Top quark and Higgs boson physics at the Tevatron

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Abstract. The search for the Higgs boson and the study of the heaviest known fundamental particle, the top quark, have been at the center of the Tevatron research program. The Higgs boson is yet to be discovered and the top quark was discovered in 1995. Both of these particles have a very special place in the “periodic table” of fundamental particles. With Tevatron having delivered more than 11 fb$^{-1}$ of data at 1.96 TeV and the Large Hadron Collider also rapidly collecting data at 7 TeV, we are entering a very exciting era where many interesting questions about these intriguing particles will be answered. Here I summarize the current status of Higgs boson and top quark studies at the Tevatron.

1. The top quark
The top quark program at the Tevatron is very broad. Since its discovery in 1995 at Fermilab, study of properties of this interesting particle and search for new physics effects in top quark decay and production has been one of the major goals of the Tevatron Run II. Here I present only few of the main and the recent results from CDF and DØ experiments. For a full list of recent results please check the webpages with the public results [1].

1.1. Top quark pair production cross section
The dominant production channel at the Tevatron in $p\bar{p}$ collisions is $q\bar{q}$ annihilation which happens in around 85% of collisions and gluon-gluon fusion which contributes only 15%. Within the Standard Model (SM) of particle physics, the top quark decays to a $W$ boson and a $b$ quark almost 100% of the time. The final state $W^+W^-bb$ from top quark pair production is classified according to how the $W$ boson decays, i.e. alljets, lepton+jets or dileptonic decay channels. The top quark pair production cross section has been determined by CDF and DØ experiments in different decay channels, with many different analysis techniques such as, simple event counting, b-jet identification (b-tagging), multivariate analysis techniques and combinations of these techniques. These measurements are consistent with theoretical predictions and a summary of these measurements done by CDF and DØ are shown in Figures 1 and 2 respectively.

1.2. Top quark mass measurement
Tevatron experiments, CDF and DØ, have measured top quark mass ($m_t$) to a very high precision in all decay modes with many different techniques. The most recent DØ results are in the lepton+jets channel using 3.6 fb$^{-1}$ of data with in situ jet energy scale (JES) calibration [2]. Compared to previous measurements at DØ, a major improvement in this new measurement

1 On behalf of the CDF and DØ Collaborations
is the significant reduction of the uncertainty associated with the modeling of differences in the calorimeter response to $b$-quark and light-quark jets originating from the introduction of a new flavor-dependent jet energy response correction. The measurement gives $m_t = 174.9 \pm 0.8 \text{ (stat)} \pm 0.8 \text{ (JES)} \pm 1.0 \text{ (syst)}$ GeV. This is the best top-quark mass measurement at DØ. The second result comes from the dilepton channel using 5.4 fb$^{-1}$ of data[3]. Here the dominant uncertainty comes from JES systematic uncertainties. The measurement gives $m_t = 174.0 \pm 1.8 \text{ (stat)} \pm 2.4 \text{ (syst)}$ GeV. This is the world’s best top-quark mass measurement in the dilepton channel. The two most recent CDF results both use the template method with in situ JES calibrations. The first one is obtained in the all hadronic channel using 5.8 fb$^{-1}$ of data [4]. The measurement gives $m_t = 172.5 \pm 1.4 \text{ (stat)} \pm 1.0 \text{ (JES)} \pm 1.1 \text{ (syst)}$ GeV. This is the second best measurement at CDF. The second new CDF result comes from the MET+jets channel using 5.7 fb$^{-1}$ of data [5]. The measurement gives $m_t = 172.3 \pm 1.8 \text{ (stat)} \pm 1.5 \text{ (JES)} \pm 1.0 \text{ (syst)}$ GeV. This measurement is complementary to the other top-quark mass measurements adding to the overall sensitivity. A summary of the direct mass measurements from CDF and DØ are shown in the following figures.
1.3. Top quark mass from top quark pair production cross section

