Inclusive W/Z Production at CMS

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At the LHC, the production cross sections of W/Z bosons are tens to hundreds of nanobarns. The production mechanism of these processes is well established in the Standard Model and these processes can be used as “standard candles” to help commission the CMS detector for physics. Leptonic decays of W/Z bosons are expected to have very high trigger efficiency and signal to background ratio. Therefore they are ideal channels to study the properties of W/Z bosons in detail, such as cross sections and charge asymmetry. In this paper early CMS results on inclusive W/Z production at 10 TeV center-of-mass energy are discussed.

I. INTRODUCTION

The W and Z bosons were first discovered at CERN more than two decades ago [1, 2]. Since then their properties have been extensively studied by different experiments to test the Standard Model (SM) predictions and to explore the physics beyond-the-SM. At the Large Hadron Collider (LHC) [3], W and Z bosons will be produced with large rates. A large set of W/Z bosons will help us with detector commissioning initially and enable us to perform a large variety of W/Z physics studies with early LHC data.

The production mechanism of W/Z bosons at the LHC is well known. Higher order predictions of many W/Z observables have been carried out. For example, a recent next-to-leading order calculation [4] of total W and Z cross sections predicted that the cross sections are tens to hundreds of nanobarns for Z and W bosons, respectively. A calculation of differential cross section as a function of boson rapidity at next-to-next-leading order has also been carried out by C. Anastasiou et al. [5]. In these theoretical predictions, errors due to the Parton Distribution Functions (PDF) dominate total theoretical errors. The PDF error could be partially canceled out if we study ratios of cross sections, such as the lepton charge asymmetry between $W^+$ and $W^-$ production, which is defined to be,

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

This charge asymmetry probes the valence-sea quark ratio in protons. Measurements of these observables at the LHC will enable us to test higher order calculations and provide new insights into proton structure.

II. CMS DETECTOR

The Compact Muon Solenoid (CMS) experiment is a 4$\pi$ general-purpose hadron-collider detector, which is suitable for high-$p_T$ physics studies at the LHC. The central feature of the Compact Muon Solenoid apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadronic calorimeter (HCAL). Muons are measured in gaseous detectors embedded in the iron return yoke. Besides the barrel and end-cap detectors, CMS has extensive forward calorimeter. The ECAL has an energy resolution of better than 0.5% above 100 GeV. The HCAL, when combined with the ECAL, measures jets with a resolution $\Delta E/E \approx 100\%/\sqrt{E} \pm 5\%$. The calorimeter cells are grouped in projective towers, of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ at central rapidities and $0.175 \times 0.175$ at forward rapidities. The muons are measured in the pseudorapidity window $|\eta| < 2.4$, with detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1 and 5%, for $p_T$ values up to 1 TeV/$c$. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select (in less than 1 $\mu$s) the most interesting events (only one bunch crossing in 1000). The High Level Trigger processor farm further decreases the event rate from 100 kHz to 100 Hz, before data storage. A much more detailed description of CMS can be found elsewhere [6].

III. EVENT SIMULATION

The Monte Carlo (MC) simulation used in the following studies was generated with the Pythia [7] event generator, where the CTEQ5L [8] PDF model was used. The center-of-mass energy was assumed to be 10 TeV. The generated events were then passed through the full CMS detector simulation with GEANT4 [9]. Physics objects such as muons and electrons were reconstructed with standard CMS offline reconstruction sequence. The missing transverse energy (MET) was reconstructed using energy deposits in CMS calorimeters.
IV. INCLUSIVE W BOSON CROSS SECTION

At the LHC, leptonic decays of W/Z bosons were used to study the properties of W/Z bosons. The experimental signature of a W boson is a high-p_{T} lepton and large MET due to presence of a neutrino in the final state. CMS conducted analyses to measure the inclusive W boson cross section in both muon and electron decays \[^{10, 11}\]. The trigger used in W \rightarrow \mu \nu analysis is a single muon trigger with a minimum p_{T} threshold of 15 GeV. The efficiency is above 90\%. The CMS single muon trigger system has coverage up to a pseudorapidity of |\eta| < 2.1. The selection of W \rightarrow \mu \nu candidates was done by first requiring an isolated muon with p_{T} > 25 GeV and muon pseudorapidity |\eta| < 2.0. Here the isolation is the p_{T} sum of all tracks in a cone of radius 0.3 around the muon direction, normalized to the muon p_{T}. This normalized isolation is required to be less than 0.09. The QCD dijet background was largely suppressed by the isolation requirement. Other processes, such as Drell-Yan, t\overline{t}, W \rightarrow \tau \nu, could also fake a W \rightarrow \mu \nu event. Background events were further suppressed by requiring transverse mass \[^{21}\] m_{T} > 50 GeV, as shown in Fig. 1 where the expected W \rightarrow \mu \nu signal and background events for an integrated luminosity of 10 pb\(^{-1}\) is shown.

