MEASURING THE W BOSON MASS AT THE TEVATRON

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For the D0 and CDF Collaborations

The measurement of the mass of the W boson is one of the prime goals of the Tevatron experiments. In this contribution, a review is given of the most recent determinations of the W boson mass (m_W) at the Tevatron. The combined Tevatron result, $m_W = 80.420 \pm 0.031$ GeV, is now more precise than the combined LEP result, leading to a world average value of $m_W = 80.399 \pm 0.023$ GeV.

1 Introduction

The mass of the W boson (m_W) is a key parameter in the electroweak model. It is connected to other parameters of the model through the following equation:

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}\left(\frac{1}{1-\Delta r}\right), \tag{1}$$

with m_Z the mass of the Z boson, α the fine-structure constant and G_F the Fermi coupling constant. The term Δr describes higher-order corrections which depend quadratically on the top quark mass and logarithmically on the Higgs boson mass. Precise measurements of the top quark mass and the W boson mass can thus provide a prediction for the mass of the undiscovered Higgs boson. For the top quark mass and the W boson mass to have equal weight in this prediction, the W boson mass has to be determined very precisely: $\Delta m_W \approx 0.006 \cdot \Delta m_{top}$. With $\Delta m_{top} = 1.1$ GeV [1], Δm_W would have to be 7 MeV.

The measurements of the W boson mass presented here were performed by the D0 and CDF experiments at the Tevatron, a p$\bar{\text{p}}$ collider at a centre-of-mass energy of 1.96 TeV. These results are based on an integrated luminosity of 1 fb^{-1} for D0 [2] and 200 pb^{-1} for CDF [3]. The total integrated luminosity delivered to each of the experiments is more than 9 fb^{-1}.

2 Measurement Strategy

In hadron collisions, only the W→eν and W→$\mu\nu$ decays can be used for precise mass measurements; hadronic W boson decays cannot be distinguished from the large multi-jet background and the W→$\tau\nu$ decays cannot be measured precisely enough. The experimental event signature is then rather simple: a lepton and a neutrino with large momentum transverse to the beam direction (p_T). The neutrino can be identified as missing transverse energy ($\not{E}_T$). The neutrino momentum in the direction of the colliding beams cannot be determined.

In the D0 analysis, both $p_T(\ell)$ and $\not{E}_T$ are required to be at least 25 GeV, in the CDF analysis the cut is at 30 GeV. The lepton has to be well identified in the barrel portion of the detector, $|\eta| < 1$ (η is the pseudorapidity). In addition, the transverse recoil momentum of the W boson (u_T) is required to be small, $u_T < 15$ GeV. Leptonic decays of the Z boson (Z$\to \ell\ell$) are selected in a similar fashion, and serve as a calibration sample. The D0 collaboration analyzes the electron channel only, whereas the CDF collaboration uses both electrons and muons.

The W boson mass is extracted from fits to distributions of kinematic quantities, simulated for a range of hypothetical W boson masses (template fits). The quantities considered are the transverse momentum of the lepton, the transverse momentum of the neutrino $p_T(\nu) = \not{E}_T$ with $\vec{p}_T(\nu) = -\vec{p}_T(\ell) - \vec{u}_T$, and the transverse mass of the lepton-neutrino system. The transverse mass is defined by $m_T^2 = 2p_T(\ell)p_T(\nu)(1 - \cos\Delta\phi_{\ell\nu})$, where $\Delta\phi_{\ell\nu}$ is the difference in azimuthal angle between the lepton and the neutrino.

To get a precise W boson mass measurement, the challenge is to accurately calibrate the measurable quantities, $p_T(\ell)$ and u_T, and to model the W boson production and the detector in a parameterized simulation. This simulation is then used to produce the fit templates.

2.1 Production

Production of W bosons is modeled with the RESBOS event generator and photon radiation is described with PHOTOS or WGRAD. Uncertainties in these theoretical models or the parameters used, and uncertainties on parton distribution functions (PDFs) lead to systematic uncertainties on the W boson mass. Both D0 and CDF estimate an uncertainty on the W boson mass of 10 MeV due to the PDF uncertainty, and 7 MeV (D0) to 11 MeV (CDF) due to photon radiation.