The mass of the top quark has been measured with a precision of <1%. But the top quark mass, beyond leading-order QCD, is a convention-dependent parameter. Therefore, in order to use this measured mass in higher-order QCD calculations or in fits of electroweak precision observables, it is important to know how to interpret this experimental result in terms of renormalization conventions. DØ has recently measured top quark mass in the pole mass scheme and the MSbar scheme using top quark pair production cross section measured with 5.3 fb$^{-1}$ of integrated...
luminosity [6]. The top quark cross section is compared with theoretical calculations assuming what we measure is the pole mass or the MSbar mass. The uncertainty on extracted top quark mass, dominated by systematic uncertainties in the measured cross section, is quite large to make some definite statement but the top mass extracted under the assumption that the Monte Carlo (MC) mass is equal to the pole mass, is found to agree with the average value of top mass from the Tevatron combination, while the mass extracted assuming that top quark mass in MC is equal to the top quark MSbar mass is found to be different from the average Tevatron value. Also, this is the first time that top quark mass has been extracted in MSbar scheme. Figure 5(6) shows measured $t\bar{t}$ cross section and theoretical NLO+NNLL and approximate NNLO calculations of cross section as a function of top quark mass, assuming that MC mass is pole mass (MC mass is MSbar mass). The colored dashed lines represent the uncertainties for the two theoretical calculations. The point shows the measured top pair cross section for MC top quark mass = 172.5 GeV, the black curve is the fit to the measured cross section, and the gray band corresponds to the total experimental uncertainty.

1.4. Top and anti-top quark mass difference
DØ has recently updated its top-antitop quark mass difference measurement with 3.6 fb$^{-1}$ of data and found $\Delta M_{\text{top}} = 0.8 \pm 1.8 \pm 0.5$ (stat+syst) GeV [7]. This result is consistent with the expectation of CPT invariance $\Delta M_{\text{top}} = 0$ GeV. Recently, CDF has also measured this difference using a template method with 5.6 fb$^{-1}$ of data, and found $\Delta M_{\text{top}} = 3.3 \pm 1.4(stat) \pm 1.0(syst)$ GeV [8]. The result deviates from the expectation of CPT invariance by about 2 standard deviations.

1.5. Top quark width
CDF has performed a direct measurement of $\Gamma_t$, and set a limit $\Gamma_t < 7.64$ GeV at 95% CL [9]. The DØ collaboration extracted the total decay width of the top quark [10], $\Gamma_t = \Gamma_{t\rightarrow Wb}/B_{t\rightarrow Wb}$, from the partial decay width $\Gamma_{t\rightarrow Wb}$ measured using the t-channel cross section for single top
quark production, and from the branching fraction $B_{t \rightarrow Wb}$ measured in top pair events. DØ finds $\Gamma_t = 1.99^{+0.69}_{-0.55}$ GeV. This constitutes the world's most precise indirect determination of $\Gamma_t$ and translates into a top quark lifetime of $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s.

1.6. Top quark spin correlation

In top pair production at hadron colliders, while the top quarks are unpolarised, the orientation of their spins is correlated. In contrast to other quarks, this correlation is not affected by fragmentation due to the short life time of the top quark, and is thus reflected in its decay products. Observation of spin correlation will place upper limit on top quark life time and scenarios beyond the SM predict changes in production and decay dynamics to change effect of spin correlation. Tevatron being a $p\bar{p}$ collider, the information on top-antitop correlation is complementary to LHC which is a $pp$ collider. The NLO QCD prediction for spin correlation is $C = 0.777^{+0.027}_{-0.042}$. CDF has investigated this correlation using template method and measures the correlation to be $C = 0.7 \pm 0.7$. DØ has recently measured this correlation in two different analyses. One, choosing the beam momentum vector as the quantization axis in the dilepton channel, using $\cos \theta_1 \cos \theta_2$ distribution (Figure 7), results in spin correlation $C = 0.1 \pm 0.5$. $\theta_1(\theta_2)$ is the angle between the line of flight of the lepton (antilepton) with the polarization direction. Two, using the matrix element technique and building a discriminant $R$ (Figure 8) using event probabilities with and without spin correlations. In this case the spin correlation is measured to be $C = 0.6 \pm 0.3$. This analysis, for the first time, excludes uncorrelated spin case at 97.7% CL.

