# First Measurements of Inclusive $W$ and $Z$ Cross Sections from Run II of the Fermilab Tevatron Collider

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We report the first measurements of inclusive $W$ and $Z$ cross sections times leptonic branching ratios for $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV, based on their decays to electrons and muons. The data correspond to an integrated luminosity of 72 pb$^{-1}$ recorded with the CDF detector at the Fermilab Tevatron. We test $e$-$\mu$ universality in $W$ decays, and we measure the ratio of leptonic $W$ and $Z$ rates from which the leptonic branching fraction $B(W \rightarrow \ell\nu)$ can be extracted as well as an indirect value for the total width of the $W$ and the Cabibbo-Kobayashi-Maskawa matrix element, $|V_{cs}|$.

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We report the first measurements of the inclusive production of $W$ and $Z$ bosons in $p\overline{p}$ collisions at the upgraded Run II Fermilab Tevatron operated at $\sqrt{s} = 1.96$ TeV. Measurements during Run I at $\sqrt{s} = 1.8$ TeV have been reported by the CDF and D0 collaborations [1]. The data were collected with the Collider Detector at Fermilab (CDF) detector and comprise $72.0 \pm 4.3$ pb$^{-1}$. $W$ and $Z$ bosons are identified by their decays to electrons and muons, from which we obtain the total rates $\sigma(p\overline{p} \rightarrow W) \times B(W \rightarrow \ell\nu)$ and $\sigma(p\overline{p} \rightarrow Z) \times B(Z \rightarrow \ell^+\ell^-)$ [2]. We test $e$-$\mu$ universality in $W$ decays using the ratio of inclusive $W$ production for the two lepton species. We derive the leptonic branching ratio $B(W \rightarrow \ell\nu)$ and an indirect value for the total $W$ width, $\Gamma_W^{\rm tot}$, from the ratio of leptonic rates,

$$R \equiv \frac{\sigma(p\overline{p} \rightarrow W) \times B(W \rightarrow \ell\nu)}{\sigma(p\overline{p} \rightarrow Z) \times B(Z \rightarrow \ell^+\ell^-)}. \quad (1)$$

Measurements of $\Gamma_W^{\rm tot}$ test the standard model (SM), which predicts $\Gamma_W^{\rm tot}$ in terms of electroweak parameters and the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements [3].

The CDF detector has been substantially upgraded since the end of the previous data-taking period [4]. The central outer tracker (COT) is a precision drift chamber which provides up to 96 space points for a track falling within its fiducial range $|\eta| < 1$ [5]. The COT sense wires are arranged in eight "superlayers," four of which provide axial coordinates and four of which provide stereo measurements. Precise track coordinates closer to the beam are provided by the silicon vertex detector. The fiducial coverage of the central electromagnetic (em) and hadronic (had) calorimeters has been extended to $|\eta| \sim 2.8$, and the muon chambers provide coverage out to $|\eta| \sim 1$.

The selection of candidate $W$ and $Z$ decays begins with the requirement of a high-$p_T$ lepton. Electrons are identified on the basis of their electromagnetic showers. We require an energy cluster in a well instrumented region of the calorimeter with $E_T > 25$ GeV, matched to a single track with $p_T > 10$ GeV that extrapolates to the position of the cluster at a depth corresponding to shower maximum. The ratio $E_T/p_T$ must be less than 2, and the energy in the hadronic calorimeter must be relatively small: $E_{\text{had}}/E_{\text{em}} < 0.055 + 0.00045 \times E_{\text{em}}$. The shape of the shower must be consistent with that observed from test-beam data. Beyond the central tracker coverage, $|\eta| > 1$, only calorimetry is used to identify electrons.

Muons are identified on the basis of a track segment ("stub") reconstructed in the muon chambers with positions well-matched to the extrapolation of a single track. We require $p_T > 20$ GeV, and energy depositions in the calorimeters consistent with those expected from a minimum-ionizing particle.

Requirements on the reconstructed track are common to both the electron and muon selections. At least three axial and three stereo COT superlayers must have seven hits or more. Not all the lepton tracks have hits from the silicon vertex detector, so for the sake of uniformity in the $p_T$ measurement, we drop these hits and constrain the track fit to the transverse beam profile. For muons, we apply a cut on the $\chi^2$ for the track fit to eliminate kaons and pions which have decayed in flight. The coordinate of the lepton along the beam line must fall within 60 cm of the center of the detector to ensure a good energy measurement in the calorimeter. This requirement eliminates ~5% of the data, according to studies with minimum-bias events.

