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Top quark mass measurements at CDF and Tevatron combinations

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We report the results of the measurements of the top quark mass using top pair events corresponding to an integrated luminosity of more than 4 fb^{-1} from proton-antiproton collisions at the Tevatron, recorded by the CDF II detector. We present different results using various techniques in the lepton+jets, dilepton, and all-jets channels, and describe the current status of the systematic uncertainties. We present also a combination by the TevEWWG (Tevatron electroweak working group) of the best top mass results from CDF and DØ in Run 1 and Run 2 of the Tevatron. This result is the current world average, and offers an uncertainty almost reaching 1 $\mathrm{GeV/c}^2$. The new mass value has been included in traditional LEP EWWG fits to precision electroweak data, and implications for the Standard Model Higgs have been derived.

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1. Introduction

The top quark mass, m_t, is an intrinsic parameter of the Standard Model (SM) of particle physics, and is of particular importance due to its strikingly large value. As a result, it has a large effect on radiative corrections to electroweak processes and has a Yukawa coupling to the Higgs field of $\mathcal{O}(1)$, providing a possible insight into the mechanism of electroweak symmetry breaking.

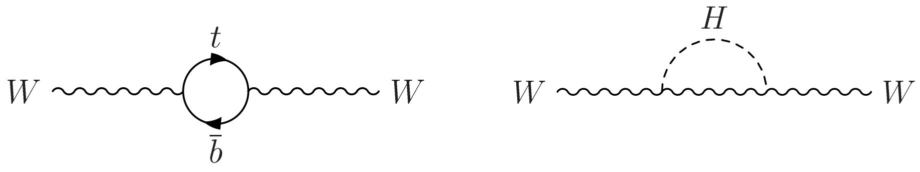

Figure 1: NLO radiative corrections to the W boson mass, left diagram $\propto m_t^2$ and right diagram $\propto \ln m_H$.

The Higgs boson mass, m_H, is not predicted by the SM, but constraints on its value can be derived from the calculation of radiative corrections to the W boson mass, m_W, and other precision electroweak variables. These corrections depend primarily on m_H and m_t (Figure 1). Precision measurements of m_W and m_t therefore provide direct constraints on m_H (Figure 2). Similar constraints can also be imposed in new physics models such as the Minimal Supersymmetric Standard Model (MSSM) [1], also illustrated in Figure 2, where the mass of the lightest neutral Higgs boson is constrained.

2. Top quark production and decay

The dominant top quark production process is pair-production via the strong interaction. At CDF, these processes are initiated using $p\bar{p}$ collisions at centre-of-mass energy $\sqrt{s} = 1.96$ TeV.

As the most massive of quarks, the top quark is very unstable. It decays rapidly with lifetime $\tau_t \sim 10^{-25}$ s, fast enough that it has essentially no time to interact and may be considered as a free quark. This allows a direct measurement of its mass from the daughter particles from its decay, and as a result m_t has the lowest relative uncertainty of all of the quark masses.

Top quarks decay via the weak interaction, almost invariably to a W boson and a b-quark. The W boson decays into lower-mass fermion-antifermion pairs: a charged lepton and a neutrino, “leptonic decay”; or an up-type quark and a down-type quark, “hadronic decay”. With one W boson produced from each of the two top quark decays, this results in three distinct decay channels for pair-produced top quarks.

- **Dilepton channel**: both W bosons decay leptonically; Branching Ratio (BR) 11%.
- **Lepton+jets channel**: one W boson decays leptonically, the other hadronically; BR 44%.
- **All-hadronic channel**: both W bosons decay hadronically; BR 44%.

The resulting spray of particles is detected in the various CDF detector components [2], which then read-out and subsequently reconstruct the event information.

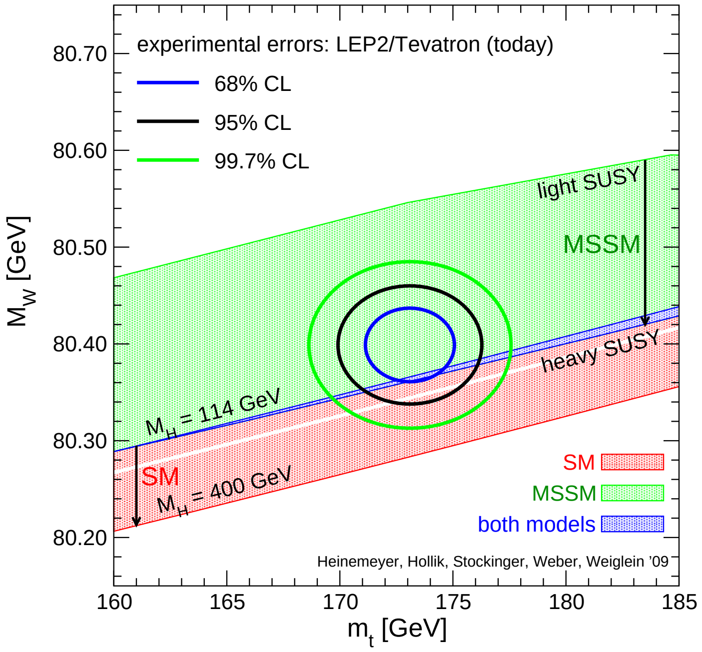

Figure 2: m_W vs m_t as a function of m_H, updated from [1]. The World Average measurements of m_W and m_t provide the constraints illustrated by the ellipses. The regions allowed by theory, and so far not experimentally excluded, are coloured red for the SM and green for the MSSM.