1.7. Top quark forward-backward asymmetry

In the SM, the pair production of top quarks in $p\bar{p}$ collisions at LO is symmetric under charge conjugation. Next-to-LO calculations predict a small forward-backward asymmetry $A_{f_b}$ of the order of few %, which is due to contributions from the interference of diagrams for initial and final state radiation, and from the interference of box and tree-level diagrams. DØ measured $A_{f_b}$ in the $t\bar{t}$ rest frame in lepton+jets final states on a dataset corresponding to 4.3 fb$^{-1}$ using $t\bar{t}$ event candidates fully reconstructed with a kinematic fitter, and found $A_{f_b} = 8\% \pm 4\%$ [14]. DØ result, shown in Figure 9, is about 2 standard deviations away from the MC@NLO prediction of 1 ± 2%. A similar measurement is performed by CDF in lepton+jets and dilepton final states [15] and the distributions corrected back to parton level. After all corrections, CDF finds
$A_{fb} = 16\% \pm 7\%$, which is about 1.5 standard deviations away from the MC@NLO prediction of $6\% \pm 1\%$. CDF also investigated the dependence of $A_{fb}$ on the invariant mass of the $t\bar{t}$ system, $M_{t\bar{t}}$, which is compared to the prediction of MC@NLO plus background in Figure 10. Motivated by the resolution in $M_{t\bar{t}}$, CDF measures $A_{fb}$ in two bins of $M_{t\bar{t}} < 450$ GeV and $M_{t\bar{t}} > 450$ GeV. The $A_{fb} = 48\% \pm 11\%$ at parton level and after all corrections in the $M_{t\bar{t}} > 450$ GeV bin is more than 3 standard deviations away from the NLO SM prediction of $A_{fb} = 9\% \pm 1\%$. Another measurement, carried out by CDF in the dilepton channel using $5.1 \, fb^{-1}$ of data, yields $A_{fb} = 42\% \pm 16\%$ parton level after all corrections, which is about 2.5 standard deviations away from the SM NLO prediction. The above results indicate tension between the measurement and the NLO MC predictions.

1.8. $W$ helicity in top pair decays and search for $Wtb$ anomalous couplings

In the SM, the top quark decays into a $W$ boson and a $b$ quark with a probability of $> 99.8\%$, where the on-shell $W$ boson can be in a left-handed, longitudinal, and right-handed helicity state. NLO calculations within the SM of the corresponding helicity fractions predicts $f_- = 0.301$, $f_0 = 0.698$, and $f_+ = 4.1 \times 10^{-4}$, respectively. A significant deviation from the SM expectation would indicate a contribution from new physics. CDF performed a model
Figure 11. Left: the result of CDF $W$ boson helicity measurement in the $f_0$, $f_+$ plane. The ellipses correspond to the negative log-likelihood profile of two-dimensional simultaneous fit of both $f_0$, $f_+$. Right: the result of the DØ boson helicity measurement in the $f_0$, $f_+$ plane. The ellipses indicate the 68% and 95% CL contours.

independent measurement [12] and found $f_0 = 0.78 \pm 0.21$ and $f_+ = 0.12 \pm 0.12$ as shown in Figure 11. DØ has also measured the $f_0$ and $f_+$ helicity fractions in a model independent measurement [11], observing $f_0 = 0.669 \pm 0.102$ and $f_+ = 0.023 \pm 0.053$ as shown in Figure 11, in agreement with the SM expectation. DØ has also combined the helicity fraction measurement with the measurement of anomalous $Wtb$ couplings in single top quark production and decay. Combining these complementary measurements helps DØ set even better limits on the anomalous $Wtb$ couplings [13].

1.9. Search for fourth generation quarks
Search for pair production of fourth generation $t'$ has been carried out by both CDF and DØ. DØ searched for $t'$ and its antiparticle, followed by their decays to a $W$ boson and a jet, based on an integrated luminosity of 5.3 fb$^{-1}$ and set an upper limit on the $t't'$ production cross section that exclude at the 95% C.L. a $t'$ quark that decays exclusively to $W$+jet with a mass below 285 GeV [16]. CDF performed a similar search using 4.6 fb$^{-1}$ and exclude a fourth-generation $t'$ quark with mass below 335 GeV at 95% C.L. [17]. Both limits are shown in Figure 12.

1.10. Single top quark production
Within the SM, top quarks are produced through two different types of interactions at hadron colliders: $t\bar{t}$ pairs, produced via the strong interaction, the mode of production in which top quark was discovered first; the electroweak production of single top quarks, observed by the DØ and CDF collaborations in 2009 [18]. The single top quark production rate is about half that for $t\bar{t}$ pairs and the signal-to-background ratio is worse, so the observation of this process is more difficult. At the Tevatron, single top quarks are produced through $W$ boson exchange, and accompanied by a $b$ quark in the s-channel (denoted as “$tb$”), or by both a $b$ and a light quark in the t-channel (denoted as “$tqb$”). A third process, usually called associated production, in which the top quark is produced together with a $W$ boson, has negligible cross section at the Tevatron. Until now DØ and CDF have measured the production cross section for the sum of $tb$ and $tqb$ while assuming the relative rate between the two processes as predicted by the SM. This relative rate can however be different in many new physics scenarios, for example, in models with 4th generation quarks, or heavy bosons or with Flavor Changing
Figure 12. Observed and expected upper limits and predicted values for the $t't'$ production cross section as a function of the mass of the $t'$ quark for CDF (left) and DØ (right). The shaded regions around the expected limit represent the 1 $\sigma$ and 2 $\sigma$ bands.

