

## $W$ mass and width measurements at the Tevatron

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**Summary.** — Most recent results of  $W$  boson mass and width measurements performed by CDF and D0 are reported at the center-of-mass energy of 1.96 TeV. Integrated luminosity ranges from  $0.2 \text{ fb}^{-1}$  to  $1.0 \text{ fb}^{-1}$  depending on the analysis.

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### 1. – Introduction

Measurement of the  $W$  boson mass ( $M_W$ ) provides us with a uniquely powerful key to uncovering the origin of the electroweak symmetry breaking and learning about new physics. A precision measurement of  $M_W$  is one of the highest priorities for the Tevatron experiments.  $M_W$  measurement combined with precise measurement of the top quark mass ( $M_{\text{top}}$ ) constrains the mass of the Higgs boson.

On the other hand, the width of the  $W$  boson ( $\Gamma_W$ ) is expected to be insensitive to new physics. Therefore its precise measurement is very important for improving the experimental knowledge of the Standard Model. Currently CDF [1] and D0 [2] provide most precise direct measurements of both  $M_W$  [3, 4] and  $\Gamma_W$  [5, 6]. For these measurements CDF uses both electron and muon decay channels of the  $W$ , while D0 uses only electron channel.

### 2. – Identification of electrons and muons

Electrons are identified as an electromagnetic (EM) cluster reconstructed with a simple cone algorithm. To reduce the background of jets faking electrons, electron candidates are required to have a large fraction of their energy deposited in the EM section of the calorimeter and pass energy isolation and shower shape requirements. Electron candidates are classified as *tight* if a track is matched spatially to EM cluster and if the track transverse momentum is close to the transverse energy of the EM cluster. In CDF electrons are reconstructed both in the central calorimeter and plug calorimeter ( $|\eta| < 2.8$ ) while electrons in D0 are reconstructed in the central and endcap calorimeters ( $|\eta| < 1.05$ ).

and  $1.5 < |\eta| < 3.2$ ). Here  $\eta = -\ln \tan(\theta/2)$ , and  $\theta$  is the polar angle with respect to the proton direction. Both CDF and D0 require *tight* electrons in the central calorimeter ( $|\eta| < 1.05$ ) for  $W \rightarrow e\nu$  candidates. Electron energies are measured with the calorimeter, while electron direction is measured with tracking detectors, using tracks that are matched to electron cluster in the calorimeter.

Muons are identified by a track in the muon system matched to a track in the central tracking system. Measurements include the muons reconstructed in the central muon extension sub-detector which extends the coverage from  $|\eta| < 0.6$  to  $|\eta| < 1$ .

### 3. – W mass

$M_W$  is measured using three transverse kinematic variables: the transverse mass  $m_T = \sqrt{2p_T^{e,\mu} p_T^\nu (1 - \cos \Delta\phi)}$ , the lepton ( $p_T^{e,\mu}$ ) and neutrino ( $p_T^\nu$ ) transverse momentum distributions, where  $\Delta\phi$  is the opening angle between the electron(muon) and neutrino momenta in the plane transverse to the beam. Neutrino transverse momentum ( $p_T^\nu$ ) is inferred from the imbalance of transverse energy. We also call it missing  $E_T$  (MET).

A sophisticated parametrized fast Monte Carlo simulation is used for modeling these variables as a function of  $M_W$ . Fast simulation includes models of electron, recoil system, and backgrounds. Electron efficiencies, resolution and energy scale parameterizations are tuned to  $Z \rightarrow ee$  data. Recoil system represents energy deposited in the calorimeter from all sources except the electron(s). Recoil system consists of three major components: hard recoil (particles that collectively balance the  $p_T$  of the W or Z boson), underlying event, and additional interactions. Contribution from the third component depends on the instantaneous luminosity. Hard recoil is modeled using full detector simulation, while the other two components are described by real data events. Full recoil model is tuned to  $Z \rightarrow ee$  data, using imbalance between Z boson momentum measured with electrons and with recoil system. Sources of backgrounds to  $W \rightarrow e\nu$  events include  $W \rightarrow \tau\nu \rightarrow e\nu\nu$ , QCD, and  $Z \rightarrow ee$  processes.

$M_W$  is extracted from a binned maximum-likelihood fit between the data and simulation.  $\Gamma_W$  is measured with  $m_T$  variable using the same analysis framework as  $M_W$ . Figure 1 shows a comparison between data and fast simulation. It also shows final  $M_W$  results from D0 and CDF along with other  $M_W$  measurements and combinations. D0 result agrees with the world average and the individual measurements and is more precise than any other  $M_W$  measurement from a single measurement. Figure 2 shows comparison between data and fast simulation for CDF  $M_W$  measurement.

