

## Vector boson (W,Z) Studies with CMS

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We report on recent measurements of W and Z boson production at CMS. These include measurements of inclusive and differential W and Z boson production sections at  $\sqrt{s} = 8$  and 13 TeV, measurements of the angular coefficients of Z boson production, forward-backward asymmetry of  $Z/\gamma^*$  events, and W charge asymmetry at  $\sqrt{s} = 8$  TeV. These measurements can be used to improve PDFs and refine QCD calculations of weak boson production processes. In addition, a W-like mass measurement using Z boson events has been performed to probe the experimental uncertainties expected for a W mass measurement at  $\sqrt{s} = 7$  TeV.

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## 1. Introduction

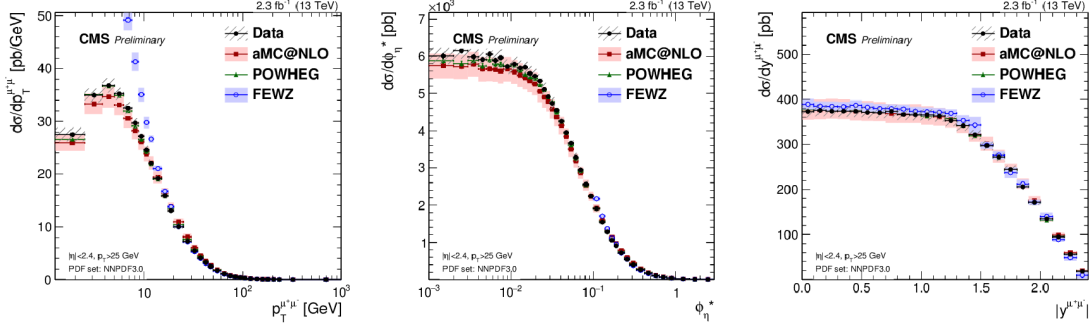
W and Z boson production processes in hadron collider are well understood and have unique signatures and high rates. Inclusive and differential measurements of W and Z boson production cross section can be used to refine calculations based on higher-order perturbative quantum chromodynamics (QCD) and improve determinations of parton distribution functions (PDFs) in global PDFs fits. Here, we present the latest measurements of vector boson production in pp collisions with the CMS detector at the Large Hadron Collider (LHC) at  $\sqrt{s} = 7$  and 8 TeV (Run I) and  $\sqrt{s} = 13$  TeV (Run II).

## 2. CMS Run II W or Z measurements at $\sqrt{s} = 13$ TeV

The inclusive W and Z boson production cross sections are measured with a sample corresponding to  $\int L = 43 \text{ pb}^{-1}$  at  $\sqrt{s} = 13$  TeV [1]. Both electrons and muons are used to reconstruct W and Z boson with the transverse energy  $E_T > 25$  GeV and  $|\eta| < 2.5$  for electrons, and  $p_T > 25$  GeV and  $|\eta| < 2.4$  for muons, respectively. Identification and selection criteria for electron and muon candidates are applied and energy isolation is required. To extract the W boson signal, the missing transverse energy distribution is fit to a sum of three components: the W boson signal template, the QCD background template, and other backgrounds template (e.g.  $W \rightarrow \tau\nu$ , Drell–Yan, diboson, and top-pair production). The background contamination in the Z boson sample is relatively small compared to the W boson case. All background processes for Z boson candidates are estimated with MC simulations in the mass range of  $60 < M(Z) < 120$  GeV. The overall systematic uncertainties in the cross sections are 2.5% for the electron and 2.0% for the muon channels, respectively. In addition, there is an overall luminosity normalization uncertainty of 4.8%. The uncertainty in the theoretical prediction is 2%. The results for the electron and muon channels are combined and compared with the theory prediction. The measured inclusive cross section is  $19950 \pm 70(\text{stat.}) \pm 360(\text{syst.}) \pm 960(\text{lumi.})$  pb for  $W \rightarrow \ell\nu$  and  $1910 \pm 10(\text{stat.}) \pm 40(\text{syst.}) \pm 90(\text{lumi.})$  pb for  $Z \rightarrow \ell^+\ell^-$ , respectively. These are in a good agreement with FEWZ predictions in next-to-next-to-leading order (NNLO QCD with NNPDF3.0 PDFs) which are  $\sigma(W \rightarrow \ell\nu) = 19700 \pm 520$  pb and  $\sigma(Z \rightarrow \ell^+\ell^-) = 1870 \pm 50$  pb, respectively. In addition, the inclusive cross sections for  $W^+$  and  $W^-$  and the ratio of W to Z boson production cross sections [1] have been measured.