CMS also studied the inclusive W boson cross section in electron decays. A single electron trigger was used, which has an efficiency of about 97\%. An electron candidate was required to have transverse energy (E_{T}) deposit in the CMS ECAL detector E_{T} > 30 GeV and |\eta| < 2.5. The shower shape of an electron candidate was also required to be consistent with an electromagnetic interaction. Comparing to the muon channel analysis, in addition to background processes such as, QCD dijet production, Drell-Yan, t\overline{t}, W \rightarrow \tau \nu, photon plus jet production also contributes. The QCD dijet background was significantly reduced by an isolation requirement. Here isolation was computed using transverse components of energy deposits in CMS calorimeters and tracks in a cone of radius 0.4 around the electron direction. Figure 1 shows the reconstructed MET distribution for W \rightarrow e\nu signal and background events after all event selections were applied.

The W \rightarrow \ell \nu cross section is related to the background subtracted number of signal events, N_{W},

\[
\sigma_{W} \times BR(W \rightarrow \ell \nu) = \frac{N_{W}}{A_{W} \times \epsilon_{W} \times \mathcal{L}} \tag{2}
\]

where A_{W} is acceptance for W signal events, \epsilon_{W} is the W reconstruction and selection efficiency, and \mathcal{L} is the integrated luminosity. While acceptance has to be estimated with MC, the lepton reconstruction and selection efficiency can be derived directly from data with a tag-and-probe method \[^{12}\]. The expected statistical error of the measured cross section is 1.5\% for an integrated luminosity of 10 pb\(^{-1}\). The systematic error is expected to be dominated by the luminosity error, which is expected to be about 10\% at the CMS start-up \[^{13}\].

V. INCLUSIVE Z BOSON CROSS SECTION

Similarly the inclusive Z boson production is another “standard candle” to help us commission CMS for physics. CMS studied experimental sensitivities to the inclusive Z boson cross section in both di-muon and di-electron decays \[^{10, 11}\]. Comparing to the W \rightarrow \ell \nu analysis, due to presence of two isolated high-p_{T} leptons the background was expected to be less than one percent after final event selection. The major background contributions were from QCD dijet, W plus jets, t\overline{t}, Z \rightarrow \tau \tau. Figure 2 shows the reconstructed Z \rightarrow ee invariant mass distribution for an integrated luminosity of 10 pb\(^{-1}\). Both expected signal and background contributions are shown. The final Z \rightarrow ee sample was selected from events with 70 GeV < m_{ee} < 110 GeV. The cross sections were obtained after correcting for efficiencies and acceptance following Eq. 2. The expected cross section for Z \rightarrow \mu \mu decays as a function of statistics corresponding to different luminosity scenarios is also shown in Fig. 2. The results were normalized to the cross section determined with a MC sample corresponding to an integrated luminosity of 133 pb\(^{-1}\). The expected statistical error at 10 pb\(^{-1}\) of integrated luminosity is about 2\%. Both analyses showed similar sensitivities. The 10\% luminosity uncertainty is again expected to dominate the total error.

VI. CONSTRAINTS TO PARTON DISTRIBUTION FUNCTIONS

The large W/Z cross sections at the LHC makes high-precision differential measurements possible. CMS performed a measurement of the muon differential cross section measurement as a function of muon pseudorapidity in inclusive W \rightarrow \mu \nu production \[^{14}\]. This analysis utilized the same trigger path as the inclusive W \rightarrow \mu \nu cross section analysis. The W \rightarrow \mu \nu candidates were selected with muon p_{T} > 25 GeV and MET>20 GeV. A calorimeter-based isolation was used to suppress the QCD dijet contribution. After correcting for efficiencies and acceptance, the expected muon pseudorapidity distributions at an integrated luminosity of 10 pb\(^{-1}\) are shown in Fig. 3. The PDF error on the experimental data points is the theoretical error in estimating acceptance. Among other systematic errors, the 10\% luminosity error dominates. The results were compared to theoretical predictions from Pythia. We estimated the PDF error using the CTEQ6M \[^{15}\] PDF model with PDF-
FIG. 1: Left) The reconstructed $W \rightarrow \mu\nu$ transverse mass distribution. Right) The reconstructed $W \rightarrow e\nu$ MET distribution. Both are normalized to 10 pb$^{-1}$ of integrated luminosity. The arrow in the left figure indicates that a cut on $m_T > 50$ GeV was applied to select final data sample.

