Combination of CDF and D0 W-Boson mass measurements

Combination of CDF and D0 *W*-Boson mass measurements

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We summarize and combine direct measurements of the mass of the W boson in $\sqrt{s} = 1.96$ TeV proton-antiproton collision data collected by CDF and D0 experiments at the Fermilab Tevatron Collider. Earlier measurements from CDF and D0 are combined with the two latest, more precise measurements: a CDF measurement in the electron and muon channels using data corresponding to 2.2 fb^{-1} of integrated

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luminosity, and a D0 measurement in the electron channel using data corresponding to 4.3 fb^{-1} of integrated luminosity. The resulting Tevatron average for the mass of the W boson is $M_W = 80387 \pm 16$ MeV. Including measurements obtained in electron-positron collisions at LEP yields the most precise value of $M_W = 80385 \pm 15$ MeV.

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I. INTRODUCTION

In the standard model (SM), quantum corrections to the mass of the W boson (M_W) are dominated by contributions dependent on the mass of the top quark (m_t), the mass of the Higgs boson (M_H), the mass of the Z boson (M_Z), and the fine-structure constant α. A precise measurement of M_W and m_t thus constrains M_H, once M_Z and α are known. Comparing this constraint with the mass of the Higgs boson recently discovered at the LHC [1] is a critical test of its nature and the consistency of the SM. Details of the experimental methods used in measurements of M_W are discussed in Ref. [2]. Prior to the combination reported here, the uncertainty on the world average M_W was 23 MeV [3,4]. Direct measurements of m_t at the Fermilab Tevatron collider have a combined uncertainty of 0.94 GeV [5], and the uncertainty on M_W would have to be 6 MeV [6] to provide equally constraining information on M_H. The experimental precision on the measured M_W is therefore currently the limiting factor on the constraints.

The CDF and D0 experiments at the Fermilab Tevatron proton-antiproton collider reported several direct measurements of the natural width [7] and mass [8–18] of the W boson, using the $e\nu_e$ and $\mu\nu_\mu$ decay modes of the W boson. Measurements of M_W have been reported by CDF with data sets collected during 1988–1989 [8], 1992–1993 [9], 1994–1995 [10], and 2001–2004 [11] and by D0 using data taken during 1992–1995 [12–15] and 2002–2006 [16].

This article describes a combination of M_W measurements including recent measurements from CDF using the 2002–2007 data set [17] and D0 using the 2006–2009 data set [18] denoted below as CDF (2012) and D0 (2012), respectively. The recent CDF (2012) measurement supersedes the previous measurement [11], which was based on an integrated luminosity of 200 pb^{-1} and was used in previous combinations [3,19]. The combination takes into account the statistical and systematic uncertainties as well as correlations among systematic uncertainties and supersedes the previous combinations [3,19,20]. All the combinations presented in this article are done using the best linear unbiased estimator (BLUE) method [21], which prescribes the construction of a covariance matrix from partially correlated measurements.

II. *W*-BOSON MASS MEASUREMENT STRATEGY AT THE TEVATRON

At the Tevatron, W bosons are primarily produced in quark-antiquark annihilation, $q\overline{q}' \rightarrow W + X$, where X can include QCD radiation, such as initial-state gluon

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radiation, that results in measurable hadronic-recoil energy. The W-boson mass is measured using low-background samples of $W \to \ell\nu_\ell$ decays ($\ell = e$, μ at CDF and $\ell = e$ at D0) that are reconstructed using the CDF [22] and D0 [23] detectors. The mass is determined using three kinematic variables measured in the plane perpendicular to the beam direction: the transverse momentum of the charged lepton (p_T^ℓ), the transverse momentum of the neutrino (p_T^ν), and the transverse mass $m_T^\ell = \sqrt{2p_T^\ell p_T^\nu(1 - \cos\Delta\phi)}$, where $\Delta\phi$ is the opening angle between the lepton and neutrino momenta in the plane transverse to the beam. The magnitude and direction of p_T^ν is inferred from the vector of the missing transverse energy $\not{E}_T^\ell$ [24]. The W-boson mass is extracted from maximum-likelihood fits to the binned distributions of the observed p_T^ℓ, $\not{E}_T^\ell$, and m_T^ℓ values using a parametrized simulation of these distributions as a function of M_W. These simulations depend on the kinematic distributions of the W-boson decay products and also on detector effects that are constrained using theoretical calculations and control samples. The kinematic distributions are determined by several effects including the W-boson transverse momentum $p_T(W)$ and the parton distribution functions (PDFs) of the interacting protons and antiprotons. Major detector effects include energy response to leptons, hadronic recoil, the response to QED radiation, and multiple-interaction pileup, together with calorimeter acceptance effects and lepton-identification efficiencies. The detailed simulations developed at CDF and D0 enable the study of these effects to better than 1 part in 10^4 precision on the observed value of M_W.