The differential cross sections for Z boson production are measured as a function of Z boson transverse momentum ( $P_T$ ), rapidity ( $y$ ), and  $\phi_\eta^* (= \tan(\frac{\pi - \Delta\phi}{2}) \cdot \sin(\theta_\eta^*))$  using the full sample at  $\sqrt{s} = 13$  TeV collected in 2015 ( $\int L = 2.3 \text{ fb}^{-1}$ ). The differential production cross section as a function of  $P_T$  tests gluon resummation and parton shower models at low  $P_T$ , and perturbative QCD calculations at high  $P_T$  (where the  $qg$  scattering process is dominant). The distribution in  $\phi_\eta^*$  also probes the Z boson  $P_T$  spectrum. However, since  $\phi_\eta^*$  only depends on the direction of the leptons, this distribution has a smaller experimental error. The differential cross section as a function of  $y$  can be used to constrain PDFs in global PDF fits. Only muons are used for the differential cross section measurements. Here, Z boson candidates are selected with  $p_T(\mu) > 25$  GeV,  $|\eta| < 2.4$ , and an dimuon invariance mass  $60 < M(\mu\mu) < 120$  GeV, corresponding to  $\sim 1.3$  million Z events. Corrections are applied for the muon  $p_T$  scale (in both data and MC), and efficiency scale factors of data to MC are applied to the MC. The backgrounds are determined with MC simulations. The differen-

tial cross section measurements are unfolded within the fiducial volume and the measurements are compared to the following theory predictions: MC@NLO, POWHEG(NLO), and FEWZ(NNLO) with NNPDF3.0 PDFs. The differential cross section measurements as a function of  $P_T$ ,  $\phi_\eta^*$ , and  $y$  are compared with theory predictions in Figure 1. The FEWZ prediction deviates from the data at low  $P_T$ . This is expected due to the absence of resummation in FEWZ. Otherwise, the measurements are a good agreement with theory predictions within errors. Additional details of these measurements are given in ref. [2].



**Figure 1:** Differential cross sections for Z boson production as a function of  $P_T$ ,  $\phi_\eta^*$ , and  $y$ . The measured cross sections are compared to MC@NLO, POWHEG(NLO), and FEWZ(NNLO) theory predictions.

### 3. W and Z CMS measurements at $\sqrt{s} = 8$ TeV (Run I)

The double differential cross section as a function of Z boson  $P_T$  and  $y$  is measured using a sample corresponding to  $\int L = 19.7 fb^{-1}$  at  $\sqrt{s} = 8$  TeV [3]. In addition to muon identification and isolation requirements, the leading (sub-leading) muon is required to have  $p_T(\mu) > 25$  (10) GeV and  $|\eta| < 2.1$  (2.4). A tight mass range,  $81 < M(\mu\mu) < 101$  GeV, is used to select the Z boson candidates. The double differential cross section is unfolded to pre-final-state radiation (FSR) within the muon kinematics. Both absolute and normalized differential cross sections ( $\frac{d^2\sigma}{dP_T dy}$  and  $\frac{1}{\sigma_{inc}} \cdot \frac{d^2\sigma}{dP_T dy}$ ) are measured [3] and compared to the theory prediction of FEWZ(NNLO) with NNPDF2.3 PDFs and radiative corrections. The measured cross sections are in agreement with theory within errors.

The general structure of the lepton angular distribution in the boson rest frame is given by

$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \left[ (1 + \cos^2\theta^*) + A_0 \frac{1}{2} (1 - 3\cos^2\theta^*) + A_1 \sin(2\theta^*) \cos\phi^* + A_2 \frac{1}{2} \sin^2\theta^* \cos(2\phi^*) \right. \\ \left. + A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^* + A_5 \sin^2\theta^* \sin(2\phi^*) + A_6 \sin(2\theta^*) \sin\phi^* + A_7 \sin\theta^* \sin\phi^* \right].$$

Here,  $\theta^*$  and  $\phi^*$  are the polar and azimuthal angles of the negatively charged lepton in the rest frame of the lepton pair. The angular coefficients ( $A_0$  to  $A_4$ ) of Z boson are measured using the same sample and selection criteria as used for the double differential cross section measurement as a function of Z boson  $P_T$  and  $y$  at  $\sqrt{s} = 8$  TeV [4]. The angular coefficients,  $A_{0,1,2}$ , are related to the polarization of the Z boson and  $A_{3,4}$  originate from  $\gamma^*/Z$  interference. Here,  $A_{0,2}$  determine the fraction of  $q\bar{q}$  and  $qg$  processes in pp collisions as a function of Z boson  $P_T$ . The  $A_4$  parameter is