Figure 13. Left: Posterior probability density for $tq_b$ vs $tb$ single top quark production in contours of equal probability density. The measured cross section and various theoretical predictions are also shown. Right: lepton charge multiplied by the pseudorapidity of the leading non-b-tagged quark jet. The t-channel signal is shown in purple, and the main backgrounds, $W+$jets and $t\bar{t}$, are shown in green and red, respectively.

Neutral Currents (FCNC) or anomalous top quark couplings. Recently DØ has performed a model-independent measurement of t-channel production of single top quarks using 5.4 fb$^{-1}$ of integrated luminosity in events containing an isolated electron or muon, missing transverse energy and one or two jets originating from the fragmentation of b quarks. DØ measured a cross section $\sigma(p\bar{p}\rightarrow tq_b + X) = 2.90 \pm 0.59$ (stat + syst) pb for a top quark mass of 172.5 GeV [19]. The probability of the background to fluctuate and produce a signal as large as the one observed is $1.6 \times 10^{-8}$, corresponding to a significance of 5.5 standard deviations. Figure 13 shows the 2D posterior probability density for $tq_b$ vs $tb$ single top quark production (left) and comparisons between the data, the background model, and the t-channel signal for a sample from final combined discriminant bins selected with signal-to-background ratio $S/B > 0.32$ (right).
1.11. Color flow or jet pull

Color charge is conserved in QCD. At leading order in the strong coupling constant $\alpha_s$, color can be traced from initial partons to final-state partons in high-energy hadron collisions. Two final-state partons on the same color-flow line are color-connected and attracted by the strong force. As these colored states hadronize, the potential energy of the strong force between them is released in the form of hadrons. Thus, knowledge of the color-connections between jets can serve as a powerful tool for separating processes that otherwise appear similar. For example, in the decay of a Higgs boson to a pair of $b$ quarks, the two $b$ quarks are color connected to each other, since the Higgs is uncolored or color singlet, whereas in $g \rightarrow b\bar{b}$ background events, they are color-connected to beam remnants because the gluon is a color-octet and carries a color and an anti-color. DØ recently used $t\bar{t}$ events to measure the fraction of uncolored $W$ bosons using a calorimeter-based vectorial variable, jet pull, which is sensitive to the color-flow structure of the final state. This variable is explained and the distribution is shown in Figure 14. We find that the fraction of uncolored $W$ bosons is $f_{\text{singlet}} = 0.56 \pm 0.42(\text{stat+syst})$ [20]. The fraction of events with light jets coming from the $W$ boson (color) singlet is $f_{\text{singlet}} = 1$ in the SM.

2. Search for Higgs boson production

Searching for the BEHHGK mechanism and boson, named after the authors (Breit, Englert, Higgs, Hagen, Guralnik, Kibble), was proposed in 1964[21]. The search for the Higgs boson is considered to be the search for the “Holy Grail” in high energy physics and is one of the highest priorities at Run II of the Tevatron. There are direct and indirect limits on the SM Higgs boson mass from LEP, SLD and Tevatron constraining the Higgs boson mass to be between 114 GeV and 185 GeV at the 95% CL. The primary Higgs channels of $H \rightarrow W^+W^-$, $WH \rightarrow t\bar{b}b$, $ZH \rightarrow \nu\bar{\nu}bb$, and $ZH \rightarrow l^+l^-bb$ from CDF and DØ correspond to about 500 Higgs bosons produced at each mass, $114 < m_H < 185$ GeV. The search is divided in two categories: low mass ($m_H < 135$ GeV) and high mass ($m_H > 135$ GeV).

