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Measurement of the W boson and top-quark masses at CDF

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Abstract. We report on the measurements of the W boson and top-quark masses with the CDF II detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron. We highlight the major features and uncertainties for the W mass measurement. The top-quark mass measurements are presented in each $t\bar{t}$ decay channels. The combination of the most precise measurements from CDF to date leads to $M_{top} = 172.4 \pm 1.5(stat.) \pm 2.2(sys.)$ GeV/c^2, corresponding to a relative uncertainty of 1.5%.

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INTRODUCTION

In the Standard Model (SM), at tree level, the W boson mass (m_W) can be predicted in terms of the Z boson mass, the electromagnetic coupling and the Fermi constant. Beyond tree level, additional radiative corrections to the mass need to be taken into account. Those corrections originate from the virtual top quark and Higgs boson effects in loop diagrams and are respectively proportional to the square of the top-quark mass (m_t) and to the logarithm of the Higgs boson mass (m_H) [1]. Since the Higgs boson, thought to be responsible for the for electroweak symmetry breaking in the SM, remains unobserved, precision measurement of m_t and m_W can be used to constrain m_H [3]. The top quark, due to its large mass, makes important radiative corrections to a number of electroweak observables [4]. Thus, a precise measurement of the top-quark mass used in conjunction with electroweak observables provides constraints on new physics which might contribute additional radiative corrections.

W BOSON MASS MEASUREMENT

At hadron colliders, the W mass is measured in the $e\nu$ and $\mu\nu$ decay channels. These channels have little background and the charged lepton momenta can be measured with high precision, thus providing the bulk of the mass information. Additional information from the neutrino can only be measured via the imbalanced in transverse energy in the event (p_T^ν), thus preventing a direct reconstruction of the W mass. Instead, we reconstruct the transverse mass defined as: $m_T = \sqrt{2P_T^l P_T^\nu(1-\cos(\Delta\phi_{l\nu}))}$. The transverse mass distribution is fitted to templates generated at various W mass values after full simulation of the physics and the detector. The W mass is obtained from a likelihood comparison of

TABLE 1. The uncertainty on the W boson mass measurement in MeV/c^2 using 0.2 fb^{-1} of Run 2 CDF data. The CDF Run 1b uncertainties are shown for comparison [2].

Systematic Uncertainties	**Electrons (Run 1b)**	**Muons (Run 1b)**	**Common (Run 1b)**
Lepton E Scale and Resolution	70 (80)	30 (87)	25
Recoil Scale and Resolution	50 (37)	50 (35)	50
Production and Decay Model	30 (30)	30 (30)	25 (16)
Backgrounds	20 (5)	20 (25)	-
Statistics	45 (65)	50 (100)	-
Total	105 (110)	85 (140)	60 (16)

these templates with the data. The main components of the mass measurement consist of the lepton momentum calibration, the hadronic recoil model and the simulation of the W boson production and decay.

The high-statistics $J/\Psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ samples provide a precise calibration of the transverse momentum that can be extrapolated to high momenta. For the electron, the energy scale is set by requiring it to match the momentum scale after simulating effects such as photon radiation in the passive material.

The hadronic recoil energy cannot be accurately modeled using a standard Monte Carlo simulation. Instead, a response function for the ratio of the measured to produced hadronic energy is determined from $Z \rightarrow \mu\mu$ data. The energy resolution model has two components, one for the underlying event and the other for the recoiling hadrons.

The distributions of the W boson p_T and rapidity affect the measurement of m_W. The p_T distribution is simulated using a NLL QCD event generator which has been tuned to Run 1 $Z \rightarrow ll$ data. The W boson rapidity distribution is affected by fractional momenta of the u and d quarks inside the proton and anti-proton. Those fractional momenta are parametrised by the parton distribution function (PDFs) using a global fit to data. Photon radiation off the decaying lepton reduces the measured m_T of a given W event. An event generator based on a NLO QED calculation simulates this radiation, however NNLO two-photon radiation process is not simulated leading to an additional uncertainty.

Table 1 summarises the uncertainties associated with the CDF m_w measurement.