In the CDF (2012) and D0 (2012) measurements, the kinematic properties of W-boson production and decay are simulated using RESBOS [25], which is a next-to-leading order generator that includes next-to-next-to-leading logarithm resummation of soft gluons at low boson p_T [26]. The momenta of interacting partons in RESBOS are calculated as fractions of the colliding (anti)proton momenta using the CTEQ6.6 [27] PDFs. The radiation of photons from final-state leptons is simulated using PHOTOS [28].

III. CDF (2012) AND D0 (2012) MEASUREMENTS

A. CDF measurement

The CDF (2012) measurement uses data corresponding to an integrated luminosity of 2.2 fb^{-1}, collected between 2002 and 2007. Both the muon ($W \to \mu\nu_\mu$) and electron ($W \to e\nu_e$) channels are considered. Decays of J/ψ and Υ mesons into muon pairs are reconstructed in a central tracking system to establish the absolute momentum scale. A measurement of the Z-boson mass (M_Z) in $Z \to \mu\mu$ decays is performed as a consistency check. This measurement, which uses the tracking detector, yields $M_Z = 91180 \pm 12(\text{stat}) \pm 10(\text{syst})$ MeV, consistent with the world average mass of 91188 ± 2 MeV [29], and is therefore also used as an additional constraint on the momentum scale. The electromagnetic calorimeter energy scale and nonlinearity are determined by fitting the peak of the E/p distribution of electrons from $W \to e\nu$ and $Z \to ee$ decays, where E is the energy measured in the calorimeter and p is the momentum of the associated charged particle. The lower tail of the E/p distribution is used to determine the amount of material in the tracking detector. The Z-boson mass measured in $Z \to ee$ decays is used as a consistency check and to constrain the energy scale. The value of $M_Z = 91230 \pm 30(\text{stat}) \pm 14(\text{syst})$ MeV from the calorimetric measurement is also consistent with the world average.

The CDF (2012) measurement of M_W is obtained from the combination of six observables: p_T^μ, $\not{E}_T^\mu$, m_T^μ, p_T^e, $\not{E}_T^e$ and m_T^e. The combined result is $M_W = 80387 \pm 12(\text{stat}) \pm 15(\text{syst})$ MeV. Table I summarizes the sources of uncertainty in the CDF measurement.

B. D0 measurement

The D0 (2012) measurement uses data corresponding to 4.3 fb^{-1} of integrated luminosity recorded between 2006 and 2009. D0 calibrates the calorimeter energy scale using $Z \to ee$ decays. Corrections for energy lost in uninstrumented regions are based on a comparison between the shower-development profiles from data and from a detailed GEANT-based simulation [30] of the D0 detector. The world average value for M_Z [29] is used to determine the absolute energy scale of the calorimeter, which is thereafter used to correct the measurement of the electron energy from the W-boson decay. This M_W measurement is therefore equivalent to a measurement of the ratio of W- and Z-boson masses. This calibration method eliminates many systematic uncertainties common to the W- and Z-boson mass measurements, but its precision is limited by the size of the available Z-boson data set.

The results obtained with the two most sensitive observables m_T^e and p_T^e are combined to determine the W-boson mass of $M_W = 80367 \pm 13(\text{stat}) \pm 22(\text{syst})$ MeV. A summary of the uncertainties is presented in Table II.