After the selection of high-$p_T$ leptons, we establish the $W$ and $Z$ samples. For $W \to \ell\nu$ candidates, we require $\not{E}_T > 25$ GeV (20 GeV) in the electron (muon) channel as evidence for the neutrino. In the muon channel, events with any second charged particle ($p_T > 10$ GeV) are rejected as potential background from $Z \to \mu^+\mu^-$. For $Z$ candidates, a second electron is required in the electron channel, and a second charged particle in the muon channel. These must pass the same $E_T$ and $p_T$ cuts as the first lepton. The identification requirements are looser for the second lepton in order to maintain good efficiency for these events. For example, for loose electrons in the central region, an associated track is required, but the requirements on $E_T/p_T$, of the match of the track to the center of the cluster, and on the lateral shower shape are dropped.

For $W \to e\nu$ candidates we accept electrons reconstructed in the central calorimeter, which corresponds to $|\eta| \lesssim 1$. For $Z \to e^+e^-$ candidates, one electron must come from the central calorimeter, while the second can come from the forward region, which extends out to $|\eta| = 2.8$.

A significant background comes from leptons from the decays of heavy-flavor hadrons, which can be reduced by requiring that the lepton be isolated. We require that the calorimetric energy not associated with the lepton in a cone of $\Delta R = 0.4$ around the lepton must be no more than 10% of the energy of the lepton [6].

Cosmic-ray muons contaminate the muon samples. We use the timing capabilities of the COT to reject events with two muon tracks, one of which travels from outside of the COT toward the beam pipe. We also require that the muon tracks pass close to the beam line, within distances less than 0.02 cm (0.2 cm) for tracks with (without) silicon hits.

The kinematic and geometric acceptance is estimated using the PYTHIA 6.203 event generator [7] and a full simulation of the CDF detector based on the GEANT simulation package [8]. The key quantity is the boson rapidity, $y$, so we extract the acceptance $A(y)$ from the simulation and convolve it with a next to next to leading order calculation of $d\sigma/dy$ [9], which depends on the parton distribution functions (PDF's). We compute the central values of the acceptance using the Martin-Roberts-Stirling-Thorne (MRST) PDF's [10]. We estimate the uncertainties using the PDF eigenvector basis sets for CTEQ6M [11], and obtain 1.3% for $W \to e\nu$ and $\mu\nu$, and 0.7% for $Z \to e^+e^-$ and 2.1% for $Z \to \mu^+\mu^-$. These are roughly a factor of 2 larger than what we obtained using the MRST error PDF's.

The amount of material an electron passes through is known to 10–30%, depending on $\eta$: this contributes $\lesssim 1\%$ to the acceptance uncertainty for the electron channels. The energies of hadronic jets recoiling against the $W$ bosons enter the calculation of $\not{E}_T$. We test the accuracy of the simulation using a $\chi^2$ test with scale factors and offsets for the components of these energies which are parallel and perpendicular to the lepton momentum vector. Taking a variation corresponding to $\Delta\chi^2 = 9$, we infer systematic uncertainties of about 0.3%. The energy and momentum scales for the leptons are treated in a similar manner, resulting in an uncertainty of 0.2%–0.3%. Finally, we vary the parameters of the PYTHIA model which influence the boson $p_T$ distribution, as allowed by $\chi^2$ tests with the Run I measurement [1], and find the uncertainty on the acceptance is negligible.

Lepton reconstruction, identification, isolation, and trigger efficiencies are measured directly with the data. We use $Z \to \ell^+\ell^-$ decays in which the standard cuts are applied to one lepton and the second candidate lepton is

TABLE I. Background estimates.

| category | channel $W \to e\nu$ | $W \to \mu\nu$ | $Z \to e^+e^-$ | $Z \to \mu^+\mu^-$ |
|---|---|---|---|---|
| multijet | $587 \pm 299$ | $220 \pm 111$ | $41 \pm 18$ | $0^{+1}_{-0}$ |
| $Z \to \ell^+\ell^-$ | $317 \pm 14$ | $1739 \pm 75$ | ··· | ··· |
| $Z \to \tau^+\tau^-$ | negligible | negligible | $3.7 \pm 0.4$ | $1.5 \pm 0.3$ |
| $W \to \tau\nu$ | $752 \pm 17$ | $998 \pm 31$ | negligible | negligible |
| $W \to \ell\nu$ | ··· | ··· | $16.8 \pm 2.8$ | negligible |
| cosmic rays | negligible | $33 \pm 23$ | negligible | $12 \pm 12$ |

tested to see whether it passes the given criteria. The statistical uncertainties are below 1% and studies with the simulation show negligible bias with respect to $W$ decays. The cuts to eliminate cosmic rays remove a very small fraction of signal events in the muon channel, as measured by applying the cuts to $W \to e\nu$ and $Z \to e^+e^-$ events. The track-reconstruction efficiency is measured using a trigger demanding an energetic calorimeter cluster which provides a sample of $W \to e\nu$ events independent of the tracking. The efficiency for rejecting $Z \to \mu^+\mu^-$ events in the $W \to \mu\nu$ channels is estimated using the simulation.