directly related to the forward-backward asymmetry of Z boson production ( $A_{FB}$ ) and is sensitive to the electroweak mixing angle,  $\sin^2 \theta_W$ . The angular coefficients are measured using the template fitting method in Collins-Soper frame [5] as a function of Z boson  $P_T$  and  $|y|$ . The measured angular coefficients are compared with MadGraph, POWHEG(NLO), and FEWZ(NNLO). There is good agreement with the MadGraph and FEWZ(NNLO) predictions. Since the MadGraph calculation doesn't include EW radiative correction, the MadGraph prediction has a higher  $A_4$  than the other theory predictions. Details of the measurement of the angular coefficients as a function of Z boson  $P_T$  for two rapidity bins,  $|y| < 1.0$  and  $1.0 < |y| < 2.1$ , are given in ref. [4]

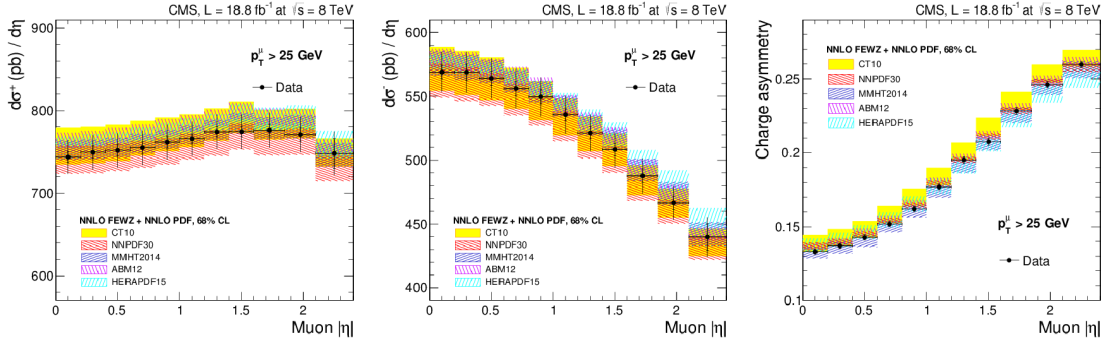
The forward-backward asymmetry of  $Z/\gamma^*$  events ( $A_{FB}$ ) is measured using a sample corresponding to  $\int L = 19.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$  [6]. The  $A_{FB}$  parameter depends on dilepton mass, quark flavor, and the electroweak mixing angle  $\theta_W$ .  $A_{FB}$  is extracted from the difference of the number of forward ( $\cos \theta^* > 0$ ) and backward ( $\cos \theta^* < 0$ ) events divided by the sum of events in bins of invariant mass (M) and  $|y|$ . Muons and electrons in the central and endcap regions are used to select the dilepton events with lepton  $p_T > 20 \text{ GeV}$  and  $|\eta| < 2.4$ . The measurement of  $A_{FB}$  is extended up to  $|y|=5$  by including electrons in the forward calorimeter ( $p_T > 20 \text{ GeV}$ ,  $3 < |\eta| < 5$ ) in conjunction with a central electron ( $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.4$ ).

The measured  $A_{FB}$  is unfolded for resolution, acceptance, efficiencies, and the effects of FSR. The unfolded  $A_{FB}$  is combined for muons and electrons up to  $|y|=2.4$ . The POWHEG prediction with  $\sin^2 \theta_W = 0.2312$  is in good agreement with the data. Measurements of  $A_{FB}$  as a function of invariant mass bins in  $|y|$  are compared with POWHEG predictions in ref. [6].

In pp collisions, the production of  $W^+$  boson is larger than  $W^-$  bosons because the proton is composed primarily of  $uud$  quarks. In addition, the W bosons are polarized because of parity violation, which also results in an asymmetry in the lepton decay kinematics. The charge asymmetry of the W boson decay lepton as a function of  $A(\eta)$  is defined as the difference of the cross section for  $W^+$  and  $W^-$  divided by the sum as a function of lepton  $\eta$ . The asymmetry  $A(\eta)$  can be used to constrain PDFs, and in particular the ratio of  $u$  and  $d$  quark distributions. In addition, the differential cross sections of  $W^\pm$  production as a function of muon  $\eta$  ( $d\sigma^\pm/d\eta$ ) are measured for events with  $p_T(\mu) > 25 \text{ GeV}$  and  $|\eta| < 2.4$  using a sample corresponding to  $\int L = 18.8 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$ . The differential cross sections for  $W^\pm$  production are corrected for the efficiency and effects of FSR. The measurements of the differential cross sections and asymmetries are compared to FEWZ predictions with various PDFs models. The agreements between data and predictions are within the uncertainties of the PDFs. A QCD analysis is performed at NNLO to test the impact of  $A(\eta)$  measurement. The  $A(\eta)$  measurement significantly improves the determination of the valence quark PDFs. Figure 2 shows the measurements of the differential cross sections for  $W^\pm$  production and asymmetry as compared to theory predictions. Additional details of this measurements are given in ref. [7].