TABLE I. Uncertainties of the CDF (2012) M_W measurement determined from the combination of the six measurements.

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal from recoil	2
Backgrounds	3
Experimental subtotal	10
Parton distribution functions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson event yield	12
Total uncertainty	19

TABLE II. Uncertainties of the D0 (2012) M_W measurement determined from the combination of the two most sensitive observables m_T^e and p_T^e.

Source	Uncertainty (MeV)
Electron energy calibration	16
Electron resolution model	2
Electron shower modeling	4
Electron energy loss model	4
Recoil energy scale and resolution	5
Electron efficiencies	2
Backgrounds	2
Experimental subtotal	18
Parton distribution functions	11
QED radiation	7
$p_T(W)$ model	2
Production subtotal	13
Total systematic uncertainty	22
W-boson event yield	13
Total uncertainty	26

This D0 (2012) measurement is combined with a previous D0 measurement [16] corresponding to an integrated luminosity of 1.0 fb^{-1}, which uses data recorded between 2002 and 2006, to yield $M_W = 80375 \pm 11(\mathrm{stat}) \pm 20(\mathrm{syst})$ MeV.

IV. COMBINATION WITH PREVIOUS TEVATRON MEASUREMENTS

The CDF measurements from Ref. [8] (1988–1989) and Ref. [9] (1992–1993) were made using superseded PDF sets and have been corrected [19] using recent PDF sets. The previous results are also adjusted to use the same combination technique (the BLUE method) as in later combinations. The templates for fitting M_W assume the Breit-Wigner running-width scheme propagator, $1/(\hat{s} - M_W^2 + i\hat{s}\Gamma_W/M_W)$, which makes the value of M_W determined by the fit dependent on Γ_W. Here, $\hat{s}$ is the square of the center-of-mass energy in the parton reference frame and Γ_W is the total width of the W boson. Different measurements have used different values of Γ_W, yielding a shift in measured values of the W-boson mass [19], $\Delta M_W = -(0.15 \pm 0.05)\Delta\Gamma_W$, where $\Delta\Gamma_W$ is the difference between the value of Γ_W predicted by the SM, $\Gamma_W = 2092.2 \pm 1.5$ MeV [31], and that used in a particular analysis. The prediction of Γ_W assumes $M_W = 80385 \pm 15$ MeV, which is a preliminary world-average combination result [32] of this article. The impact of the corrections on the final M_W combination reported in this article is found to be less than 0.2 MeV. Table III summarizes all inputs to the combination and the corrections made to ensure consistency across measurements.

V. CORRELATIONS IN THE CDF AND D0 M_W MEASUREMENTS

The increased statistical power of CDF (2012) and D0 (2012) M_W measurements necessitates a more detailed treatment of the systematic uncertainties due to the W-boson production and decay model that are independent of the data-sample size. We assume that for each uncertainty category, the smallest uncertainty across measurements is fully correlated while excesses above that level are generally assumed to be due to uncorrelated differences between measurements. One exception corresponds to the two D0 measurements that use very similar models and are treated as fully correlated [16,18].

The experimental systematic uncertainties of the D0 measurement are dominated by the uncertainty in the

TABLE III. The input data used in the M_W combination. All entries are in units of MeV.

	CDF [8]	CDF [9]	CDF [10]	D0 [12–15]	D0 [16]	CDF [17]	D0 [18]
	(1988–1989)	(1992–1993)	(1994–1995)	(1992–1995)	(2002–2006)	(2002–2007)	(2006–2009)
	4.4 pb^{-1}	18.2 pb^{-1}	84 pb^{-1}	95 pb^{-1}	1.0 fb^{-1}	2.2 fb^{-1}	4.3 fb^{-1}
Mass and width							
M_W	79 910	80 410	80 470	80 483	80 400	80 387	80 367
Γ_W	2 100	2 064	2 096	2 062	2 099	2 094	2 100
M_W uncertainties							
PDF	60	50	15	8	10	10	11
Radiative corrections	10	20	5	12	7	4	7
Γ_W	0.5	1.4	0.3	1.5	0.4	0.2	0.5
Total	390	181	89	84	43	19	26
M_W corrections							
$\Delta\Gamma_W$	+1.2	−4.2	+0.6	−4.5	+1.1	+0.3	+1.2
PDF	+20	−25	0	0	0	0	0
Fit method	−3.5	−3.5	−0.1	0	0	0	0
Total	+17.7	−32.7	+0.5	−4.5	+1.1	+0.3	+1.2
M_W corrected	79 927.7	80 377.3	80 470.5	80 478.5	80 401.8	80 387.3	80 368.6

