Top quark mass results at Tevatron

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Abstract. The importance of the precise measurement of the top-quark mass (and W-boson mass) origin in possibility to predict the mass of the Higgs boson. The top-quark mass has been measured by the CDF and DØ experiments in many channels using different methods. The most precise measurement is still the Tevatron combination using the collected data with integrated luminosity of up to 5.8 fb$^{-1}$. The determined mass value is 173.18 ± 0.56(stat)±0.75(syst) GeV or 173.18 ± 0.94 GeV, what gives a precision of ±0.54%. However this article also reports the results using the full datasets, which are not included in the combination. In addition, the measurement of the mass difference of top and anti-top quarks is present showing the difference of 1.95 ± 1.26 GeV.

1. Introduction
Since the discovery of the top quark [1, 2] many properties has been studied. Top quark due to its big mass plays important role in the QCD corrections. The precise measurement of the top-quark and W-boson masses leads to better constrain of the Higgs-boson-mass window. The fact that the top-quark mass is close to the scale of electro-weak symmetry breaking evoke the question if the top quark have more fundamental role in this mechanism. The top-quark sector is expected to be sensitive to a new physics.

At the Tevatron $p\bar{p}$ collider top quarks are produced mainly in pairs through strong force quark-antiquark annihilation (∼ 85%) and gluon-gluon fusion (∼ 15%) processes. Due to the very short life time, it decays before hadronization into W boson and bottom quark in almost 100% of the time. We distinguish three different topologies of $tt$ events, which can be defined by decays of W bosons - dilepton channel, all-hadronic channel and lepton+jets channel. In case of dilepton channel both W bosons decay leptonically - into electron or muon and corresponding antineutrinos. This channel is also called the cleanest one as it has the smallest amount of background what is caused by the presence of two leptons. However dilepton channel has smallest branching ratio. The lepton+jets channel covers the events with one W boson decaying leptonically and the other one hadronically. The lepton+jet channel is also called "golden channel" as the branching ratio is relatively large and the amount of background is manageable. The largest branching ratio has the all-hadronic channel, in which both W bosons decay hadronically. However in this case the amount of QCD multijets background is big.

2. Methodology
Event though there are several methods used to measure top-quark mass, we describe only two of them as they are used in the measurements mentioned in this article:
Template method uses variables sensitive to the top quark mass, which is reconstructed from its decay products. After generating the Monte Carlo (MC) samples with different top-quark masses, the templates are obtained by reconstructing the variables. The result of the measured top-quark mass is then obtained by comparing the template of the sensitive variables obtained from the data with the ones extracted from different MC samples. This method is fast, but the statistical uncertainty is worse than the ones from the other methods.

Matrix element method is based on calculating the event probability density $P_E$, which express the probability that the event with the certain input top-quark mass ($m_t$) is fitted to the measured variables which are seen in the detector:

$$P_E(x; m_t, f_{ii}) = f_{ii}P_t(x; m_t) + (1 - f_{ii})P_b$$

where $x$ stands for measured kinematic variables, $f_{ii}$ is fraction of signal events, and $P_t$ ($P_b$) is the probability that the event represent signal $t\bar{t}$ (background) event. The probability $P_t$ can be expressed by parton distribution functions of the colliding proton and anti-proton, the detector response, and the differential partonic cross section, which is defined by matrix element. This method uses the full event information and take into account also event-by-event differences. The final result of measured top-quark mass is extracted from the sample likelihood defined as $L = \prod P_E$.

3. Measurements
3.1. CDF measurement using data sample of 8.7 fb$^{-1}$ in lepton+jets channel

The measurement is based on the template method, where templates of three sensitive variables are obtained from MC samples generated with 76 different $m_t$ assuming 29 possible shifts in jet energy scale (JES).

The events are required to contain one isolated electron (muon) with the transverse energy $E_T$ (momentum $p_T$) greater than 20 GeV (GeV/c) and at least four jets with $E_T > 20$ GeV and $|\eta| < 2.4$. The jets can be tagged as $b$-jets using SECVTX $b$-tagging algorithm [3]. Due to the presence of neutrino the amount of the missing transverse energy is required ($E_{\text{MET}} > 20$ GeV).

For the further suppression of the background in the events with zero and one $b$-tagged jets we allow the fourth jet to have $E_T > 12$ GeV and $|\eta| < 2.4$. To increase the subsamples of events with one and two $b$-tagged jets we allow the fourth jet to have $E_T > 12$ GeV and $|\eta| < 2.4$.

To obtain the background predictions we use MC simulations or in case of QCD multijets data-driven method. The individual sources are then combined using their relative cross-section and acceptances. The backgrounds are assumed to have no dependence on top-quark mass, but all MC-based background are allowed to have $\Delta_{\text{JES}}$ dependence.

