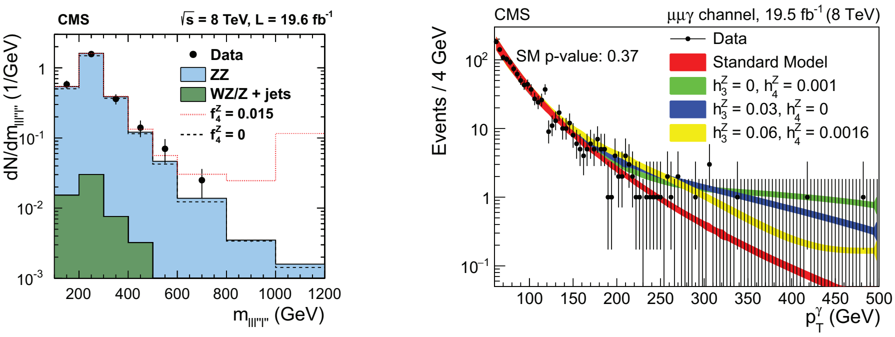

Fig. 5. – Distribution of the reconstructed four lepton invariant mass, for the combination of the $4e$, 4μ and $2e2\mu$ channels (left). The p_T^{γ} distribution in the $\mu\mu\gamma$ channel, compared to the SM expectation and to prediction of several combinations of the aTGC parameter values (right).

The ZZ production in the $2l2\nu$ channel was also used to probe the existence of the ZZZ and $ZZ\gamma$. Here the dilepton p_T distribution is the most sensitive observable to the presence of aTGCs. The limits were calculated using the modified frequentist construction CL_S, with a binned profile likelihood used as a test statistic. One-dimensional limits on the four parameters are set by varying independently each single parameter while setting the other three to zero. The limits resulting from the combination of the 7 and 8 TeV data are found to be $-0.0030 < f_4^Z < 0.0034$, $-0.0039 < f_4^{\gamma} < 0.0031$, $-0.0036 < f_5^Z < 0.0032$ and $-0.0038 < f_5^{\gamma} < 0.0038$, surpassing the previously set limits and exceeding the ones obtained in the four lepton analysis by approximately 25%.

The search for $ZZ\gamma$ and $Z\gamma\gamma$ aTGCs was performed using 19.5 fb^{-1} of data recorded at 8 TeV, following the effective field theory approach (EFT) [17] and considering the dimension 6 and dimension 8 operators that fulfill the Lorentz invariance and local $U(1)$ gauge symmetry. The existence of aTGCs would enhance the measured $Z\gamma$ cross section and this would be particularly pronounced as an increased number of high E_T^{γ} events, as shown in fig. 5. The unbinned profile likelihood ratio was used in order to find the best fitting aTGC model and corresponding 95% confidence level (CL) region. Without any loss of generality, only the h_3^V and h_4^V parameters were considered. The one dimensional limits were found to be $-0.0038 < h_3^Z < 0.0037$, $-0.000031 < h_4^Z < 0.000030$, $-0.0046 < h_3^{\gamma} < 0.0046$ and $-0.000036 < h_4^{\gamma} < 0.000035$. They represent a factor of three improvement with respect to the previously set limits at 7 TeV [18].

Two photon production of a pair of W bosons is sensitive to aQGCs. The CMS Collaboration set limits [19] two orders of magnitude more stringent than the LEP limits [20] and about 20 times better than Tevatron results [21]. Search for aQGCs in the $WV\gamma$ final state, where W boson decays to leptons and $V(W$ or $Z)$ to jets, are the first limits [22] on anomalous $WWZ\gamma$ couplings. The $WW\gamma\gamma$ aQGC limits are presented in the fig. 6.

8. – Vector boson scattering in $W^{\pm}W^{\pm}$ events

The vector boson scattering (VBS) is a key process to probe the nature of the electroweak symmetry breaking. The discovery of the Higgs boson suggests a mechanism that could prevent unitarity violation in the VBS process at the high center-of-mass energy. Various beyond SM scenarios predict an enhancement in the VBS production. The CMS

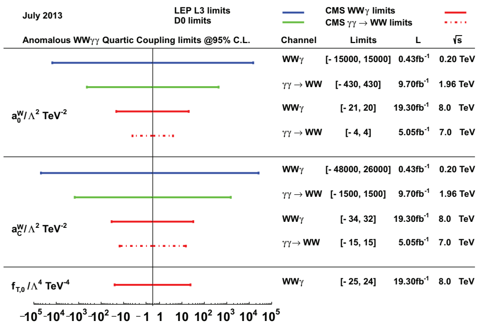

Fig. 6. – The limits with respect to the $WW\gamma\gamma$ aQGCs, derived using the EFT approach and considering the dimension 6 and dimension 8 operators.