TABLE IV. Relative weights of the contributions to the combined Tevatron measurement of M_W.

Measurement	Relative weight in %
CDF [8]	0.1
CDF [9]	0.5
CDF [10]	1.9
D0 [12–15]	2.8
D0 [16]	7.9
CDF [17]	60.3
D0 [18]	26.5

energy scale for electrons and are nearly purely of statistical origin, as they are derived from the limited sample of $Z \to ee$ decays. CDF uses independent data from the central tracker to set the muon and electron energy scales. Thus, we assume no correlations between the experimental uncertainties of CDF and D0, or between independent measurements by either experiment.

Three sources of systematic uncertainty due to modeling of the production and decay of W and Z bosons are assumed to be at least partially correlated across all Tevatron measurements: (1) the choice of PDF sets, (2) the assumed Γ_W value, and (3) the electroweak radiative corrections.

A. PDF sets

Both experiments use the CTEQ6.6 [27] PDF set in their W-boson production model. D0 uses the CTEQ6.1 [33] uncertainty set to estimate the PDF uncertainties, while CDF uses MSTW2008 [34] and checks consistency with the CTEQ6.6 uncertainty set. Since these PDF sets are similar and rely on common inputs, the uncertainties introduced by PDFs in the recent measurements are assumed to be correlated and treated using the prescription for partial correlations described above.

B. Assumed Γ_W value

We assume that the small uncertainty due to Γ_W is fully correlated across all measurements.

C. QED radiative corrections

Current estimates of the uncertainties due to electroweak radiative corrections include a significant statistical component due to the size of the simulated data sets used in the uncertainty-propagation studies. The PHOTOS [28] radiative correction model is used in the recent measurements with consistency checks from W(Z)GRAD [35] and HORACE [36]. These studies yield model differences consistent within statistical uncertainties. We assume that uncertainties from purely theoretical sources, totaling 3.5 MeV, are correlated while remaining uncertainties, partially dependent on detector geometry, are uncorrelated.

VI. COMBINATION OF TEVATRON M_W MEASUREMENTS

The measurements of M_W obtained at Tevatron experiments included in this combination are given in Table III and include both the latest measurements [17,18] discussed above, but exclude the superseded 0.2 fb^{-1} CDF measurement [11]. Table IV shows the relative weight of each measurement in the combination. The combined value of the W-boson mass obtained from measurements performed at Tevatron experiments is

$$M_W = 80387 \pm 16 \text{ MeV}. \quad (1)$$

The χ^2 for the combination is 4.2 for 6 degrees of freedom, with a probability of 64%. The global correlation matrix for the seven measurements is shown in Table V.

VII. WORLD AVERAGE

We also combine the Tevatron measurements with the value $M_W = 80376 \pm 33$ MeV determined from $e^+e^- \to W^+W^-$ production at LEP [29]. Assuming no correlations, this yields the currently most precise value of the W boson mass of

$$M_W = 80385 \pm 15 \text{ MeV}. \quad (2)$$

The combination of the seven statistically independent Tevatron measurements and the LEP measurement yields a χ^2 of 4.3 for 7 degrees of freedom with a probability of 74%. Figure 1 shows the individual measurements and the most recent combined world average of M_W.

VIII. SUMMARY

The latest high-precision measurements of M_W performed at the CDF and D0 experiments, combined with

TABLE V. Correlation coefficients among measurements.

