Recent Standard Model measurements at CMS

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Abstract. Recent results of Standard Model physics using 7 and 8 TeV data recorded by the CMS detector are reviewed. This overview includes studies of vector boson production, results on V+jets production with light and heavy flavours, multiboson measurements and anomalous couplings searches and also the latest results on jet production and properties. The most recent 13 TeV results are presented as well. The outlined results are compared to the prediction of the Standard Model.

1. Introduction
The most recent results of the Standard Model (SM) measurements are presented in this overview. The full statistics from the LHC Run 1 was used, corresponding to an integrated luminosity of around 5 fb$^{-1}$ and 20 fb$^{-1}$ at the energy of 7 and 8 TeV, respectively. As of 2015, the LHC Run 2 has started with proton-proton collisions at the world-record energies of 13 TeV, with the initial goal to deliver around 100 fb$^{-1}$ by the end of 2018. One of the first results from the LHC Run 2 is the measurement of the charged hadron pseudorapidity distribution and it is presented at the end of this overview.

2. Vector boson studies
2.1. Angular coefficients of Z bosons at 8 TeV
The first measurement of the five most significant angular coefficients of Z boson produced in proton-proton collisions and decaying to muon pairs was performed [1]. These coefficients govern the kinematics of Z boson decay and follow from the vector and axial vector (V-A) structure of boson-fermion couplings. The parameters $A_0$, $A_1$ and $A_2$ are related to the polarisation of the Z boson, while $A_4$ and $A_5$ are sensitive to the V-A couplings of muons. The contribution of the qg Compton process is significant in proton-proton collisions. The angular coefficients were measured in eight $q_T$ and two $|y|$ bins. The measurement of the $A_0 - A_2$ for rapidity of $|y| < 1$ is shown in figure 1 and compared with MadGraph (LO) [2], POWHEG (NLO) [3] and FEWZ (NNLO) [4, 5, 6] predictions. The violation of the Lam-Tung relation [7] ($A_0 = A_2$) is observed, where $A_0 > A_2$, especially at the high $q_T$. This is anticipated by QCD calculations beyond the leading order.

2.2. Final state radiation in Z decay at 7 TeV
The study of final state radiation photons in Z boson decaying to muon pairs was performed at the 7 TeV [8]. The differential cross section was measured as a function of the photon transverse momentum and its separation from the nearest muon. This result will support future
measurements of the W mass, the study of $Z\gamma$ production and searches for new physics with photons in the final state. The differential cross section $d\sigma/dE_T$ was measured for photons close to a muon ($0.05 < \Delta R_{\mu\gamma} < 0.5$) and far from the muon ($0.5 < \Delta R_{\mu\gamma} < 3$). The differential cross sections $d\sigma/dE_T$ and $d\sigma/d\Delta R_{\mu\gamma}$ were measured for the events with large ($> 50$ GeV) and small ($< 10$ GeV) transverse momentum of the Z boson. The prediction from POWHEG interfaced to PYTHIA [9, 10] reproduces the data well, with the discrepancies below 5% for the events with $5 < E_T < 50$ GeV and $0.05 < \Delta R_{\mu\gamma} < 2$, that is within the uncertainties. The measured differential cross section $d\sigma/dE_T$, for the case of $q_T > 50$ GeV, and its comparison with the simulation is shown in figure 2.

### Figure 1.

The difference between the angular coefficients $A_0$ and $A_2$ for $|y| < 1$, as a function of $q_T$, and its comparison to the prediction of MadGraph, POWHEG and FEWZ event generators. The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement.

### Figure 2.

The measured $Z(\mu\mu)\gamma$ differential cross section as a function of the photon transverse momentum, for $q_T > 50$ GeV. The shaded bands represent the POWHEG+PYTHIA calculation including the theoretical uncertainties and at bottom is the ratio of data to the MC expectation.