Backgrounds fall into three categories: multijet events with no $W$ or $Z$ bosons, weak-boson backgrounds ($Z \to \ell^+\ell^-$ and $W \to \tau\nu$ appearing in $W \to \ell\nu$, and $Z \to \tau^+\tau^-$ and $W \to \ell\nu$ appearing in $Z \to \ell^+\ell^-$), and noncollision backgrounds, primarily cosmic rays. Estimates of these backgrounds are summarized in Table I.

The multijet background is estimated with the data. Such events are characterized by a significant energy in the cone around the lepton and a small $\not{E}_T$, with tails in both quantities. We assume that these tails are not correlated, and estimate the number of background events by comparing to control regions with either low $\not{E}_T$ or high energy in the isolation cone, after taking into account the $W$ events which fall in the control regions. We vary the cuts on $\not{E}_T$ and isolation which define the control regions, and then estimate changes in a manner reproduced by the simulation. We assign a systematic uncertainty of 50% for this background estimate.

The weak-boson backgrounds are obtained using the simulation to compute the acceptance relative to that of the signal. To normalize the contribution of $Z \to \ell^+\ell^-$ backgrounds to $W \to \ell\nu$ channels, we use the theoretical value for the ratio of cross sections, with an uncertainty corresponding to previous measurements of $W$ and $Z$ cross sections [1]. Backgrounds from diboson and $t\bar{t}$ production are negligible.

For estimating the cosmic-ray contamination in the $W \to \mu\nu$ sample, we use the azimuthal distribution of muon chamber hits opposite the high-$p_T$ muon. For the $Z \to \mu^+\mu^-$ sample, we use the distribution of the cosine of the angle between the two muon tracks. In both cases, the contribution from cosmic rays is very small.

The uncertainty on the luminosity measurement is 6.0%, of which 4.4% comes from the acceptance and operation of the luminosity monitor and 4.0% comes from the calculation of the total $p\bar{p}$ cross section [12].

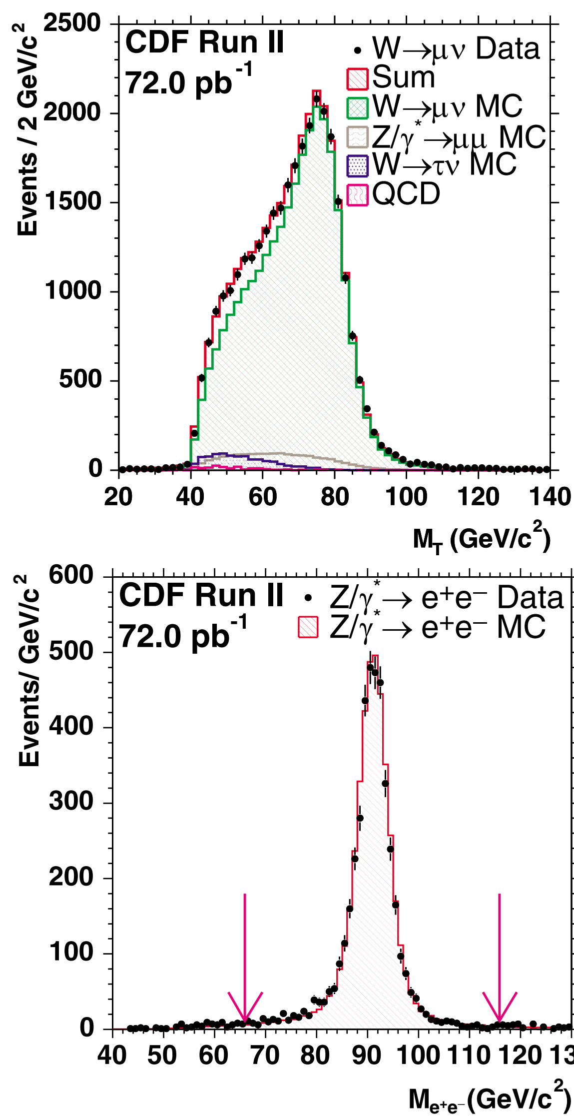


FIG. 1 (color online). Distributions of $M_T$ for $W \to \mu\nu$ (top) and $M_{e^+e^-}$ for $Z/\gamma^* \to e^+e^-$ (bottom). The arrows in the $M_{e^+e^-}$ distribution define the mass window.