	CDF [8]	CDF [9]	CDF [10]	D0 [12–15]	D0 [16]	CDF [17]	D0 [18]
CDF [8]	1	0.002	0.003	0.002	0.007	0.015	0.011
CDF [9]		1	0.007	0.005	0.014	0.033	0.024
CDF [10]			1	0.009	0.029	0.066	0.049
D0 [12–15]				1	0.019	0.044	0.032
D0 [16]					1	0.137	0.137
CDF [17]						1	0.230
D0 [18]							1

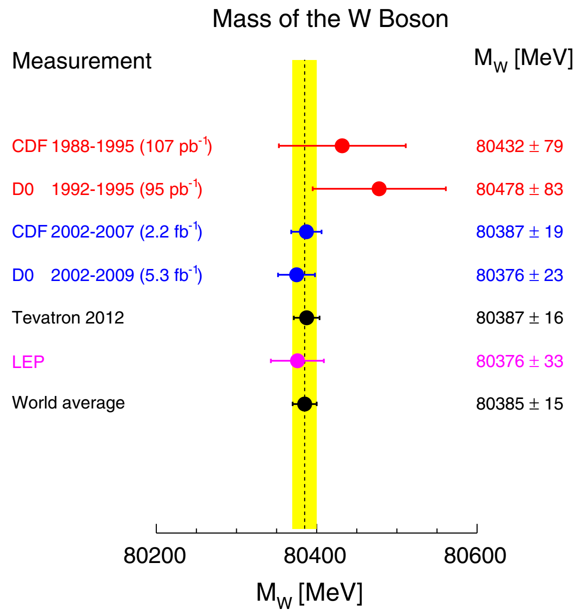

FIG. 1 (color online). W-boson mass determinations from the CDF and D0 Run I (1989 to 1996) and Run II (2001 to 2009) measurements, the new Tevatron average, the LEP combined result [29], and the world average obtained by combining the Tevatron and LEP averages assuming no correlations between them. The world-average uncertainty (15 MeV) is indicated by the shaded band.

previous measurements by the Tevatron experiments, improve the uncertainty on the combined Tevatron M_W value to 16 MeV. The combination of this measurement with the LEP average for M_W further reduces the uncertainty to 15 MeV. The substantial improvement in the experimental precision on M_W leads to tightened indirect constraints on the mass of the SM Higgs boson. The direct measurements of the mass of the Higgs boson at the LHC [1] agree, at the level of 1.3 standard deviations, with these tightened indirect constraints [37]. This remarkable success of the standard model is also shown in Fig. 2, which includes the new world average W-boson mass, the Tevatron average top-quark mass measurement [5], and shows consistency among these with the calculation of M_W [6], assuming Higgs-boson mass determinations from the ATLAS and CMS experiments [1].

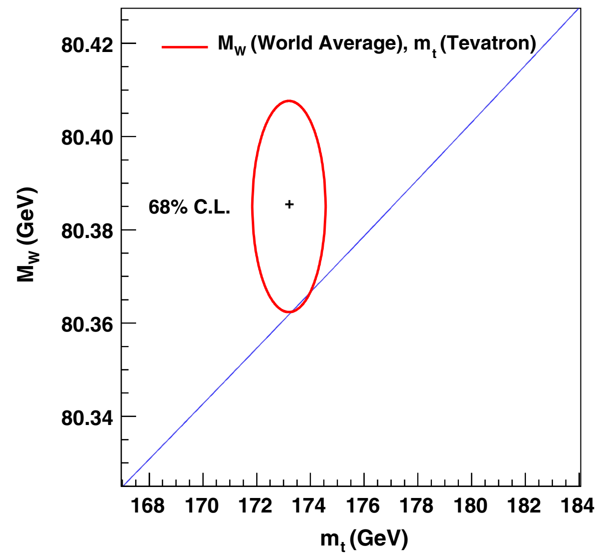

FIG. 2 (color online). The most recent world average of M_W is displayed along with the mass of the top quark m_t [5] at 68% C.L. by area. The diagonal line is the indirect prediction of M_W as a function of m_t, in the SM given by Ref. [6], assuming the measurements of the ATLAS and CMS [1] experiments of the candidate Higgs-boson masses of 126.0 GeV and 125.3 GeV respectively.

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