### 3. Vector boson + jets studies

#### 3.1. $Z/\gamma^*+jets$ to $\gamma+jets$ cross section ratio at 8 TeV

The ratio of the differential cross sections for the processes $Z/\gamma^*+jets$ and $\gamma+jets$ was measured [11]. For high transverse momentum of the vector boson and at the LO, the effects due to the mass of Z boson are small and this ratio is expected to become constant. This is important for the studies of final states with hard jets and large missing transverse energy, such as the search for supersymmetry using the $M_{T2}$ variable [12], performed by the CMS Collaboration. In this study, the $Z \rightarrow \nu\nu+jets$ background was modelled by measuring the $\gamma+jets$ and scaling it by the simulated ratio of the $Z \rightarrow \nu\nu+jets$ to $\gamma+jets$. The measurement of this ratio can help to reduce the uncertainties related to background estimation in these searches. The comparison was made with the prediction of MadGraph and BlackHat [13] generators and this is shown in
figure 3. It was observed that both generators are overestimating the data by 20% at the high transverse momentum.

3.2. Electroweak W production cross section at 8 TeV

The electroweak production cross section of W boson in association with two jets was performed at the 8 TeV [14]. The study of this process could be used as a potential probe for the anomalous triple gauge couplings (aTGC) and it presents an important background to Higgs boson searches in the vector boson fusion (VBF) topology. The events with isolated electron or muon, two jets well separated in rapidity and significant missing transverse energy are selected. To distinguish between the signal and background events a Boosted Decision Tree (BDT) is used and an unbinned maximum likelihood fit to the dijet invariant mass distribution, shown in figure 4, is performed in order to extract the number of signal events from data. A good agreement between the measured cross section and the prediction of MadGraph interfaced to PYTHIA6 was observed.

![Figure 3](image1.png)

**Figure 3.** The ratio of the differential cross sections for the $Z/\gamma^* + \text{jets}$ and $\gamma + \text{jets}$, shown for the central bosons ($|y^V| < 1.4$) and comparison to BlackHat and MadGraph generators. The hatched (gray) band represent the total uncertainty of the measurement.

![Figure 4](image2.png)

**Figure 4.** Distribution of the invariant mass of the dijet pair associated to the W boson, shown in the electron channel. Overall, the applied approach produces a high quality model of the data.

4. Multiboson studies

4.1. $Z\gamma\rightarrow\nu\nu\gamma$ production at 8 TeV

The $Z(\nu\nu)\gamma$ production was studied at the 8 TeV [15]. This process has six times larger branching ratio (BR) than for a decay to a particular lepton pair and also the acceptance for neutrino is higher. The cross section is measured in the kinematic region with high missing transverse energy, high photon transverse momentum and pseudorapidity of photon restricted to the barrel region of the CMS detector, where purity is the highest. The measured cross section was found to be in a good agreement with the NNLO calculation by Grazzini et. al. No evidence was found for the aTGC couplings and 95% CL limits were set on the $h^V_3$ and $h^V_4$ parameters of $ZZ\gamma$ and $Z\gamma\gamma$ couplings. The expected and observed confidence level contours in the $(h_3, h_4)$ parameter space are shown in figure 5. These are the most stringent limits to date on neutral aTGCs.


4.2. $W^+W^-$ production at 8 TeV

The production cross section for the WW process is the highest among the diboson pairs. This process was studied at the 8 TeV by selecting two electrons or muons with the high transverse momentum, large missing transverse energy and zero or one jet with high transverse momentum [16]. The measured cross section was found to be in a good agreement with the NNLO prediction [17]. The differential cross section was measured as a function of various kinematic variables and overall good agreement was found in comparison to the predictions of MadGraph, MC@NLO [18] and POWHEG generators. Search for the aTGC was performed in the framework of the effective field theory [19]. No evidence of the anomalous WWZ and WW$\gamma$ vertices was observed.

The aTGC limits were extracted using the reconstructed dilepton invariant mass distribution, shown in figure 6. An improved measurement of the coupling constant $c_{WWW}/\Lambda^2$ was obtained.

