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The standard model (SM) [2] invokes the Higgs mechanism of spontaneous symmetry breaking to generate mass for the $W$ and $Z$ bosons, which mediate the weak force. The $SU(2) \times U(1)$ symmetry of the electroweak interaction predicts the relation between the $W$ and $Z$ boson masses and the electromagnetic and weak gauge couplings. The prediction for the $W$ boson mass $M_W$ in terms of the precisely measured $Z$ boson mass $M_Z$, the Fermi decay constant $G_F$ extracted from the muon lifetime measurement, and the electromagnetic coupling $\alpha$ at the scale $M_Z$, is given in the “on-shell” scheme by [3]

$$M_W^2 = \frac{\hbar^3}{c} \frac{\pi \alpha}{\sqrt{2} G_F} \frac{1}{(1 - c_W^2)(1 - \Delta r)} , \quad (1)$$

where $c_W = M_W/M_Z$ and $\Delta r$ is the quantum-loop correction. A precise measurement of $M_W$ provides a measurement of $\Delta r$. In the SM the contributions to $\Delta r$ are dominated by the top quark and the Higgs boson loops, such that $M_W$ in conjunction with the top quark mass constrains the mass $m_H$ of the undiscovered Higgs boson. An $m_H$ constraint inconsistent with direct searches can indicate the presence of new physics, such as contribu-
tions to $\Delta r$ from supersymmetric particles [4].

The $W$ boson mass [3] has been measured most precisely by the LEP [5, 6] and Tevatron [7] experiments, with the world-average $M_W = (80392 \pm 29)$ MeV/$c^2$ [6]. At the Tevatron, $W$ bosons are mainly produced in quark ($q'$) anti-quark ($\bar{q}$) annihilation $q'\bar{q} \rightarrow W + X$. Here $X$ includes the QCD radiation that forms the "hadronic recoil" balancing the boson's transverse momentum $p_T$ [8]. The $W \rightarrow \ell \nu$ decays, characterized by a high-$p_T$ charged lepton ($\ell = e$ or $\mu$) and neutrino, can be selected with high purity and provide precise mass information.

This analysis [9, 10] uses 200 pb$^{-1}$ collected by the CDF II detector [9] in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Tevatron. CDF II is a magnetic spectrometer surrounded by calorimeters and muon detectors. We use the central drift chamber (COT) [11], the central calorimeter [12] with embedded wire chambers [13] at the electromagnetic (EM) shower maximum, and the muon detectors [14] for identification of muons and electrons with $|\eta| < 1$ [8] and measurement of their four-momenta. The muon (electron) trigger requires a COT track with $p_T > 18(9)$ GeV/$c$ [8], and matching muon chamber hits (EM calorimeter cluster with $E_T > 18$ GeV).

In the analysis, we select muons with a COT track matched to muon chamber hits and passing quality requirements, track $p_T > 30$ GeV/$c$, and a minimum- ionization signal in the calorimeter. Cosmic rays are rejected using COT hit timing [15]. We select electrons with track $p_T > 18$ GeV/$c$, EM cluster $E_T > 30$ GeV [8, 9], and passing quality requirements on the COT track and the track-cluster matching. Additional requirements are based on the ratio of the calorimeter energy $E$ to track momentum $p$ ($E/p < 2$), the ratio of energies detected in the hadronic and EM calorimeters $E_{\text{Had}}/E_{\text{EM}} < 0.1$, and the transverse shower profile [9]. A veto on the presence of a second lepton suppresses $Z$ boson background, with negligible loss of $W$ boson events. Control samples of $Z$ boson events require two oppositely charged leptons with the above criteria.

The $\vec{p}_T$ of the hadronic recoil ($\vec{u}$) is computed as the vector sum $\vec{u} = \Sigma_i E_i \sin(\theta_i) \hat{n}_i / c$ over calorimeter towers [12], with energy $E_i$, polar angle $\theta_i$, and transverse directions specified by unit vectors $\hat{n}_i$. Energy associated with the charged lepton(s) is not included. We impose $\vec{p}_T$ balance to infer the neutrino’s transverse momentum $\vec{p}_\nu \equiv | - \vec{p}_T \cdot \vec{u} |$ [8] and the $W$ transverse mass $m_T = \sqrt{2 (p_T^2 + p_T^\nu - \vec{p}_T \cdot \vec{p}_\nu) / c}$. We require $p_T > 30$ GeV/$c$ and $|\vec{u}| < 15$ GeV/$c$ to obtain a $W$ candidate sample of high purity, whose $m_T$ and lepton $p_T$ distributions are strongly correlated with the $W$ boson mass. Our final sample consists of 63964 $W \rightarrow e\nu$ candidates and 51128 $W \rightarrow \mu\nu$ candidates.