Dominant uncertainties in  $M_W$  measurements come from lepton energy scale measurements. At first-order fractional error on the lepton energy scale translates to fractional error on the W mass [8].

D0 determines electron energy scale using high- $p_T$  electrons from  $Z \rightarrow ee$  decays. Precision of such calibration is limited mostly by the size of the  $Z \rightarrow ee$  sample.

CDF relies on tracking detector for both electron and muon energy scale calibration. First tracking detector is calibrated using  $J/\psi \rightarrow \mu\mu$  events.  $J/\psi$  invariant mass is measured as a function of muon momentum. Figure 3 shows the correction needed to make measured  $J/\psi$  mass to be at its PDG value (overall offset) and independent of muon momentum (slope). This correction was implemented in the simulation by adjusting the energy-loss model. Then tracker calibration is transported to the calorimeter using  $W \rightarrow e\nu$  electrons near the peak of the  $E/p$  distribution, shown also in fig. 3. Tables I and II show uncertainties for  $M_W$  measurements by D0 and CDF, respectively.

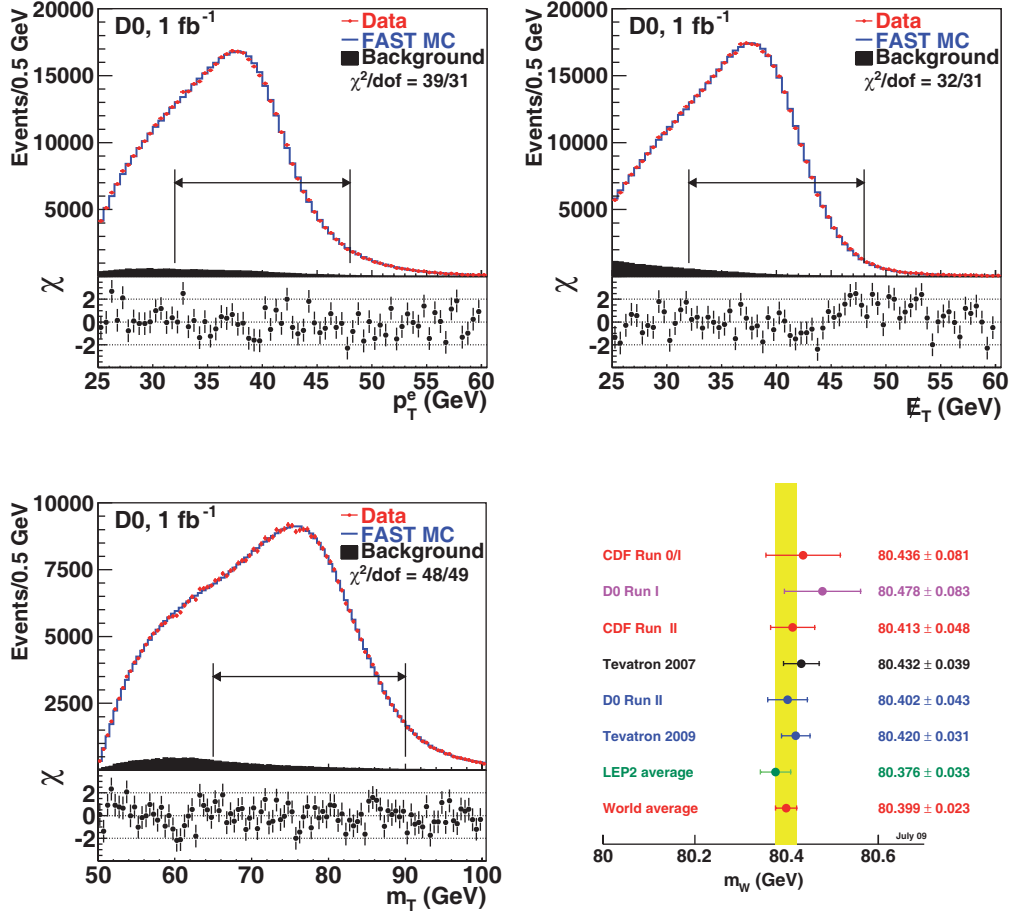


Fig. 1. – Top left, top right, and bottom left show electron  $p_T$ ,  $m_T$ , and MET distributions in  $W \rightarrow e\nu$  data and fast simulation (FASTMC). Added background is shown as well. Signed  $\chi$  distributions are shown in the bottom part of each plot. Signed  $\chi$  is defined as  $\chi_i = [N_i - (\text{FASTMC}_i)]/\sigma_i$  for each point in the distribution,  $N_i$  is the data yield in bin  $i$  and  $\sigma_i$  is the statistical uncertainty in bin  $i$ . Bottom right: summary of the measurements of the  $W$  boson mass and their average. The result from the Tevatron corresponds to the values which include corrections to the same  $W$  boson width and PDFs. The LEP II results are from [7]. An estimate of the world average of the Tevatron and LEP results is made assuming no correlations between the Tevatron and LEP uncertainties.

#### 4. – $W$ width

Although  $M_W$  and  $\Gamma_W$  measurements are performed with the same method and both rely on  $m_T$  distribution, they are mostly sensitive to different features of the latter.  $M_W$  is mostly sensitive to the position of the Jacobian peak.  $\Gamma_W$  is mostly sensitive to the tail of the  $m_T$  distribution. At first order  $\Gamma_W$  is proportional to the fraction of events in the tail. Fit for  $\Gamma_W$  is performed in the high  $m_T$  tail region (90–200 GeV for both CDF and D0). This region is sensitive to the Breit-Wigner lineshape and less sensitive to the detector resolution.

