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High-precision measurement of the W boson mass with the CDF II detector

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The mass of the W boson, a mediator of the weak force between elementary particles, is tightly constrained by the symmetries of the standard model of particle physics. We measure the W boson mass to be 80433.5 ± 9.4 MeV using data corresponding to 8.8 fb^{-1} of integrated luminosity collected in proton-antiproton collisions at $\sqrt{s}$ = 1.96 TeV with the CDF II detector at the Fermilab Tevatron collider. The measurement is in tension with the prediction of the standard model.

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[*] Speaker

1. Introduction

The masses of the electroweak bosons are key components of the standard model (SM) and provide remarkable sensitivity to new high-scale processes. At tree level the masses are predicted by the Higgs mechanism to be equal to the Higgs vacuum expectation value multiplied by a function of the electroweak couplings (for the W and Z bosons) or the Higgs self-coupling (for the Higgs boson). Loop corrections to the propagators introduce a dependence on all particle masses, with the most significant corrections involving the top quark. The difference in the masses of the top and bottom quarks leads to a difference in the W and Z loop corrections, while the lack of a gauge symmetry in the Higgs-fermion interactions leads to an untamed correction to the Higgs boson mass. If there is no new physics up to O(6 TeV), then the loop corrections must cancel the tree-level parameters at the percent level. At higher scales this cancellation becomes even more unnatural, motivating new physics at the TeV scale.

The CDF Collaboration have measured the W boson mass (m_W) in $\sqrt{s} = 1.96$ TeV proton-antiproton collisions using data taken between 2003 and 2011 [1]. The data correspond to an integrated luminosity of 8.8 fb^{-1} and consist of 4.2 million W boson candidates. The W bosons are identified using their decays to $e\nu$ and $\mu\nu$ and the mass is measured by fitting template distributions of transverse momentum and mass[1]. The transverse mass is defined as $m_T = \sqrt{2p_T^\ell p_T^\nu(1 - \cos\Delta\phi)}$, where p_T^ℓ is the charged-lepton transverse momentum, $\Delta\phi$ is the azimuthal angle between the charged lepton and neutrino, and the neutrino transverse momentum $\vec{p}_T^{\,\nu}$ is inferred by vectorially summing $\vec{p}_T^{\,\ell}$ and the net transverse momentum $\vec{u}_T$ of the particles balancing the W boson momentum, $\vec{p}_T^{\,\nu} = -(\vec{p}_T^{\,\ell} + \vec{u}_T)$. The measured transverse mass distribution has a kinematic edge at m_W, with some spread due to the W boson width and the detector resolution. A 100 MeV shift in m_W changes the number of events with m_T below the edge by 2‰ relative to those above the edge.

The mass measurement requires high-precision calibrations of the scale and resolution of $\vec{p}_T^{\,\ell}$ and $\vec{u}_T$. The calibrations use a custom detector simulation based on a GEANT [2] model with adjustable parameters tuned using events from resonances or well-constrained kinematic distributions. Prior to the calibrations a detailed reconstruction and correction procedure is applied to the data in order to achieve an approximately uniform response and resolution throughout the detector. The calibrations are validated using independent samples and distributions.

2. Lepton momentum calibrations

The lepton calibrations are performed in two steps: first the charged track momentum measured with the central outer tracker (COT) is calibrated by matching the known resonant masses of the J/ψ and Υ mesons, and of the Z boson, using their decays to muons; next the electromagnetic calorimeter is calibrated by translating the calibrated track momentum to the calorimeter using the measured ratio of calorimeter energy to track momentum in W and Z boson decays to electrons.