The $W$ boson mass is extracted by performing binned maximum likelihood fits to the distributions of $m_T$, $p_T$ and $p_T^\nu$. We generate 800 templates as functions of $M_W$ between 80 GeV/$c^2$ and 81 GeV/$c^2$ using a custom Monte Carlo (MC) simulation [9] of $W$ boson production and decay, and of the detector response to the charged lepton and hadronic recoil. The custom MC optimizes computing speed and control of systematic uncertainties. The kinematics of $W$ and $Z$ boson decays are obtained from the RESBOS [16] program. RESBOS calculates the differential production cross section $\frac{d^5 \sigma}{dq dq_T dq_T^\nu dq_T^\nu dq_T^\nu dq_T^\nu dq_T^\nu}$, where $Q$, $y$, and $q_T$ are the boson invariant mass, rapidity, and $p_T$ respectively, and $dq_T$ is the solid angle element in the decay lepton direction. The non-perturbative form factor which describes the $q_T$ spectrum at low $q_T$ is tuned on the dilepton $p_T$ distributions in the $Z$ boson data. Single photons (FSR) radiated from the final-state leptons are generated according to the WGRAD program [17]. The FSR photon energies are increased by 10% (with an absolute uncertainty of 5%) to account for additional energy loss due to two-photon radiation [18]. WGRAD is also used to estimate the uncertainty due to QED radiation from the initial state (ISR) and interference between ISR and FSR. We use the CTEQ6M [19] set of parton distribution functions and their uncertainties.

The custom MC performs a hit-level simulation of the lepton track. A fine-grained model of passive material properties is used to calculate ionization and radiative energy loss and multiple Coulomb scattering. Bremsstrahlung photons and conversion electrons are generated and propagated to the calorimeter. COT hits are generated according to the resolution ($\approx 150 \mu$m) and efficiencies measured from muon tracks in $\Upsilon, W$, and $Z$ boson decays. A helix fit (with optional beam constraint) is performed to simulate the reconstructed track.

The alignment of the COT is performed using a high-purity sample of high-$p_T$ cosmic ray muons. Each muon’s complete trajectory is fit to a single helix [15]. The fits determine the relative locations of the sense wires, including gravitational and electrostatic displacements, with a precision of a few microns. We constrain remaining misalignments, which cause a bias in the track curvature, by comparing $\langle E/p \rangle$ for electrons and positrons.

The tracker momentum scale is measured by template-fitting the $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass peaks. The $J/\psi$ fits are performed in bins of $\langle 1/p_T^\mu(\mu) \rangle$ to measure any non-linearity due to mismodelling of the ionization energy loss and other smaller effects, and in bins of $\langle \cot \theta(\mu) \rangle$ to measure the magnetic field non-uniformity. To account for the observed momentum non-linearity, a 6% correction to the predicted ionization energy loss is applied to make the measured $J/\psi$ mass independent of $\langle 1/p_T^\mu(\mu) \rangle$. Applying the calibration derived from the $J/\psi$ and $\Upsilon$ data to the $Z \rightarrow \mu\mu$ data, we measure $M_Z = (91184 \pm 43_{\text{stat}})$ MeV/$c^2$ (Fig. 1), consistent with the world average [3, 6] of $(91188 \pm 2)$ MeV/$c^2$. The systematic uncertainties due to QED radiative corrections and magnetic field non-uniformity dominate the total uncertainty of 0.02% on the combined momentum scale, derived from the $J/\psi$, $\Upsilon$ and $Z$ boson mass fits.

We simulate the electron cluster by merging the energies of the primary electron and the proximate bremsstrahlung photons and conversion electrons. The
inclusive electron sample. The distribution of the constant term \(1\) applied only to the energies of bremsstrahlung photons \(E/pc\) is sensitive to the number of radiation lengths \(\eta\). The resolution of \(\vec{u}\) has jet-like and underlying event components, with the latter modelled using data triggered on inelastic \(p\bar{p}\) interactions. The recoil parameterizations are tuned on the mean and r.m.s. of the \(p_T\) imbalance between the dilepton \(p_T\) and \(\vec{u}\) in \(Z \rightarrow \ell\ell\) events. The lepton identification efficiency is measured as a function of \(u_\parallel = \vec{u} \cdot \vec{p}_T/p_T\) using the \(Z \rightarrow \ell\ell\) data, in order to model its effect on the \(p_T^\ell\) and \(p_T^{\ell\ell}\) distributions. Cross-checks of the recoil model using the W boson data show good agreement (Fig. 3).