TABLE II. Number of selected events, and estimated acceptance, efficiency, and expected number of background events. Cross sections are reported in picobarn, with a statistical and systematic uncertainty. A common uncertainty due to the luminosity measurement is 166 pb (15 pb) for the $W$ ($Z$) channels.

| | channel | | | |
|---|---|---|---|---|
| category | $W \to e\nu$ | $W \to \mu\nu$ | $Z/\gamma^* \to e^+e^-$ | $Z/\gamma^* \to \mu^+\mu^-$ |
| $N$ candidates | 37584 | 31722 | 4242 | 1785 |
| acceptance | $0.2397 \pm 0.0039$ | $0.1970 \pm 0.0027$ | $0.3182 \pm 0.0041$ | $0.1392 \pm 0.0030$ |
| efficiency | $0.749 \pm 0.009$ | $0.732 \pm 0.013$ | $0.713 \pm 0.012$ | $0.713 \pm 0.015$ |
| background | $1656 \pm 300$ | $2990 \pm 140$ | $62 \pm 18$ | $13 \pm 13$ |
| cross section (pb) | $2780 \pm 14 \pm 60$ | $2768 \pm 16 \pm 64$ | $255.8 \pm 3.9 \pm 5.5$ | $248.0 \pm 5.9 \pm 7.6$ |

We compute the transverse mass of each candidate $W$ decay: $M_T \equiv \sqrt{E_T \not{E}_T - (E_x \not{E}_{T,x} + E_y E_{T,y})}$, where $E_x$ and $E_y$ are measured with the calorimeter for electrons, and with the COT for muons. In the $Z \to \ell^+\ell^-$ channels, we compute the invariant mass of the lepton pair, and count the candidates in the mass window 66 GeV $< M_{\ell^+\ell^-} <$ 116 GeV. The cross sections $\sigma(p\overline{p} \to Z/\gamma^* \to \ell^+\ell^-)$ reported here include the contributions from virtual photon exchange. Distributions for $W \to \mu\nu$ and $Z \to e^+e^-$ are shown in Fig. 1, which demonstrate that the simulations match the data well.

The measurement of the cross section requires the number of events selected for the given luminosity, and the estimates of the acceptance, efficiencies, and backgrounds. A summary of these quantities and the inferred cross sections is given in Table II.

We test $e$-$\mu$ universality in $W$ decays by taking ratios of the $W$ cross sections. Many uncertainties cancel in this ratio, and we find for the ratio of $W$-$\ell$-$\nu$ couplings: $g_\mu/g_e = 0.998 \pm 0.004_{(\mathrm{stat})} \pm 0.011_{(\mathrm{syst})}$.

Since there is no sign of nonuniversality, we combine our measurements taking correlated uncertainties into account and obtain

$$\sigma \times B(p\overline{p} \to W \to \ell\nu) = 2775 \pm 10_{(\mathrm{stat})} \pm 53_{(\mathrm{syst})} \pm 167_{(\mathrm{lum})}\ \mathrm{pb}$$

$$\sigma \times B(p\overline{p} \to Z/\gamma^* \to \ell^+\ell^-) = 254.9 \pm 3.3_{(\mathrm{stat})} \pm 4.6_{(\mathrm{syst})} \pm 15.2_{(\mathrm{lum})}\ \mathrm{pb}.$$

Agreement with SM predictions [13,14] is good.

We compute the ratio, $R$ [Eq. (1)], taking all correlations among channels into account, and obtain $R = 10.92 \pm 0.15_{(\mathrm{stat})} \pm 0.14_{(\mathrm{syst})}$, after correcting for virtual photon exchange (we multiply the measured $Z/\gamma^*$ cross section by a factor $1.004 \pm 0.001$). Using the measured value $B(Z \to \ell^+\ell^-) = 0.033\,658 \pm 0.000\,023$ [15] and a theoretical calculation of the ratio of production cross sections [14], we extract the leptonic branching ratio $B(W \to \ell\nu) = 0.1089 \pm 0.0022$.

Using the theoretical value for the leptonic partial width, $\Gamma(W \to \ell\nu) = 226.4 \pm 0.3$ MeV [15], we extract the total width of the $W$ boson: $\Gamma_W^{\mathrm{tot}} = 2079 \pm 41$ MeV which can be compared to the SM value, $2092.1 \pm 2.5$ MeV and the current world average, $2118 \pm 42$ MeV [15]. Alternatively, rather than using the measured value for $B(Z \to \ell^+\ell^-)$, we can use the SM value for $\Gamma(Z \to \ell^+\ell^-)$ and extract the ratio of total widths: $\Gamma_W^{\mathrm{tot}}/\Gamma_Z^{\mathrm{tot}} = 0.833 \pm 0.017$.

Finally, in the SM, the total width $\Gamma_W^{\mathrm{tot}}$ depends on electroweak parameters and certain CKM matrix elements, which we can constrain using $\Gamma_W^{\mathrm{tot}}$ [3]. Using world average values [15] for all CKM matrix elements except $|V_{cs}|$, we derive $|V_{cs}| = 0.967 \pm 0.030$.

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