TOP-QUARK MASS MEASUREMENT

At the Tevatron, top quarks are primarily produced in pairs, each decaying almost instantly to a W boson and a b-quark. Their decays are classified according to the W boson decays: dilepton ($t\bar{t} \rightarrow \bar{b}l^-\bar{\nu}_l b l'^+ \nu_{l'}$), lepton+jets ($t\bar{t} \rightarrow \bar{b}l^-\bar{\nu}_l bqq^{'}$) and all-hadronic ($t\bar{t} \rightarrow \bar{b}qq^{'}bqq^{'}$). Challenges of the top-quark mass measurement come from the combinatorics originating from the the jet-parton assignment, the undetected neutrino, the jet energy correction necessary to estimate the energy of the associated parton and SM backgrounds. The combinatorics and SM backgrounds can be reduced by identifying the b-jets. The jet energy corrections are determined using data and Monte Carlo simulation [5]. They are comprised of the corrections necessary to scale the jet energy to the final state particle level jet and then to the parent parton energy. The uncertainty on the jet energy scale (JES) is the dominant uncertainty on the top mass measurement. This uncertainty can be reduced by simultaneously constraining the jet energy scale from the $W \rightarrow qq$ to the W mass when determining the top mass.

The dilepton channel has the smallest branching ratio but benefits from a very small background. However, the two undetected neutrinos make the reconstruction of m_t kinematically difficult. The measurement presented here uses a matrix-element approach [6]. Each event gets assigned a probability as a function of the top mass integrating over the quantities not directly measured using the LO matrix-element. The final likelihood is a linear combination of the probabilities for signal and background.

Currently, the most precise single measurement of the top-quark mass has been made in the lepton+jets channel with a template method which simultaneously constrains the JES using the dijet invariant mass (m_{jj}) from $W \rightarrow qq^{'}$ [7]. The template method selects a reconstructed m_t by choosing from the possible jet-parton assignments that which yields the smallest χ^2, using the additional constrains from b-tagging when available. Templates are generated for various values of the top-quark mass and background processes. The reconstructed m_t distributions from data are compared to the signal and background templates using an unbinned likelihood fitting for signal and background events, top-quark pole mass and jet energy scale.

A novel method to measure the top-quark mass using the transverse decay length of B-hadrons from top decay has been developed [8]. Since this method relies solely on tracking, it is independent on the JES uncertainty and therefore uncorrelated to the other top mass measurements. Although the current measurement is statistically limited, the method could offer in the future a nice cross-check to the other measurements and reduce the overall uncertainty on the combined top mass measurement.

Measurement of the top-quark mass in the all-hadronic channel is extremely challenging due to the overwhelming background from QCD multi-jet events and the combinatorics. The method presented here tackles the problem by combining both the template and matrix-element methods in order to extract the maximum amount of information from the $t\bar{t}$ candidate events selected from the all-hadronic sample with at least one b-tagged jet [9]. To this purpose, a two-dimensional likelihood is constructed as a function of the top-quark mass and the signal purity left as a free parameter. The event likelihood accounts for the 90 possible combinations of jet-parton assignments weighting each by its goodness of fit and b-jet probability information. The signal part of the likelihood is data driven and consists of the two-dimensional convolution of the Breit-Wigners and Gaussian resolution functions. The QCD multi-jet background is parametrised by a two-dimensional mass template.

Figure 1 summarizes the measurements of the top-quark mass in each top-decay channel. The most precise measurement in each channel from CDF Run 1 and Run 2 has been combined resulting in a the top-quark mass of $m_t = 172.4 \pm 1.5_{stat} \pm 2.2_{sys}$ GeV/c^2 [10].

CONCLUSIONS

The measurement of the W mass is already at an advanced stage with a total combined error of 76 MeV, after taking into account correlations between the two channels. This systematic error is a preliminary one and is expected to be further reduced before

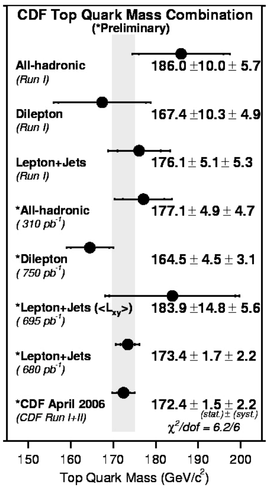

FIGURE 1. A summary of the input measurements and resulting CDF combined top-quark mass in April 2006

publication. The expectation is that with 2 fb^{-1} dataset, the Tevatron will measure a W mass with a combined uncertainty of $\sim$ 30 MeV. With less than 1 fb^{-1} of data, direct measurement of the top-quark mass has yielded a precision of 2.6 GeV$/$c^2 with CDF alone. With increasing statistics, the measurements in all three decay channels are expected to become limited by systematic uncertainties, allowing for a comparison of the measured mass in each channel and a total precision less than 1%.

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