Backgrounds in the W boson candidate samples arise from misidentified jets containing high-\(p_T\) tracks and EM clusters, \(Z \rightarrow \ell\ell\) where one of the leptons is not reconstructed and mimics a neutrino, \(W \rightarrow \tau\nu\), and \(\tau\nu\) decays in flight (DIF), and cosmic rays (the latter two in the muon channel only). Jet, DIF, and cosmic ray backgrounds are estimated from the data to be less than 0.5% combined. The \(W \rightarrow \tau\nu\) background is 0.9% (0.24%), and the \(Z \rightarrow \ell\ell\) background is 6.6% (0.24%) in the muon (electron) channel, as estimated using a detailed GEANT-

![FIG. 2: The distribution of \(E/pc\) for the \(W \rightarrow e\nu\) data (points) and the best-fit simulation (histogram) including the small jet background (shaded). The arrows indicate the fitting range used for the electron energy calibration.](image)

![FIG. 3: Left: The \(u_\parallel\) distribution for the electron channel data (points) and simulation (histogram). Right: The \(|\vec{u}|\) distribution for the muon channel. The mean and r.m.s. of the histograms agree between data and simulation, within the statistical precisions of \(\approx 1\%\).](image)
and hidden by adding an unknown offset in the range [-100, 100] MeV/c² until the analysis was finalized. The systematic uncertainties (Table II) were evaluated by fitting MC events to propagate the previously discussed analysis parameter uncertainties to $M_W$.

The consistency of the fit results (Table I) obtained from the different distributions shows that the $W$ boson production, decay, and the hadronic recoil are well-modeled. The statistical correlations (evaluated using ensembles of MC events) between the $m_T$ and $p_T^f$ ($p_T^{f*}$) fit values is 69% (68%), and between the $p_T^f$ and $p_T^{f*}$ fit values is 27%. We combine (using the BLUE method) the six $W$ boson mass fits including all correlations to obtain $M_W = (80413 \pm 34_{\text{stat}} \pm 34_{\text{syst}})$ MeV/c², with $\chi^2$/dof = 4.8/5. The $m_T$, $p_T^f$ and $p_T^{f*}$ fits contribute weights of 80%, 12% and 8% respectively. The muon (electron) channel alone yields $M_W = (80352 \pm 60)$ MeV/c² ($M_W = (80477 \pm 62)$ MeV/c²) with $\chi^2$/dof = 1.4/2 (0.8/2). The $m_T$ ($p_T^f$, $p_T^{f*}$) fit results from the muon and electron channels are consistent with a probability of 7% (18%, 43%), taking into account their correlations.

In conclusion, we report the first measurement of the $W$ boson mass from Run II of the Tevatron, using 200 pb⁻¹ and the muon and electron decay channels. We measure $M_W = (80413 \pm 48)$ MeV/c², the most precise single measurement to date, and we update the world average [6] to $M_W = (80398 \pm 25)$ MeV/c². This analysis significantly improves in precision over previous Tevatron measurements, not only through the increased integrated luminosity but also through improved analysis techniques and understanding of systematic uncertainties. As many simulation parameters are constrained by data control samples, their uncertainties are statistical in nature and are expected to be reduced with more data. Inclusion of our result in the global electroweak fit [9] reduces the predicted mass of the SM Higgs boson by 6 GeV/c² and decreases its range to $m_H = 76_{-24}^{+33}$ GeV/c².

Table I shows the fit results from the $m_T$ (Fig. 4), $p_T^f$, and $p_T^{f*}$ distributions. These fits are partially uncorrelated and have different systematic uncertainties, thus providing an important cross-check. The fit values were hidden by adding an unknown offset in the range [-100, 100] MeV/c² until the analysis was finalized. The systematic uncertainties (Table II) were evaluated by fitting MC events to propagate the previously discussed analysis parameter uncertainties to $M_W$.

The fit values were correlated. The last row shows the combined statistical and systematic uncertainty.
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[1] With visitors from aUniversity of Athens, 15784 Athens, Greece, bUniversity of Bristol, Bristol BS8 1TL, United Kingdom, cUniversity Libre de Bruxelles, B-1050 Brussels, Belgium, dCornell University, Ithaca, NY 14853, eUniversity of Cyprus, Nicosia CY-1678, Cyprus, fUniversity College Dublin, Dublin 4, Ireland, gUniversity of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, hUniversity of Heidelberg, D-69120 Heidelberg, Germany, iUniversidad Iberoamericana, Mexico D.F., jUniversity of Manchester, Manchester M13 9PL, England, kNagasaki Institute of Applied Science, Nagasaki, Japan, lUniversity of Oviedo, E-33007 Oviedo, Spain, mUniversity of London, Queen Mary College, London, E1 4NS, England, nUniversity of California Santa Cruz, Santa Cruz, CA 95064, oTexas Tech University, Lubbock, TX 79409, pUniversity of California, Irvine, Irvine, CA 92697, qIFIC(CSIC-Universitat de València), 46071 Valencia, Spain.


[8] CDF uses a cylindrical coordinate system in which θ (ϕ) is the polar (azimuthal) angle, r is the radius from the nominal beamline, and z points along the proton beam and is zero at the center of the detector. The pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$. Energy (momentum) transverse to the beam is denoted as $E_T (p_T)$.


[21] The underlying event refers to the spectator parton and additional inelastic $p+p$ interactions that produce low $p_T$ particles roughly uniformly in phase space.