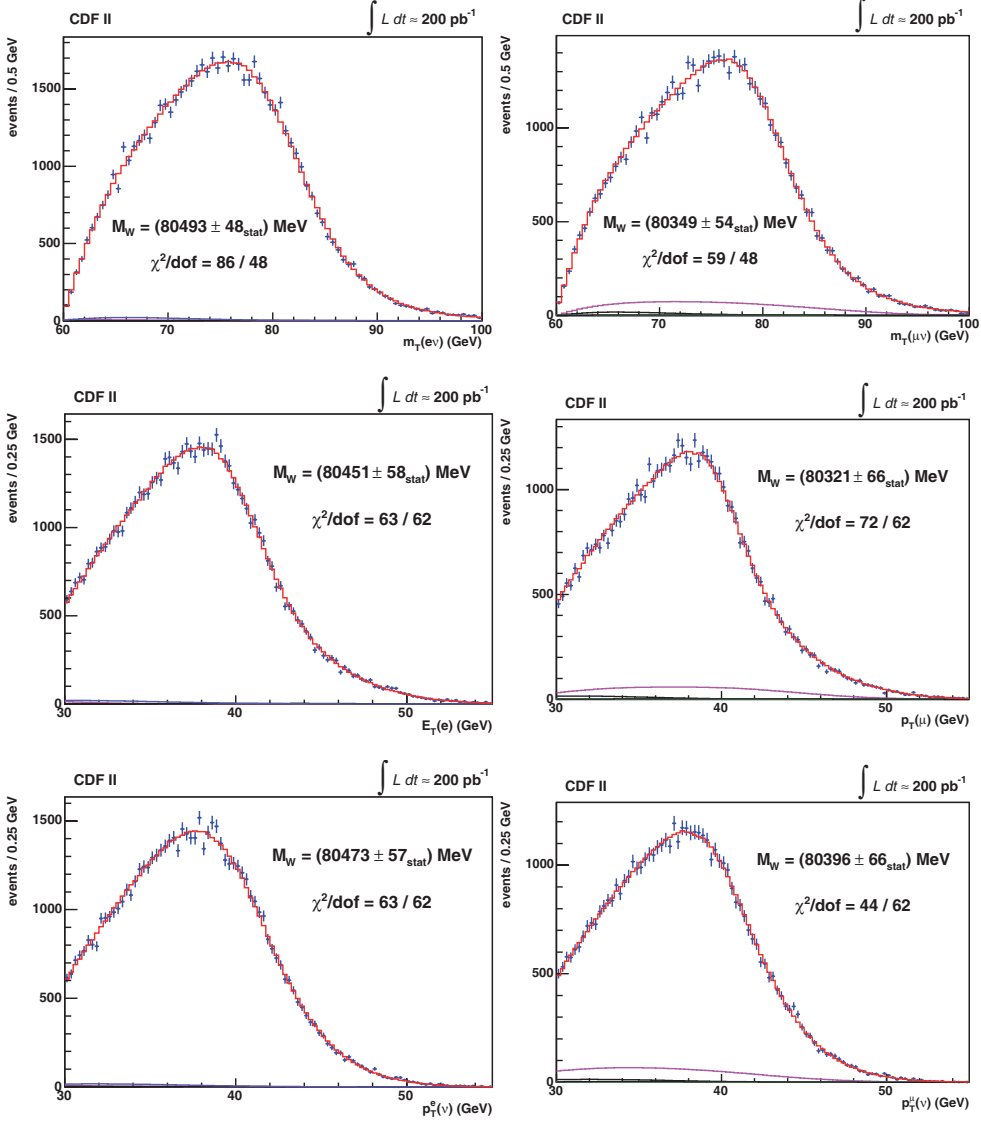


Fig. 2. – (Colour on-line) Distributions of  $M_W$  observables in CDF measurement. Blue—data. Red—fast simulation. Fit results and statistical errors are indicated. Left column: electron channel. Right column: muon channel. Top row:  $m_T$ . Middle row: charged lepton  $p_T$ . Bottom row: neutrino  $p_T$ .

Figure 4 shows  $m_T$  distributions from CDF and D0 as well as final results compared with other measurements and combinations. D0 result is  $\Gamma_W = 2.028 \pm 0.039(\text{stat}) \pm 0.061(\text{syst}) = 2.028 \pm 0.072 \text{ GeV}$ . CDF result is  $\Gamma_W = 2.032 \pm 0.045(\text{stat}) \pm 0.057(\text{syst}) = 2.032 \pm 0.073 \text{ GeV}$ . Combined Tevatron average is  $\Gamma_W = 2.046 \pm 0.049 \text{ GeV}$  [9]. Tables III and IV give the detailed breakdown of uncertainties for  $\Gamma_W$  measurements at D0 and CDF.

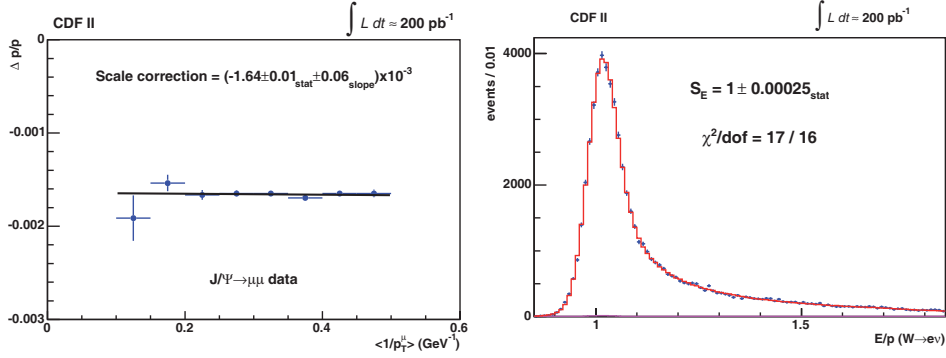


Fig. 3. – Left: fractional muon momentum correction as a function of inverse momentum. Right: ratio of electron energy measured in the calorimeter to electron momentum measured by the tracking system in  $W \rightarrow e\nu$  events.