3. Measurement of m_t

There are a number of challenges associated with the measurement of m_t. First, top quark events are very rare, with $\sigma_{t\bar{t}}/\sigma_{p\bar{p}} \sim 10^{-10}$, making it important to construct a finely tuned set of event selection criteria. Even then, a number of "background" processes can mimic the $t\bar{t}$ decay signature, contaminating the data sample and providing spurious information about m_t. Second, neutrinos cannot be detected at CDF or DØ, resulting in missing kinematic information in the lepton+jets and dilepton channels. Third, it is not always possible to distinguish between final-state jets, making it impossible to unequivocally make the jet-to-quark assignments required to kinematically reconstruct each event. Identification of the jets generated by b-quarks ("b-tagging") is important in reducing both the number of background events and the number of possible jet-to-quark assignments, and is provided by silicon vertex detectors that allow the identification of the secondary vertices characteristic of the decay of b-hadrons. Fourth, when jets enter the detector the effects of particle showering, detector response and noise, as well as energy from any additional scatterings from the same beam crossing, adversely affect the jet reconstruction. The resulting uncertainties are referred to as Jet Energy Scale (JES) uncertainties.

These challenges make it impractical to calculate m_t for each individual event, and instead m_t is extracted using the information provided by the entire data sample. Generally, a likelihood technique is used to estimate the most likely value of m_t given the analysed data. Two broad categories of methods are used. "Template methods" make use of simulated kinematic distribution(s) at different supposed values of m_t, with the measured m_t corresponding to the best fit to the distribution(s) seen in data. "Matrix element methods" employ an unbinned maximum likelihood fit, where the m_t-dependent probability density function (p.d.f.) for each event is calculated using theoretical knowledge (based on LO matrix elements) of the production and decay of the top quark.

In terms of measurement sensitivity, the lepton+jets channel provides the best compromise among the effects of the measurement challenges. The dilepton channel has a lower background but also a lower BR and two undetected neutrinos. The all-hadronic channel has a higher BR and no neutrino, but also has more background and many possible sets of jet-to-quark assignments. In the lepton+jets channel, the background is low when at least one jet is required to be *b*-tagged, and the transverse momentum of the neutrino can be reconstructed by imposing momentum conservation.

Both types of method are used to make m_t measurements in each of the three decay channels, but the large background of the all-hadronic channel disfavours the use of a matrix element method (due to the challenges of constructing an accurate event p.d.f.), while in the lepton+jets and dilepton channels matrix element methods generally succeed in extracting more information from each event, with corresponding greater sensitivity to m_t. The most precise single measurement of m_t, as of March 2009, comes from a matrix element method using 3.2 fb^{-1} of data from the lepton+jets channel, measuring $m_t = 172.1 \pm 0.9(\text{stat}) \pm 0.7(\Delta_{\text{JES}}) \pm 1.1(\text{syst}) = 172.1 \pm 1.6\ \text{GeV}/\text{c}^2$ [3].

With the decreasing statistical uncertainties as a result of larger data samples (the measurements presented here were all made with $\sim 3\ \text{fb}^{-1}$ of data), systematic uncertainties now typically make the largest contribution to the overall uncertainty on m_t. When treated as an independent systematic uncertainty, the JES uncertainties can contribute a systematic uncertainty of up to about 3 GeV/c^2 on the final measured m_t. To help reduce the overall uncertainty, a parameter known as the JES correction (Δ_{JES}) is introduced, describing an overall correction to the jet energy measurements. In events with a hadronically decaying *W* boson, Δ_{JES} can be constrained via the invariant mass of the two jets from the *W* boson decay, allowing a simultaneous measurement of Δ_{JES} along with m_t. This effectively replaces a large component of the JES systematic uncertainty on m_t with a typically much smaller Δ_{JES} statistical uncertainty on m_t. Of course, this approach is limited to the lepton+jets and all-hadronic decay channels.

Despite the reduction from the *in situ* Δ_{JES} calibration, the remaining JES component of the systematic uncertainty is still the largest single systematic uncertainty in most m_t measurements (typically $\sim 0.6\ \text{GeV}/\text{c}^2$ [3]). Other significant systematic uncertainties are mainly a result of assumptions made in the simulation of the events that are used in the tuning and calibration of the measurement methods, including uncertainties in background modelling ($\sim 0.5\ \text{GeV}/\text{c}^2$), Monte Carlo $t\bar{t}$ generator ($\sim 0.5\ \text{GeV}/\text{c}^2$), initial and final state gluon radiation ($\sim 0.3\ \text{GeV}/\text{c}^2$), and parton distribution functions ($\sim 0.2\ \text{GeV}/\text{c}^2$) [3]. The systematic uncertainties for each effect are added in quadrature to calculate the overall systematic uncertainty on the measured m_t.