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[1] The CDF cylindrical coordinate system has the z axis along the beam line in the proton direction. The polar and azimuthal angles are θ and ϕ, respectively. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

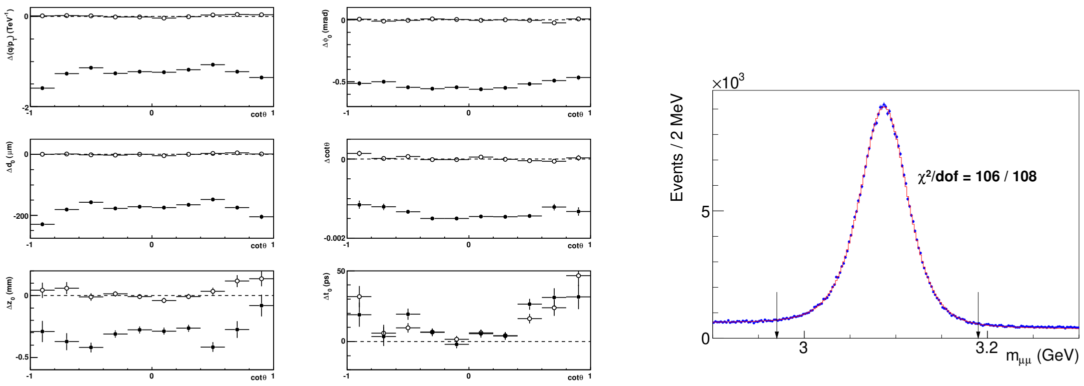

Figure 1: Left: The difference in the track parameters between incoming and outgoing reconstructed tracks from a cosmic-ray muon, as a function of $\cot\theta$ [3]. The track parameters are the charge divided by p_T (top left), the impact parameter in the transverse direction d_0 (middle left), the impact parameter in the longitudinal direction z_0 (bottom left), ϕ (top right), $\cot\theta$ (middle right), and the time (bottom right) of the track at the closest point to the beam line. The closed (open) circles show the differences before (after) the cosmic-ray-based alignment. Right: The $J/\psi \to \mu\mu$ mass peak for mean muon $p_T \approx 5$ GeV.

2.1 Charged track calibration

The calibration of charged tracks consists of the alignment [3] of the COT for the track reconstruction followed by a global correction to the momentum scale of the tracks. The global correction is first performed using the decays of J/ψ and Υ mesons and then validated using decays of the Z boson. The final calibrated momentum consists of a statistical combination of all three resonances.

COT alignment

The COT consists of two large endplates with sense wires strung between them. The endplates extend from 40-130 cm in the radial direction from the beam line, with a length of 310 cm along the beamline, where the nominal collision point is at the center. The wires are strung in eight radial 'superlayers' consisting of individual cells in the azimuthal direction, where each cell consists of twelve sense wires. Altogether each endplate consists of 2520 cells.

The first step of the alignment procedure is to fix the position and tilt angle of each cell in each endplate. A correction relative to the nominal position at construction is obtained using cosmic-ray tracks passing through the COT in-time with a beam crossing, but with no other reconstructed tracks. Over the nine-year running period a sufficient number of cosmic rays were collected to provide $O(1\mu\text{m})$ statistical precision on the cell positions. Additional corrections are applied to the wire positions between the endplates due to electrostatic and gravitational forces on the sense wires and the neighbouring field-inducing plates. These corrections are obtained using differences in the measured track parameters of incoming and outgoing cosmic-ray muons. Representative distributions of these differences are shown in Fig. 1. The alignment procedure removes significant biases from the measured tracks and improves the measurement resolution.

Calibration from J/ψ and Υ meson decays

A large sample of J/ψ decays to muons is used for an initial calibration of the overall track momentum scale. The production of J/ψ mesons is modelled using the PYTHIA event generatorwith an additional boost applied to match the longitudinal and transverse momentum distributions observed in data. The matching of these distributions, along with the sum of the measured track curvatures of the two measured muons, facilitates the resolution modelling of the J/ψ resonance. Another important feature of the resonance peak is the asymmetry due to final-state photon radiation, which reduces the observed dimuon mass relative to the pole mass. The radiation is modelled with a next-to-leading order form factor, and Fig. 1 shows that the resulting model describes the observed distribution in a representative range of mean inverse p_T of the two muons.