#### 4. W-like measurement of the Z boson mass at $\sqrt{s} = 7 \text{ TeV}$

The W mass ( $M_W$ ) provides a critical test on the consistency of Standard Model (SM) predictions (using the measured masses of the top quark ( $M_t$ ) and Higgs( $M_H$ )). The world average of  $M_W$  direct measurements is  $80.385 \pm 0.015 \text{ GeV}$ . A global electroweak fit predicts  $M_W = 80.358 \pm 0.008 \text{ GeV}$ . The world average of  $M_t$  measurements is  $174.34 \pm 0.76 \text{ GeV}$  and the most precise direct  $M_t$

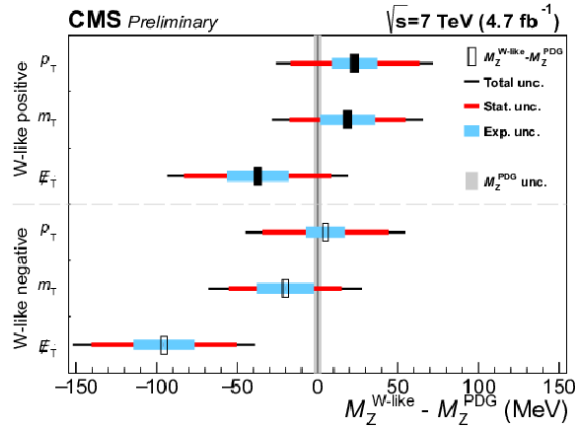


**Figure 2:** Differential cross sections for  $W^+$  (left),  $W^+$  (middle), and the  $W$  charge asymmetry (right) as a function of muon  $\eta$ . The measurements are compared to FEWZ predictions with various PDFs sets, (CT10, NNPDF3.0, MMHT2014, HERAPDF1.5 and ABM12).

measurement has an error of 0.66 GeV. A direct measurement of  $M_W$  should be at a level of precision of 6 MeV or better to test the consistency of the SM (given the presently available accuracy of  $M_t$  and  $M_H$ ). A direct  $W$  mass measurement is on-going at CMS using Run I data at  $\sqrt{s} = 7$  and 8 TeV. To test the technique, CMS has measured the  $Z$  boson mass by removing one of two muons to form  $W$ -like  $Z$  boson candidates. This measurement provides a proof of principle and a quantitative validation of the technique to be used in the measurement of the  $W$  mass. The measurement is done with a sample of 0.2 million  $Z \rightarrow \mu\mu$  events corresponding to  $\int L = 4.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 7$  TeV. The measurement utilizes improvements in calibration of muon  $p_T$  ( $< 15$  MeV) and recoil calibration ( $< 14$  MeV). Three observables, muon  $p_T$ , the transverse mass ( $m_T$ ), and the missing transverse energy are used to extract the  $W$ -like mass measurement. The  $W$ -like mass measurements from muon  $p_T$ ,  $m_T$ , and the missing transverse energy fits are compared with the PDG  $Z$  boson mass ( $M_Z^{\text{PDG}}$ ) in Figure 3. The most precise  $W$ -like mass measurement is from  $m_T$  fit and it differs from the PDG value by  $18 \sim 20$  MeV, which is within the uncertainties of the  $W$ -like measurement (stat.  $\oplus$  syst. = 48 MeV level). Additional details of the measurement are given in ref. [8].

## 5. Summary

We report on recent CMS measurements of  $W$  and  $Z$  boson production at  $\sqrt{s} = 7$  and 8 TeV (Run I), and preliminary results for the inclusive and differential cross sections of  $Z$  boson production at  $\sqrt{s} = 13$  TeV (Run II). We also report on various other published CMS measurements with  $W$  and  $Z$  bosons at  $\sqrt{s} = 8$  TeV. These detailed studies of  $W$  and  $Z$  boson production processes probe various aspects of the SM. In addition, the measurements can be used to provide additional constraints on PDFs and test QCD theory predictions. A  $W$ -like mass measurement with  $Z$  boson events at  $\sqrt{s} = 7$  TeV provides a cross-check on the technique for the  $W$  mass measurement which is on-going.



**Figure 3:** The difference between the fitted W-like mass and  $M_Z^{\text{PDG}}$  using each of three observables with corresponding statistical and systematic uncertainties.

## References

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