Collaboration probed the WW same sign production, selecting the events with two same sign leptons, two largely separated jets and a moderate MET in the final state [23]. The invariant mass of the dijet sistem, as shown in fig. 7, was found to be optimal for the signal extraction. The statistical analysis of the event yields was performed in eight bins, four m_{jj} bins times two charge bins. The cross section was extracted for a fiducial region of $p_T^l > 10\,\text{GeV}, |\eta_l| < 2.5, p_T^{\text{jet}} > 20\,\text{GeV}, |\eta_{\text{jet}}| < 5.0, m_{jj} > 300\,\text{GeV}$ and $|\Delta\eta_{jj}| > 2.5$ and found to have a value of $\sigma(W^\pm W^\pm jj) = 4.0^{+2.4}_{-2.0}(\text{stat})^{+1.1}_{-1.0}(\text{syst})\,\text{fb}$, in agreement with the SM expectation of $5.8 \pm 1.2\,\text{fb}$. The WZ production cross section was also measured, by requiring an additional lepton with $p_T > 10\,\text{GeV}$ in the final state, resulting with a value of $\sigma(WZjj) = 10.8 \pm 4.0(\text{stat.}) \pm 1.3(\text{syst.})\,\text{fb}$, that is in agreement with the SM prediction of $14.4 \pm 4.0\,\text{fb}$ within the uncertainties. The observed (expected) significance for the VBS process was found to be $2.0(3.1)\sigma$. The limits with respect to the aQGCs that could modify the VBS process were extracted [23]. The exclusion limits for the double charged Higgs boson [24] with the same $W^\pm W^\pm$ signature were also derived.

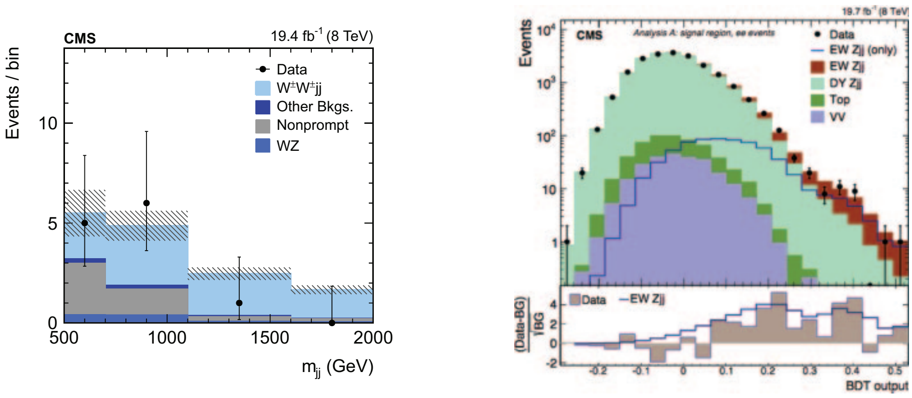

Fig. 7. – The dijet invariant mass distribution in the signal region, with the W^+W^+ and W^-W^- candidates combined (left). Distribution of the BDT discriminant, shown for the ee channel of the signal region, as obtained by using one of the above mentioned analysis methods (right).

9. – Electroweak Z boson production

The production of a Z boson in the association with two jets through the vector boson fusion (VBF) process was studied using $19.7\,\text{fb}^{-1}$ of 8 TeV data [25]. The total Zjj production is a mixture of the electroweak and a strong (DY Zjj) component. The electroweak part which is considered here as the signal, albeit being very rare (order of α_{EW}^4), has a characteristic signature, with large $\Delta\eta_{jj}$ and large M_{jj}. Three independent multivariate methods, with different jet reconstruction algorithms and kinematical input variables, were used to separate the electroweak and strong components from the inclusive $lljj$ spectrum. One of the methods includes a data-driven approach that estimates the QCD Zjj background using the γjj events. The measured signal cross section of $\sigma_{EW}(lljj) = 174 \pm 15(\text{stat.}) \pm 40(\text{syst.})\,\text{fb} = 174 \pm 42(\text{total})\,\text{fb}$ is in a good agreement with the SM prediction of $\sigma_{EW}(lljj) = 208 \pm 18\,\text{fb}$ at the LO.

10. – Conclusion

The diboson and electroweak studies performed by the CMS Collaboration using the full LHC Run I data showed a good agreement with the SM NLO expectation. The incoming importance of the NNLO predictions was demonstrated in modeling of the $Z\gamma$ and $\gamma\gamma$ production. No signal of the anomalous couplings was observed and limits were extracted. The studies of VBS and VBF processes showed good agreement with the SM.

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