FIG. 2: Left) The reconstructed $Z \rightarrow ee$ invariant mass distribution for an integrated luminosity of 10 pb$^{-1}$. Right) The $Z \rightarrow \mu\mu$ cross section as a function of MC statistics corresponding to different luminosity scenarios. The results were normalized to the cross section determined with 133 pb$^{-1}$ of integrated luminosity. Only statistical errors are shown.

The charge asymmetry, $A^\text{obs.}(\eta)$, with background subtracted number of $W \rightarrow \mu\nu$ signal events, $N_{W^+\rightarrow\mu^+\nu}(\eta)$,

$$A^\text{obs.}(\eta) = \frac{N_{W^+\rightarrow\mu^+\nu}(\eta) - N_{W^-\rightarrow\mu^-\nu}(\eta)}{N_{W^+\rightarrow\mu^+\nu}(\eta) + N_{W^-\rightarrow\mu^-\nu}(\eta)},$$

assuming that reconstruction and selection efficiency ratios between $\mu^+$ and $\mu^-$ are one. Because of the weak decay of $W$ bosons, the acceptance ratio between $\mu^+$ and $\mu^-$ differs from unity. In this analysis, we did not correct for the acceptance difference in $A^\text{obs.}(\eta)$ but absorbed it into the theoretical predictions. The charge asymmetry as a function of muon pseudorapidity for an integrated luminosity of 100 pb$^{-1}$ is shown in Fig. 4. The result is compared to theoretical predictions from Pythia, where the PDF error was estimated with CTEQ6M PDF model. The systematic error is dominated by the statistical error on the efficiency ratio between $\mu^+$ and $\mu^-$ determined using 100 pb$^{-1}$ of Drell-Yan MC.
measurement are comparable to the PDF errors and potentially could provide new constraints on different PDF models.

where for each bin $i$ of rapidity ($y_i$), $N_i$ is the number of background subtracted $Z \rightarrow ee$ candidates, $\Delta_i$ is the bin width, and $(\epsilon \times A)_i$ is the product of the efficiency and acceptance for detecting and reconstructing a Z boson with rapidity $y_i$.

With conventional electron reconstruction at the CMS, where both CMS ECAL and tracking system are utilized, the coverage for electrons is up to pseudorapidity of about 2.5. The reconstructed $Z \rightarrow ee$ candidates can be used to directly probe partons with kinematics [22] outside the range of previous experiments [4]. The kinematics reach was further extended by using electrons reconstructed using the CMS Forward Hadronic (HF) calorimeter [19], which has a coverage up to pseudorapidity of 4.6. The shower shape of HF reconstructed electron candidates was utilized to remove $Z \rightarrow ee$ background events effectively.

The final results for the rapidity measurement for an integrated luminosity of 100 pb$^{-1}$ is shown in Fig. 5. The background in the HF region is well under control. The expected measurements are compared to predictions with CTEQ6.1 PDF model [20]. With an integrated luminosity of 100 pb$^{-1}$, we are expecting to provide new constraints on different PDF models.

VII. SUMMARY

CMS performed MC studies to explore W/Z boson production with initial LHC data. With 10 pb$^{-1}$ of integrated luminosity, the inclusive W/Z cross sections could be established with 1-2% statistical precision. However, it is expected that the luminosity

The Z boson differential cross section as a function of Z rapidity can also be used to test higher order perturbation calculations and put constraints on PDF models. CMS performed a study of this observable using Z $\rightarrow ee$ events [18]. To remove the luminosity uncertainty in this measurement, the following observ-
uncertainty will dominate the total error in these measurements.

The sensitivities to constrain different PDF models at CMS were also explored using measurements of the muon charge asymmetry in inclusive $W \rightarrow \mu\nu$ process and the Z rapidity shape in inclusive $Z \rightarrow ee$ process. With about 100 pb$^{-1}$ of integrated luminosity, both measurements could provide constraints on different PDF models.

Acknowledgments

We thank the technical and administrative staff at CERN and other CMS Institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTDS (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie IEF program (European Union); the Leventis Foundation; the Alexander von Humboldt Foundation.

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[21] Here $m_T = \sqrt{2 \cdot p_T \cdot MET \cdot (1 - \cos(\Delta\phi_{\mu, MET}))}$, where $\Delta\phi_{\mu, MET}$ is the angular difference between muon and missing transverse moment in the plane transverse to the beam direction.
[22] Here the initial state parton momentum fraction $x_{1, 2} = \frac{M_T}{s} \cdot e^{\pm y}$, where $s$ is the center of mass energy at the LHC.