The CDF and DØ collaborations are making a joint effort to define a common way to evaluate the systematic uncertainties, not only to avoid possible overlaps and double-counting but also to improve the knowledge of the effects, as well as studying possible sources thus far neglected. The colour reconnection systematic uncertainty was new to the Winter 2009 analyses and the subsequent combinations, with a typical value of $\sim 0.4\ \text{GeV}/\text{c}^2$ [3].

The results of the most precise measurement from CDF for each channel are given in Figure 3a, along with their estimated uncertainties. Note that the Δ_{JES} statistical uncertainties are added in quadrature as part of the systematic uncertainties for the purpose of result combination.

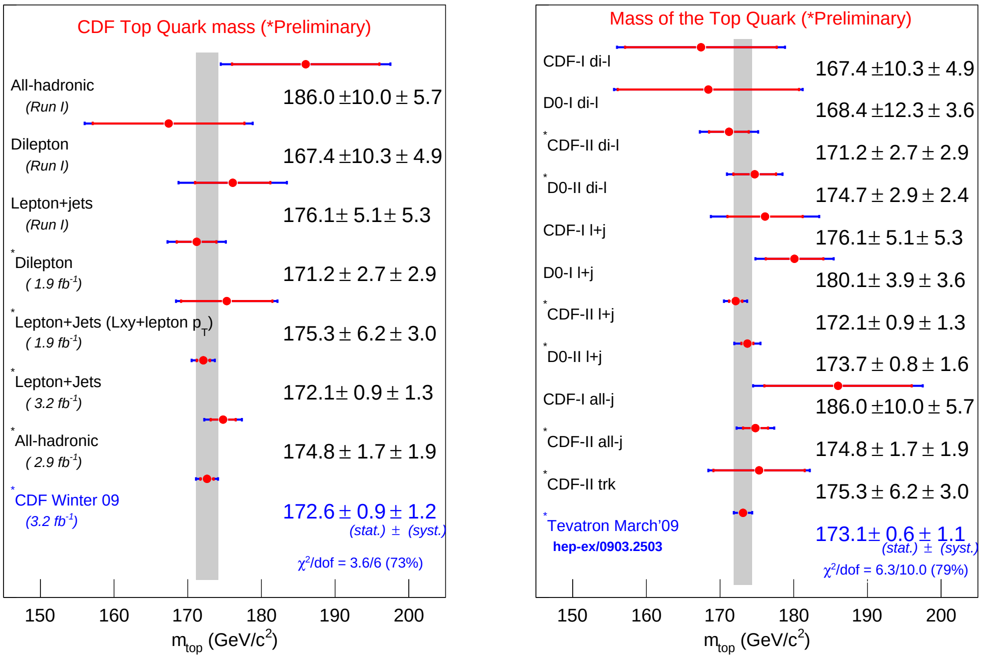

Figure 3: Left (a): A summary of the most precise CDF m_t measurements in the various channels for Runs I and II, and the resulting CDF combined m_t. Right (b): A summary of the most precise CDF and DØ m_t measurements in the various channels, and the resulting World Average m_t.

4. Combination

The best measurements of m_t from each channel are combined to create the CDF combination [4] (Figure 3a), taking into account any correlations between systematic uncertainties. A similar combination is calculated at DØ and the results are combined to create the Tevatron combination [5], a joint measurement representing the World Average value of m_t. The March 2009 World Average is $m_t = 173.1 \pm 0.6(\mathrm{stat}) \pm 1.1(\mathrm{syst})\ \mathrm{GeV/c^2} = 173.1 \pm 1.3\ \mathrm{GeV/c^2}$, with a χ^2 probability for the combination of 79% and no result with an anomalously large pull (Figure 3b), indicating that the results are all consistent. The relative precision is $\delta m_t/m_t = 0.72\%$. The World Average values from the different decay channels are also calculated, yielding $m_t^{\mathrm{dilepton}} = 171.4 \pm 2.7\ \mathrm{GeV/c^2}$, $m_t^{\mathrm{lepton+jets}} = 172.7 \pm 1.3\ \mathrm{GeV/c^2}$, and $m_t^{\mathrm{all-hadronic}} = 175.1 \pm 2.6\ \mathrm{GeV/c^2}$ [5].

Finally, the implications of the updated World Average m_t for the Standard Model Higgs are derived, yielding $m_H = 87^{+35}_{-26}\ \mathrm{GeV/c^2}$, with 95% one-sided confidence level $m_H < 157\ \mathrm{GeV/c^2}$. The contraints imposed by the updated World Average m_t are illustrated in Figure 2.

References

[1] S. Heinemeyer et al., *Precise prediction for M_W in the MSSM* [`hep-ph/0604147`].

[2] CDF Collaboration, *The CDF-II detector: Technical design report*, FERMILAB-PUB-96-390-E.

[3] CDF Collaboration, CDF public note 9692 (February 2009).

[4] CDF Collaboration, CDF public note 9714 (March 2009).

[5] TevEWWG, *Combination of CDF and DØ Results on the Mass of the Top Quark* [`hep-ex/0903.2503`].