TABLE I. – *Uncertainties of  $D0 M_W$  measurement (MeV).*

Source	$m_T$	$p_T^e$	$\cancel{E}_T$
Experimental			
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron energy offset	4	6	7
Electron energy loss model	4	4	4
Recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental subtotal	35	37	41
Production model			
PDF	10	11	11
QED	7	7	9
Boson $p_T$	2	5	2
Production model subtotal	12	14	14
Statistical	23	27	23
Total	37	40	43

TABLE II. – *Uncertainties of CDF  $M_W$  measurement (MeV).*

Source	$m_T$	$p_T^e$	$\cancel{E}_T$
	$e, \mu, \text{common}$	$e, \mu, \text{common}$	$e, \mu, \text{common}$
Lepton scale	30,17,17	30,17,17	30,17,17
Lepton resolution	9,3,0	9,3,0	9,5,0
Recoil scale	9,9,9	17,17,17	15,15,15
Recoil resolution	7,7,7	3,3,3	30,30,30
$U_{  }$ efficiency	3,1,0	5,6,0	16,30,0
Lepton removal	8,5,5	0,0,0	16,10,10
Backgrounds	8,9,0	9,19,0	7,11,0
$p_T(W)$	3,3,3	9,9,9	5,5,5
PDF	11,11,11	20,20,20	13,13,13
QED	11,12,11	13,13,13	9,10,9
Total systematic	39,27,26	45,40,35	54,46,42
Statistical	48,54,0	56,68,0	57,66,0
Total	62,60,26	73,77,35	79,80,42