An important additional calibration is provided by a sample of Υ meson decays to muons. The prompt decay of the Υ meson allows the track momentum measurement to include a constraint at the interaction point, significantly improving the resolution. A high-precision comparison of the measured Υ mass using tracks with and without this constraint demonstrates that it does not bias the momentum scale.

Z boson mass and calibration

As a test of the charged-track calibration, the mass of the Z boson is measured in the dimuon final state. Procedurally the measurement consisted of freezing the calibration procedure and removing a random blinding offset in the range [-50,50] MeV. The result is a measured mass consistent with that of the Large Electron-Positron collider (91187.6 ± 2.3 MeV), specifically $m_Z = 91192.0 \pm 7.5$ MeV. Given this consistency, the Z boson mass measurement is combined with the measurements of the meson masses to provide a charged-track calibration for the W boson mass measurement with a relative precision of 0.002%.

2.2 Calorimeter energy calibration

The first step of the calorimeter energy calibration is a set of local energy corrections to improve the uniformity of the detector response, and thus the resolution. The next step is the transfer of the charged-track calibration to the calorimeter using electrons from W and Z boson decays. After setting the calorimeter energy scale using the ratio of calorimeter energy E to track momentum p, the Z boson mass is measured in the same manner as for the dimuon decay channel. The final calorimeter energy calibration combines the E/p and Z boson mass calibrations.

E/p calibration

The uniformity of the calorimeter energy measurement is achieved through a coarse correction to remove variations in the mean E/p of electrons from W boson decays as a function of time and position with a single calorimeter tower (the calorimeter is split in the azimuthal and longitudinal directions into ’towers’ of scintillator and absorber material). More precise tower-to-tower corrections are applied using a fit to the measured E/p distribution as a function of electron pseudorapidity. The data are modelled with a simulation that includes small corrections to the amount of material upstream and downstream of the calorimeter, where the energy loss in these regions is modelled with a parameterized model based on GEANT. The calibration also includes a small scale correction to the primary electron as a function of its energy.

After the uniformity corrections are applied to the data and the material and energy-dependent corrections are applied to the simulation, the overall calorimeter energy scale is determined from a fit to the E/p distribution of electrons from W and Z boson decays. The relative uncertainty on the energy scale is 0.007%, including the uncertainty on the charged-track momentum.

2.2.1 Z boson mass and calibration

The Z boson mass is measured in its decay to electron pairs with the calorimeter energy calibrated using E/p. The same procedure was used as for the measurement in the muon decay channel, with the same blinding offset. The measured mass of $m_Z = 91194.3 \pm 15.8$ MeV is again consistent with the more precise measurement from the Large Electron-Positron collider, albeit with lower statistical precision due to dead regions between calorimeter towers.

3. Recoil momentum calibration

The calibration of the recoil momentum consists of four steps: corrections to the calorimeter alignment to achieve uniform response in the azimuthal direction; the reconstruction of the recoil vector using calorimeter towers not traversed by the charged lepton; the calibration of the overall recoil momentum scale; and finally the calibration of the recoil resolution. The calibration is performed using Z boson decays to electrons and muons, and is validated using the leptonic decays of the W boson.

The central calorimeter consists of two tower wedges extending in the longitudinal direction and meeting at the nominal interaction point. If the calorimeter wedges are not centered on the beam pipe there is a non-uniform response and a mismeasured angle of each energy deposit, if uncorrected. The calorimeter position is thus adjusted to remove a nonuniform azimuthal energy distribution observed in minimum-bias data (which only requires energy deposits in the detector).

The recoil vector is reconstructed by summing the momentum vector of each energy deposit in the calorimeter, except for deposits in the vicinity of a charged lepton. In order to model the recoil particles in this region a distribution of recoil momentum is obtained from particles in an equivalent region rotated by 90 degress from the charged lepton in candidate W boson events. The model is tested by comparing data to simulation in a region rotated 180 degrees from the charged lepton.