2.2 Lepton Momentum Calibration

The D0 measurement relies on a precise calorimeter calibration. The amount of energy that an electron loses in uninstrumented material is corrected for using a detailed GEANT simulation of the calorimeter, in combination with measured energy depositions in the four electromagnetic layers of the calorimeter, as a function of energy. This leads to energy and η dependent parameterizations of the response and resolution of the calorimeter. The electron momentum scale and offset are then set using a data sample of 18700 Z$\to$ e$^+$e$^-$ events and the world average value of the Z boson mass.

In the CDF analysis, the central tracking detector is used to calibrate the lepton momentum. The elements of the tracking detector are aligned with cosmic muons. A sample of 600000 J/$\psi \to \mu^+\mu^-$ decays is then used to determine the momentum scale. By doing this in bins of $1/p_T(\mu)$ and $\cot\theta_\mu$, the description of the material in the detector and of the non-uniformities in the magnetic field can be fine-tuned. The electron momentum scale is set by comparing the energy measurement in the calorimeter with the momentum measurement in the tracking detector.

Uncertainties on the lepton momentum scale are the dominant sources of systematic uncertainty on the W boson mass. For D0, a 34 MeV uncertainty is assigned. CDF assigns a 17 MeV uncertainty in the muon channel and 30 MeV in the electron channel. These uncertainties are largely of statistical nature and will decrease with larger calibration samples.

2.3 Recoil Momentum Calibration

The recoil $\vec{u}_T$ consists not only of a "hard" component due to the particles that are truly recoiling against the W boson, but also of "soft" components which cannot be distinguished from the hard component on an event-by-event basis. These are, e.g., contributions due to the

underlying event or additional hadron-hadron interactions. The hard and soft components of the recoil are modeled separately. A sample of Z boson decays is then used to fix the recoil momentum scale and resolution, using the imbalance between the transverse momentum of the Z boson (determined using the well-measured leptons) and the measured recoil momentum.

The magnitude of the systematic uncertainty on the W boson mass due to the recoil modeling strongly depends on which kinematic variable is used to fit for the W boson mass. For D0 (CDF), the uncertainties are 6 MeV (9 MeV) for the fit using the transverse mass, 12 MeV (17 MeV) for the fit with the lepton transverse momentum and 20 MeV (30 MeV) for the fit to the $\not{E}_{\mathrm{T}}$ spectrum.

3 Results

The CDF collaboration analyzed a data-set corresponding to an integrated luminosity of 200 pb^{-1}. In the muon (electron) channel, 51000 (64000) W boson candidates were identified. In Fig. 1, distributions of the transverse mass in the two channels are shown. The data points agree well with the expectation from the parameterized simulation, for the best-fit value of the W boson mass. A statistical combination, taking into account all correlations, of in total six measurements (electron and muon channel, using $p_{\mathrm{T}}(\ell)$, $\not{E}_{\mathrm{T}}$ or m_{T}) yields $m_{\mathrm{W}} = 80.413 \pm 0.034_{\mathrm{stat}} \pm 0.034_{\mathrm{syst}}$ GeV, corresponding to a total uncertainty of 48 MeV.

The results of the D0 analysis, based on a data-set corresponding to an integrated luminosity of 1 fb^{-1}, are shown in Fig. 2. Very good agreement is seen between the 500000 W boson candidates in data and the simulation. The three measurements of m_{W} are: $80.401 \pm 0.023_{\mathrm{stat}}$ GeV for the fit to the transverse mass, $80.400 \pm 0.027_{\mathrm{stat}}$ GeV for the lepton transverse momentum and $80.402 \pm 0.023_{\mathrm{stat}}$ GeV for the neutrino transverse momentum. Combining these three measurements, taking into account the strong correlations between them gives $m_{\mathrm{W}} = 80.401 \pm 0.021_{\mathrm{stat}} \pm 0.038_{\mathrm{syst}}$ GeV, or a total uncertainty of 43 MeV. This is the most precise single measurement of the W boson mass.