TABLE III. – *Uncertainties of D0  $\Gamma_W$  measurement (MeV).*

Source	$\Delta\Gamma_W$ (MeV)
Electron energy scale	33
Electron resolution model	10
Recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson $p_T$	1
$M_W$	5
Total systematic	61
Statistical	39
Total	72

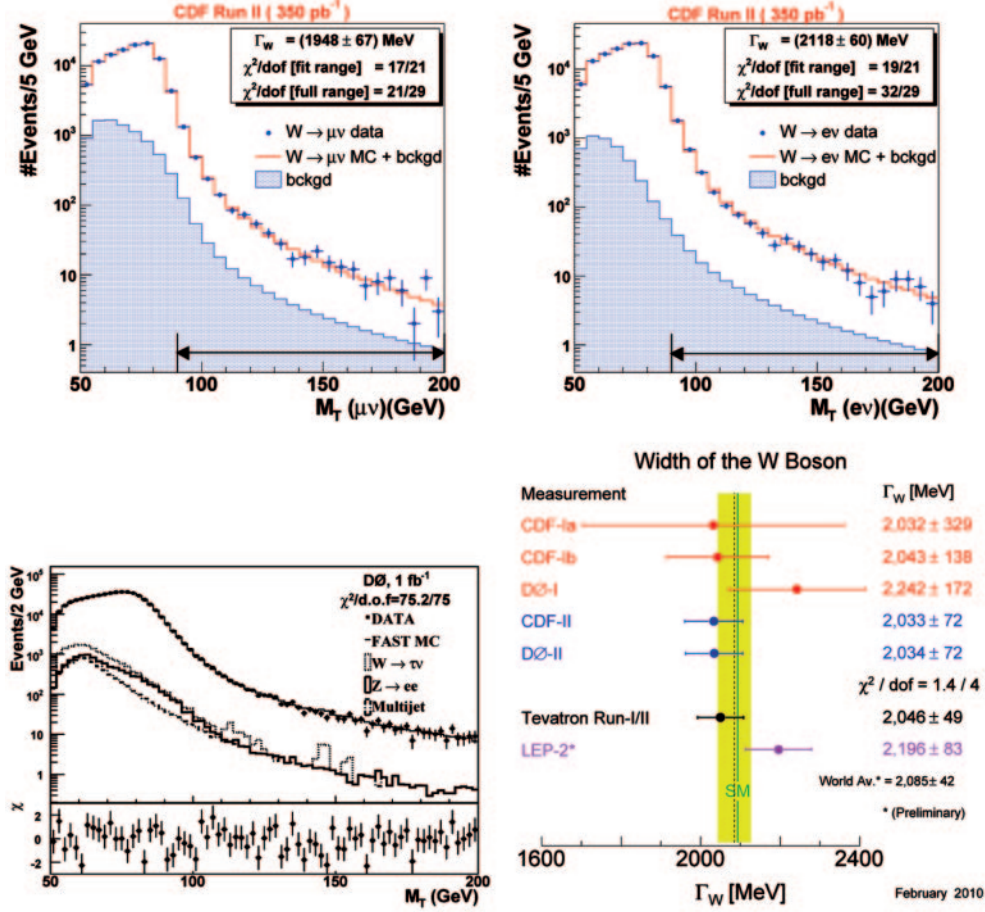


Fig. 4. – Top left, top right, and bottom left:  $M_T$  distributions for data and fast MC simulation with background added. Two top plots: CDF. Bottom left plot from D0 shows also signed  $\chi$  values for each bin (bottom part of the plot). Signed  $\chi$  is defined in the caption of fig. 1. D0 used fitted  $\Gamma_W$  value for the fast MC prediction rather than the PDG value. The distribution of the fast MC simulation with background added is normalized to the number of data events in the region  $50 < M_T < 100 \text{ GeV}$  (D0) and  $50 < M_T < 90 \text{ GeV}$  (CDF).

TABLE IV. – Uncertainties of CDF  $\Gamma_W$  measurement (MeV).

Source	$e$	$\mu$	common
Lepton scale	21	17	12
Lepton resolution	31	26	0
Simulation	13	0	0
Recoil	54	49	0
Lepton ID	10	7	0

TABLE IV. – *Continued.*

Source	$e$	$\mu$	common
Backgrounds	32	33	0
$p_T(W)$	7	7	7
PDF	20	20	20
QED	10	6	6
$M_W$	9	9	9
Total systematic	79	71	27
Statistical	60	67	0
Total	99	98	27

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