To reconstruct the top-quark mass $m_t^{\text{reco}}$, we use the kinematic fitter [4] which assigns the four highest-$p_T$ jets to the four final-state quarks from $t\bar{t}$ decay and associate the leptonically decaying $W$ boson to the $b$ jet originating in the same top-quark decay. It minimizes the $\chi^2$ variable defined as:

$$\chi^2 = \sum_{i=t,\text{4jets}} \frac{(\hat{p}_T^i - p_T^i)^2}{\sigma^2_i} + \sum_{j=x,y} \frac{(\hat{p}_T^{j/E} - p_T^{j/E})^2}{\sigma^2_j} + \frac{(M_{jj} - M_{W})^2}{\sigma^2_W} + \frac{(M_{b\ell}\nu - M_{W})^2}{\sigma^2_W} + \frac{(M_{b\ell\nu} - m_t^{\text{reco}})^2}{\sigma^2_t} + \frac{(M_{b\ell\nu} - m_t^{\text{reco}})^2}{\sigma^2_t}$$

The first term constrain the best-fit value $\hat{p}_T$ of the jets and lepton, within their uncertainties ($\sigma_i$), to remain close to their measured values $p_T$. Similarly the second term constrain the value of the unclustered energy, which represents the energy in the calorimeter towers not associated
3.2. DØ measurement using data sample of 3.6 fb⁻¹ in lepton+jets channel

This measurement is based on matrix element method. It uses 2.6 fb⁻¹ of the collected data and at the end combine the result with the one obtained previously, what leads to most precise measurement of DO collaboration.

The events are required to contain exactly one isolated electron (muon) with \( E_T > 20 \text{ GeV} \) and \( |\eta| < 1.1 \) (\( p_T > 20 \text{ GeV}/c \) and \( |\eta| < 2 \)), and exactly four jets with \( |\eta| < 2.5 \) with the highest \( p_T \) jet having \( p_T > 40 \text{ GeV}/c \) and the other three jets \( p_T > 20 \text{ GeV}/c \). The missing transverse energy is required to be greater than \( 20 \text{ GeV} \) (\( 25 \text{ GeV} \)) in case of electron+jets (\( \mu \)+jets) events. The QCD multijets background is suppressed by requiring a minimal azimuthal separation between the lepton and missing transverse energy \( \Delta \phi(e, \mathbb{E}_T) > 0.7 \pi - 0.045 \mathbb{E}_T \) or \( \Delta \phi(\mu, \mathbb{E}_T) > 2.1 - 0.035 \mathbb{E}_T \) in electron+jets or \( \mu \)+jets events, respectively. We further require at least one jet to be \( b \)-tagged by NN \( b \)-tagging algorithm [7].

The method used in this measurement is described in Sec. 2. The event probability density (used to express the overall likelihood) is defined by the probability of representing the signal \( t \bar{t} \) (\( P_t \)) and the probability of representing background (\( P_b \)). The \( P_t \) is dependent on top-quark mass \( (m_t) \) and jet energy scale factor \( (k_{\text{JES}}) \), while the \( P_b \) is independent on top-quark mass and depend on jet energy scale factor.

The measured value of the top-quark mass done on the dataset of 2.6 fb⁻¹ is \( m_t = 174.94 \pm 0.83 \text{(stat.)} \pm 0.78 \text{(JES)} \pm 0.96 \text{(syst.)} \text{ GeV}/c^2 \) [10]. The main systematic uncertainty (except of JES) comes from modeling of hadronization and underlying events.

3.3. CDF measurement using data sample of 8.7 fb⁻¹ in MET+jets channel

Similarly as in case of previously mentioned CDF measurement, this template based measurement uses MC samples generated with 76 different \( m_t \) assuming 29 possible shifts in jet energy scale (JES).

The events are selected by multijet trigger and are required to have at least four and at most six jets with \( E_T > 15 \text{ GeV} \) and \( |\eta| < 2 \). In addition to that no lepton is required and the significance of \( \mathbb{E}_T \) (\( \mathbb{E}_T/\sqrt{\sum E_T} \)) has to be less than \( 3 \text{ GeV}^{1/2} \). For further suppression of the background at least one jet has to be \( b \)-tagged using SECVTX \( b \)-tagging algorithm. The Neural Network (NN, described in Ref. [11]) is trained to better separation of the background from signal events. Only events with 1 (2) \( b \)-tagged jet(s) and NN output above 0.9 (0.8) are used.

The background is dominated by QCD multijets production and so is estimated by data-driven method. A per-jet \( b \)-tag rate matrix is build from a \( t \bar{t} \)-signal-negligible data sample,
which consists of events with exactly three jets. The matrix is applied to events with higher jet-multiplicity to estimate the background rate. The background estimation is then validated at different jet-multiplicities at the background dominant region.

