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First Measurement of the W Boson Mass
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We present a measurement of the $W$ boson mass using 200 pb$^{-1}$ of data collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV by the CDF II detector at Run II of the Fermilab Tevatron. With a sample of 63964 $W\rightarrow e\nu$ candidates and 51128 $W\rightarrow \mu\nu$ candidates, we measure $M_W = (80413 \pm 34_{\text{stat}} \pm 34_{\text{syst}} = 80413 \pm 48)$ MeV/c$^2$. This is the most precise single measurement of the $W$ boson mass to date.

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ions 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 $W \rightarrow ℓν$ decays, characterized by a high-$p_T$ charged lepton ($ℓ = e$ or $µ$) 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 detector [14] for identification of muons and electrons with $|η| < 1$ [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 $E_{Had}/E_{EM} < 0.1$, 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 $\vec{u} = Σ_i E_i sin(θ_i)\vec{n}_i/c$ over calorimeter towers [12], with energy $E_i$, polar angle $θ_i$, and transverse directions specified by unit vectors $\vec{n}_i$. Energy associated with the charged lepton(s) is not included. We impose $\vec{p}_T$ balance to infer the neutrino’s transverse momentum $p'_\nu ≡ |\vec{p}_\nu − \vec{u}|$ [8] and the W transverse mass $m_{W_T} = \sqrt{2(\vec{p}_T^2 + p'_\nu^2 − \vec{u}^2)/c}$. We require $p'_\nu > 30$ GeV/$c$ and $|\vec{u}| < 15$ GeV/$c$ to obtain a $W$ candidate sample of high purity, whose $m_{W_T}$ and lepton $p_T$ distributions are strongly correlated with the $W$ boson mass. Our final sample consists of 63964 $W \rightarrow ℓν$ candidates and 51128 $W \rightarrow ℓν$ candidates.

The W boson mass is extracted by performing binned maximum likelihood fits to the distributions of $m_{W_T}$, $p_T^2$ and $p'_\nu$. 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 $d^4σ/dQ dy dq_T dz dτ$, where $Q, y$, and $q_T$ are the boson invariant mass, rapidity, and $p_T$ respectively, and $dz$ 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 ($≈ 150$ $\mu$m) and efficiencies measured from muon tracks in $γ, W$, 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 $⟨E/pc⟩$ for electrons and positrons.

The tracker momentum scale is measured by template-fitting the $J/ψ \rightarrow ℓℓ$ and $γ \rightarrow ℓℓ$ mass peaks. The $J/ψ$ fits are performed in bins of $1/p_T^2(μ)$ to measure any non-linearity due to mismodelling of the ionization energy loss and other smaller effects, and in bins of $⟨cot θ(μ)⟩$ 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 $J/ψ$ mass independent of $1/p_T^2(μ)$. Applying the calibration derived from the $J/ψ$ and $γ$ data to the $Z \rightarrow ℓℓ$ data, we measure $M_Z = (91184 ± 43_{stat})$ MeV/$c^2$ (Fig. 1), consistent with the world average [3, 6] of $(91188 ± 2)$ 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 $J/ψ, γ$ 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
distributions of electron and photon energy loss in the solenoid coil, and leakage into the hadronic calorimeter, are determined using GEANT [20] as a function of $E_T$. The fractional energy resolution is given by the quadratic sum of a sampling term (13.5%/$/sqrt{E_T/\text{GeV}}$) and a constant term $\kappa = (0.89 \pm 0.15)$% applied to the cluster energy, and an additional constant term $\kappa_\gamma = (8.3 \pm 2.2)$% applied only to the energies of bremsstrahlung photons and conversion electrons. The $\kappa_\gamma$ term contributes $\approx 1.3$% in quadrature to the effective constant term for the inclusive electron sample. The distribution of the underlying event energy [21] in the cluster is simulated. We tune $\kappa$ on the width of the $E/pc$ peak (Fig. 2) of the $W$ boson sample, and $\kappa_\gamma$ on the width of the $Z \rightarrow ee$ mass peak when both electrons are radiative ($E/pc > 1.06$).

Given the tracker momentum calibration, we fit the $E/pc$ peak in bins of electron $E_T$ to determine the electron energy scale and non-linearity. The position of the $E/pc$ peak is sensitive to the number of radiation lengths $x_0$ ($\approx 19$%), due to bremsstrahlung upstream of the COT. We constrain $x_0$ by comparing the fraction of electrons with high $E/pc$ between data and simulation. Applying the $E/pc$-based energy calibration, we fit the $Z \rightarrow ee$ mass peak and measure $M_Z = (91190 \pm 67_{\text{stat}})$ MeV/c$^2$ (Fig. 1), consistent with the world average [3, 6]. For maximum precision, the energy scales from the $E/pc$ fit and the $Z \rightarrow ee$ mass fit are combined using the Best Linear Unbiased Estimate (BLUE) method [22], with a resulting uncertainty that is predominantly statistical.