Given the corrected data and the procedure for reconstructing the recoil vector, the calorimeter response is calibrated in the simulation by balancing the recoil momentum against the charged-lepton momentum from Z boson decays. The response function is $\approx 50\%$ of the boson p_T at low p_T and $\approx 70\%$ at the highest p_T relevant to the measurement (≈ 30 GeV).

The final step of the calibration is the modelling of the recoil resolution. Multiple phenomena contribute to the resolution and are included in the parameterized model: jet-like energy and angular resolution; dijets at low boson p_T; the underlying event from the breakup of the proton and antiproton; and the additional interactions from the bunch crossing ("pileup"). The values of the model parameters are obtained using Z boson decays by fitting recoil resolution projections along or perpendicular to the direction of the boson p_T.

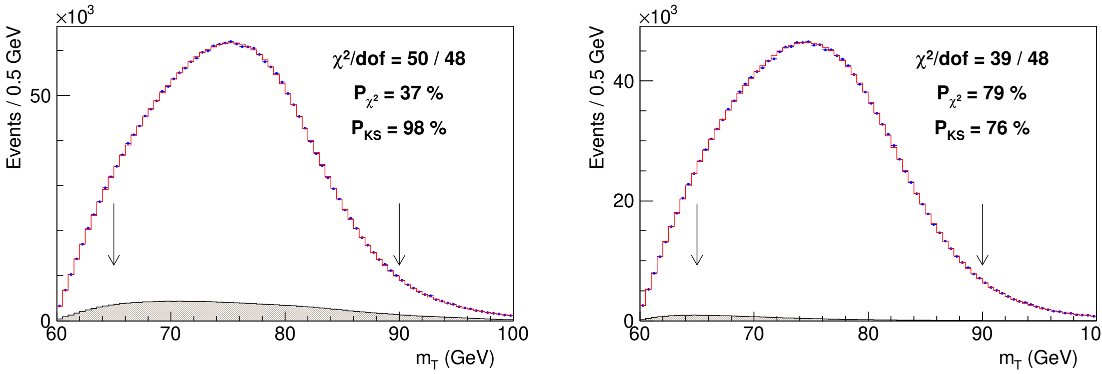

Figure 2: The transverse mass distribution fit to the W boson mass in the muon (left) and electron (right) channels. The shaded region indicates the background processes and the arrows indicate the fit region.

Distribution	$W \to \mu\nu$	$W \to e\nu$
m_T	$80446.1 \pm 9.2_{\text{stat}} \pm 7.2_{\text{sys}}$ MeV	$80429.1 \pm 10.3_{\text{stat}} \pm 8.5_{\text{sys}}$ MeV
p_T^ℓ	$80428.2 \pm 9.6_{\text{stat}} \pm 10.3_{\text{sys}}$ MeV	$80411.4 \pm 10.7_{\text{stat}} \pm 11.8_{\text{sys}}$ MeV
p_T^ν	$80428.9 \pm 13.1_{\text{stat}} \pm 10.9_{\text{sys}}$ MeV	$80426.3 \pm 14.5_{\text{stat}} \pm 11.7_{\text{sys}}$ MeV

Table 1: The values of the W boson mass determined from fits to the distributions.

The most direct test of the recoil model is the projection of the recoil along the direction of the charged lepton in $W \to \ell\nu$ events. A bias in the mean of this distribution is expected to give an equivalent bias in m_W. The mean is observed to be modelled to an accuracy of ≈ 4 MeV.

4. Results

Following the detailed precise calibrations of the charged-lepton and recoil momenta, the background processes are estimated and a binned likelihood fit is performed on the m_T (Fig. 2), p_T^ℓ, and p_T^ν distributions in the electron and muon channels. Prior to freezing the analysis procedures the fit values included a random offset drawn from a flat distribution between -50 and 50 MeV. The unblinded fit results shown in Table 1 are consistent with each other within uncertainties, and yield a combined W boson mass of 80433.5 ± 9.4 MeV. The result is the first determination of the W boson mass to precision better than 10 MeV, from either a single experiment or a combination, and is 0.1% higher than the SM prediction with a high significance on the difference.

References

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