![Figure 6. The invariant mass of the dilepton pair, shown for data, simulated SM and aTGC predictions. The last bin includes all the events with $m_{ll} > 575$ GeV.](image)

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5. Jet physics studies

5.1. Dijet azimuthal decorrelation at 8 TeV

The dijet azimuthal decorrelations between the two jets with the largest transverse momenta are measured [20]. At the LO in pQCD the two final-state partons balanced in transverse momentum are produced in back-to-back topology and non-perturbative effects of the multiparton interaction perturb this correlation only mildly. The production of a third jet leads to a decorrelation in the azimuthal angle. The measurement of the dijet azimuthal decorrelation enables to study the multijet production process while considering only the two jets with the highest transverse momentum. Figure 7 shows the normalised dijet cross section measured as a function of the dijet azimuthal angular separation in seven regions of the leading jet transverse momentum and compared to pQCD calculations for 3-jet production with up to four outgoing partons ($\propto \alpha_S^3$), that provide LO and NLO predictions for $(\pi/2 < \Delta\phi_{Dijet} < 2\pi/3)$ and $(2\pi/3 < \Delta\phi_{Dijet} < \pi)$, respectively. From the LO dijet MC event generators PYTHIA6, HERWIG++ [21] and POWHEG, PYTHIA8 shows the best agreement, while a very good description was observed using the multijet improved MadGraph generator interfaced to PYTHIA6 for showering, hadronisation and multiparton interactions, as shown in figure 8.

![Figure 5. The observed and expected contours in $(h_3, h_4)$ parameter space showing two-dimensional 95% CL limits on ZZ$\gamma$ couplings.](image)
6. Forward and small-x QCD studies
6.1. Pseudorapidity distribution of charged hadrons at 13 TeV

The pseudorapidity distribution of charged hadrons was measured at the energy of 13 TeV, when the CMS operated at zero magnetic field [22]. The yields of charged hadrons represent a
first step towards exploring the physics of a new energy frontier. The special low-intensity beam configuration was used, with 0.2-5% proton-proton interaction probability per bunch crossing. Products of secondary interactions are excluded and contributions from prompt leptons are removed. Two reconstruction techniques were used, based on the hits in the CMS pixel detector. The tracklet method uses hit pairs and has the background estimated from data, while the track method is based on identifying pixel hit triplets that fall on a straight line. The two methods agree within 2% in the central and with less than 3% in the forward pseudorapidity region. The charge hadron density was measured in the most central region of $|\eta| < 0.5$. A good agreement with EPOS generator using LHC tune [23] was obtained, while the PYTHIA8 with CUETP8S1 [24] underestimates the data in the forward pseudorapidity region, as it is presented in figure 9. The comparison of the center-of-mass dependence of $dN_{ch}/d\eta$ at 13 TeV was made with the previous measurements at lower energies (ISR [25, 26], UA5 [27, 28], PHOBOS [29] and ALICE [30, 31]). It was observed that the PYTHIA8 and EPOS LHC globally reproduce the energy dependence of hadron production in inelastic pp collisions, as shown in Figure 10.

Figure 9. Distribution of the pseudorapidity density of charged hadrons for $|\eta| < 2$ and comparison with the PYTHIA8 and EPOS LHC event generators. The blue band is the envelope of CUETP8S1 tune parametric uncertainties.

Figure 10. Center-of-mass energy dependence of $dN_{ch}/d\eta|_{\eta<0.5}$ observed at the 13 TeV, compared to PYTHIA8 and EPOS LHC predictions, and also lower energy ISR, UA5, PHOBOS and ALICE data.

7. Conclusion
Recent SM results from CMS using LHC Run 1 data provided extensive tests of the electroweak and strong interactions. Vector bosons were studies with an unprecedented precision and pQCD was tested in the regions never been probed before. Measurements of vector bosons associated with jets are improved and new PDF constraints can be derived. Multiboson studies are performed in the various final states and some of the world leading aTGC and aQCG limits were extracted. Jet production was studied in the extended phase space. The pseudorapidity distribution of charged hadrons at 13 TeV is presented as well.

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