A low mass Higgs boson preferentially decays $H \rightarrow b\bar{b}$. It is most easily identified in events produced via associated Higgs production, $WH$ and $ZH$, when the $W$ and $Z$ decay leptonically, into final states of $WH \rightarrow t\nu\bar{b}b$, $ZH \rightarrow \nu\nu\bar{b}b$, and $ZH \rightarrow l^+l^-bb$ where $l = e$ or $\mu$. In events
Figure 15. Distributions of log10(S/B), for the data from all contributing channels from CDF and DØ, for Higgs boson masses of 115 (left), 140 (middle), and 165 (right) GeV. The data are shown with points, and the expected signal is shown stacked on top of the backgrounds. Underflow and overflow entries are collected into the leftmost and rightmost bins.

Figure 16. Integrated distributions of S/B, starting at the high S/B side, for Higgs boson masses of 115 (left), 140 (middle), and 165 (right) GeV. The total signal+background and background-only integrals are shown separately, along with the data sums. Data are only shown for bins that have data events in them.

with a reconstructed $W$ or $Z$ boson and two or more additional jets, the di-jet invariant mass is used to search for a resonance originating from $H \rightarrow b\bar{b}$. Expected sensitivity is improved by categorizing events according to the number of identified $b$ quark jets. For details of the CDF and DØ Higgs results, please visit the public wepages of the experiments [22].

In searches for a high mass Higgs boson the most sensitive mode at the Tevatron is $gg \rightarrow H \rightarrow WW \rightarrow l\nu l\nu$ due to the high cross section and well identified final state. The high mass analysis benefits from separating events into categories according to the number of jets and the number of leptons because of the difference in the kinematics of the signal production mechanisms and background processes.

Since 2006, CDF and DØ experiments have been producing combined Higgs searches and constant efforts are made to improve signal acceptance by re-visiting the kinematic cuts and the use of sophisticated analysis techniques. The most recent combination combines up to 8.6 fb$^{-1}$ [23]. Figure 15 shows combined discriminant outputs for three Higgs mass points from
Figure 17. Background-subtracted data distributions for all channels, summed in bins of S/B, for Higgs boson masses of 115 (left), 140 (middle), and 165 GeV. The background has been fit, within its systematic uncertainties, to the data. The points with error bars indicate the background-subtracted data; the sizes of the error bars are the square roots of the predicted background in each bin. The unshaded (blue-outline) histogram shows the systematic uncertainty on the best-fit background model, and the shaded histogram shows the expected signal for SM Higgs boson.

The multiple search channels (dozens of them) summing up those bins with the same S/B into the same bins, and then sorting the bins from lowest to highest S/B. These distributions can be integrated from the high-S/B side downwards, showing the sums of signal, background, and data for the most pure portions of the selection of all channels added together. These integrals can be seen in Figure 16. An excess in these bins relative to the background prediction drives the Higgs boson cross section limit upwards, while a deficit drives it downwards. The lower-S/B bins show that the modeling of the rates and kinematic distributions of the backgrounds is very good. The integrated plots show a slight excess of events in the highest-S/B bins for the analyses seeking a Higgs boson mass of 115 GeV and 140 GeV, and a slight deficit of events in the highest-S/B bins for the analyses seeking a Higgs boson of mass 165 GeV. Figure 17 shows the distributions of the data after subtracting the expected background, and the comparison with the expected signal yield for a SM Higgs boson, after collecting all bins in all channels sorted by S/B. Finally Figure 18 shows the ratios of the 95% C.L. expected and observed limit to the SM cross section. We exclude $156 < m_H < 177$ GeV and $100 < m_H < 108$ GeV. The expected exclusion region, given the current sensitivity, is $148 < m_H < 180$ GeV and $100 < m_H < 109$ GeV and we did not study masses below $m_H < 100$ GeV. The Tevatron is scheduled to deliver up to 12 fb$^{-1}$, providing about 10 fb$^{-1}$ of analyzable data for Higgs analysis per experiment. With this dataset, a full combination of Higgs searches will have at least 2.4 $\sigma$ level sensitivity for $100 < m_H < 185$ GeV.

There are many beyond SM (BSM) scenarios or alternative Higgs boson models. Many of these models can be probed at the Tevatron energies and can be constrained in the absence of any excess observed. For both CDF and DØ searches of BSM Higgs, please see CDF and DØ public results webpages [22].

References
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Figure 18. Observed and expected (median, for the background-only hypothesis) 95\% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and DØ analyses. The limits are expressed as a multiple of the SM prediction for test masses (every 5 GeV) for which both experiments have performed dedicated searches in different channels. The points are joined by straight lines for better readability. The bands indicate the 68\% and 95\% probability regions where the limits can fluctuate, in the absence of signal. The limits displayed in this figure are obtained with a Bayesian calculation.