The recoil $\vec{u}$ excludes towers in which the lepton(s) deposit energy. The underlying event energy in these towers is measured from the nearby towers in $W$ boson data, including its dependence on $\eta$ and $\vec{u}$. 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 $\vec{p}_T$ and $\vec{u}$ in $Z \rightarrow \ell\ell$ events. The lepton identification efficiency is measured as a function of $u_{||} = \vec{u} \cdot \vec{p}_T/\vec{p}_T$ using the $Z \rightarrow \ell\ell$ data, in order to model its effect on the $p_T$ and $p_T^\ell$ 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, $W \rightarrow \tau\nu$, kaon and pion decays in flight (DIF), and cosmic rays (the latter two in the monochannel 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% (0.9%), and the $Z \rightarrow \ell\ell$ background is 6.6% (0.24%) in the muon (electron) channel, as estimated using a detailed GEANT-
and $p_{T}(\nu)$, providing an important cross-check. The fit values were
binned near 65 GeV/$c$ for the $p_{T}^{\ell}$ and $p_{T}^{\mu}$ fits. The $\chi^{2}$ of the fit is computed using the expected statistical errors on the data points.

Table I shows the fit results from the $m_{T}$ (Fig. 4), $p_{T}^{\ell}$, and $p_{T}^{\mu}$ 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/$c^2$ 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 $p_{T}^{\ell}$ ($p_{T}^{\mu}$) fit values is 69% (68%), and between the $p_{T}^{\ell}$ and $p_{T}^{\mu}$ 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/$c^2$, with $\chi^{2}/\text{dof} = 4.8/5$. The $m_{T}$, $p_{T}^{\ell}$ and $p_{T}^{\mu}$ fits contribute weights of 80%, 12% and 8% respectively. The muon (electron) channel alone yields $M_{W} = (80352 \pm 60)$ MeV/$c^2$ ($M_{W} = (80477 \pm 62)$ MeV/$c^2$) with $\chi^{2}/\text{dof} = 1.4/2$ (0.8/2). The $m_{T}$ ($p_{T}^{\ell}$, $p_{T}^{\mu}$) 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/$c^2$, the most precise single measurement to date, and we update the world average [6] to $M_{W} = (80398 \pm 25)$ MeV/$c^2$. 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/$c^2$ and decreases its range to $m_{H} = 76^{+33}_{-24}$ GeV/$c^2$.

### Table I: Fit results and uncertainties for $M_{W}$.

| Distribution | $W$ boson mass (MeV/$c^2$) | $\chi^{2}$/\text{dof} |
|--------------|-----------------------------|-------------------------|
| $m_{T}(e, \nu)$ | $80493 \pm 48_{\text{stat}} \pm 39_{\text{syst}}$ | 86/48 |
| $p_{T}^{\ell}(e)$ | $80451 \pm 58_{\text{stat}} \pm 45_{\text{syst}}$ | 63/62 |
| $p_{T}^{\mu}(e)$ | $80473 \pm 57_{\text{stat}} \pm 54_{\text{syst}}$ | 63/62 |
| $m_{T}(\mu, \nu)$ | $80349 \pm 54_{\text{stat}} \pm 27_{\text{syst}}$ | 59/48 |
| $p_{T}^{\ell}(\mu)$ | $80321 \pm 66_{\text{stat}} \pm 40_{\text{syst}}$ | 72/62 |
| $p_{T}^{\mu}(\mu)$ | $80396 \pm 66_{\text{stat}} \pm 46_{\text{syst}}$ | 44/62 |

Table II: Systematic uncertainties in MeV/$c^2$ for the $m_{T}$ fits, which are the most precise. The last column shows the correlated uncertainties. The last row shows the combined statistical and systematic uncertainty.

| Systematic | $W \rightarrow \ell \nu$ | $W \rightarrow \mu \nu$ | Common |
|------------|-------------------------|-------------------------|--------|
| $p_{T}(W)$ model | 3 | 3 | 3 |
| QED radiation | 11 | 12 | 11 |
| Parton distributions | 11 | 11 | 11 |
| Lepton energy scale | 30 | 17 | 17 |
| Lepton energy resolution | 9 | 3 | 0 |
| Recoil energy scale | 9 | 9 | 9 |
| Recoil energy resolution | 7 | 7 | 7 |
| $u_{||}$ efficiency | 3 | 1 | 0 |
| Lepton removal | 8 | 5 | 5 |
| Backgrounds | 8 | 9 | 0 |
| Total systematic | 39 | 27 | 26 |
| Total uncertainty | 62 | 60 | 26 |
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