3.1 Combination

The two W boson mass measurements presented here are in excellent agreement with each other. These measurements and previous Tevatron measurements have been combined, taking into account correlated systematic uncertainties (due to parton distribution functions, photon radiation and the W boson width). The combination also corrects the measurements to the same value of the W boson width. The result, $m_{\mathrm{W}} = 80.420 \pm 0.031$ GeV, is in good agreement with the LEP combined measurement of $m_{\mathrm{W}} = 80.376 \pm 0.033$ GeV. Based on the Tevatron and LEP measurements, the world average is $m_{\mathrm{W}} = 80.399 \pm 0.023$ GeV.
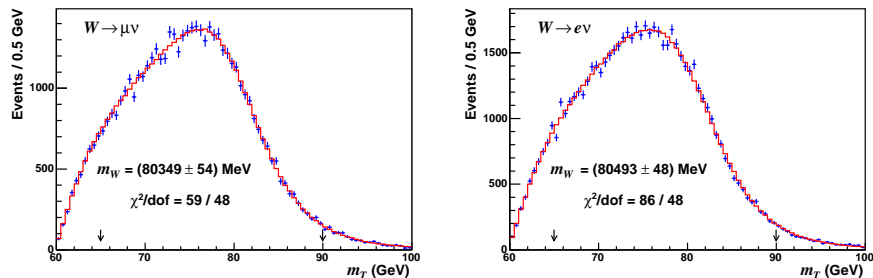

Figure 1: Distributions of the transverse mass in the muon channel (left) and electron channel (right) in 200 pb^{-1} of CDF data. The data are shown by the points, the histogram indicates the simulation for the best-fit m_{W}. The fit range is indicated by the arrows.
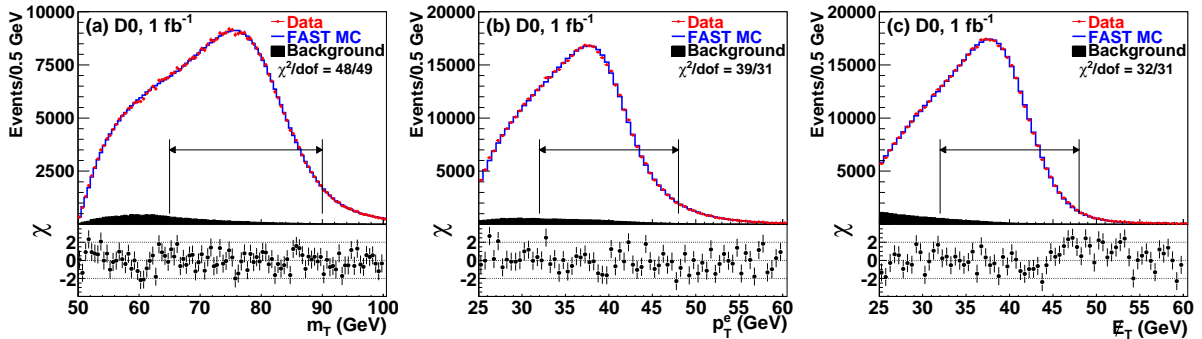
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Figure 2: Distributions of the transverse mass (left), electron transverse momentum (middle) and missing transverse energy (right) in 1 fb^{-1} of D0 data. The data are shown by the points, the histogram indicates the simulation for the best-fit m_W. The fit range is indicated by the arrows. The χ values shown below each histogram are the differences between data and simulation, divided by the statistical uncertainty.

3.2 Interpretation

As mentioned in the introduction, direct measurements of the W boson mass and the top quark mass (and other parameters) constrain the mass of the Higgs boson, assuming validity of the electroweak model. With the W boson mass measurement presented here, and $m_{top} = 173.1 \pm 1.3$ GeV, the Higgs boson mass is found to be $m_H = 87^{+35}_{-26}$ GeV [4].

After this conference, a new top quark mass measurement [1] was included in the standard model fit [4]. This leads to a shift in the expected Higgs boson mass of $+2$ GeV, but no reduction in the uncertainty.

4 Conclusion and Outlook

The world's most precise W boson mass measurements are now obtained by the Tevatron experiments: $m_W = 80.420 \pm 0.031$ GeV. Combining these results with those from LEP leads to an average of $m_W = 80.399 \pm 0.023$ GeV.

The precision of the Tevatron measurements is expected to improve significantly in the future. The addition of more data will decrease both the statistical and systematic uncertainties, since the estimation of systematic uncertainties is largely based on data samples, and therefore also limited by the size of the data set.

The CDF collaboration has already performed preliminary studies of a larger data sample of up to 2.4 fb^{-1}. The additional data were recorded at a higher instantaneous luminosity, which implies that some deterioration in, e.g., the recoil resolution is to be expected and to be accounted for. No significant degradation of the transverse mass resolution was found [5].

The final precision of the Tevatron experiments on the W boson mass could reach the level of 15 MeV [6], which will also significantly improve the prediction of the Higgs boson mass.

References

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