As in case of the measurement described in Sec. 3.1 the top mass kinematic fitter is used to reconstruction top-quark mass. However the $\chi^2$ is defined by modified equation:

$$\chi^2 = \sum_{i=\ell,4\text{jets}} \frac{(\hat{p}_i^\ell - p_i^\ell)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(\hat{p}_j^{UE} - p_j^{UE})^2}{\sigma_j^2} + \frac{(M_{ij} - M_W)^2}{\sigma_W^2} + \frac{(M_{bjj} - m_{t\mu}^{\text{reco}})^2}{\sigma_{b\mu}^2} + \frac{(M_{b\bar{T}} - m_{t\nu}^{\text{reco}})^2}{\sigma_{t\nu}^2}$$

where the first four terms are the same as in Eq. 2 and the last term represent the difference of top-quark mass and the invariant mass of $b$-jet and $E_T$ assuming that $E_T$ information include not only the neutrino, but also the undetected lepton information.

The final results is obtain by the same method as is described in Sec. 3.1 using three top-quark-mass sensitive variables $m_{t\mu}^{\text{reco}}$, $m_{t\nu}^{\text{reco}(2)}$ and $m_{bjj}$. The measured top-quark mass is 173.9$^{+1.6}_{-1.7}$(stat.+JES)$^{+0.9}_{-0.8}$(syst.) GeV/$c^2$. The main source of the systematic uncertainty comes from the residual JES and MC generator. [11]

3.4. DΟ measurement using data sample of 5.3 fb$^{-1}$ in dilepton channel

This measurement is based on neutrino weighting technique ($\nu$WT, kind of matrix element method) [12]. It uses 4.3 fb$^{-1}$ of the collected data and at the end combines the result with the one obtained previously.

The events with two isolated leptons ($ee$, $e\mu$, $\mu\mu$) with $p_T > 15$ GeV/$c$ are further required to have at least two jets with $E_T > 20$ GeV and $|\eta| < 2.5$. The electrons (muons) are selected if satisfy the requirement of $|\eta| < 2.5$ ($< 2$). In addition to that $\mu\mu$ events are required to have $E_T > 40$ GeV, sum of the leading-lepton $p_T$ and jets' $p_T$ has to be higher than 120 GeV in case of $e\mu$ events, and in case of $ee$ and $\mu\mu$ events, the $E_T$ has to be significantly different than typical values found in the distribution from $Z$ boson events. Detailed description of the selection criteria can be found in Ref. [13].

The background coming from $Z/\gamma^*$ and dibosons are simulated by MC, while background from instrumental effects resulting in lepton misidentification are modeled by data.

To extract the top-quark mass, we employ the $\nu$WT technique. We integrate over the $\eta$ distributions of both neutrinos and solve the event kinematics to allow a calculation of $E_T$ from the neutrino momentum solutions. By comparing the calculated $E_T$ to the measured one for each event, we calculate a weight for a given $m_t$. For each neutrino rapidity sampling, we sum the weight values calculated from all combinations of neutrino momentum solutions and jet assignments. We therefore arrive at a distribution of relative weight for a range of $m_t$ for each event (MC samples are generated for $m_t$ range from 140 to 200 GeV). Requiring the integral of this distribution to be nonzero excludes events with a measured $E_T$ that is incompatible with coming from neutrinos from top quark decay. We generate distributions of $tt$ signal as a function of $m_t$ and the mean and RMS values of the event weight distributions. Finally we perform a binned maximum likelihood fit of an analyzed event sample to these probability distributions according to the total signal and background yields expected in our data. [14]

Applying this method to the data sample of 4.3 fb$^{-1}$ we obtain the value of the top mass $173.7^{+2.8}_{-2.4}$(stat.)$^{+1.5}_{-1.4}$(syst.) GeV/$c^2$. This result is combined with the previous measurement done on 1 fb$^{-1}$ of data using the $\nu$WT and matrix weighting methods [15]. The combine measurements yields $m_t = 174.0^{+2.4}_{-2.1}$(stat.)$^{+1.4}_{-1.4}$(syst.) GeV/$c^2$ [14]. The systematic uncertainty coming from jet energy calibration is reduced by using a correction obtained from DΟ lepton+jet measurement described in Sec. 3.2.
4. Tevatron combination
The CDF and DØ collaborations measure the top-quark mass in the different final states using the different techniques. There are twelve individual measurements which are combined to result in a more precise value of the mass, than any individual decay channel can provide. In Fig. 1 we show the results of the individual measurements using the data sample with integrated luminosity of up to 5.8 fb$^{-1}$. The determined combined top-quark mass value is $m_{t}^{\text{comb}} = 173.18 \pm 0.56 \pm 0.75$ GeV, which has a precision of $\pm 0.54\%$. It makes the combined result the most precise one. [16].

The precision can be improved by including the measurements done on the full statistics of available collected data samples.

5. Top anti-top mass difference
This measurement is done on the lepton+jets data sample selected by the same criteria as are described in Sec. 3.1. To reconstruct the mass difference of top and anti-top quark, the kinematic fitter is used. The $\chi^2$ value calculated by the fitter can be expressed by doing simple substitution of $m_{t}^{\text{reco}}$ by term $(\overline{M}_t + dm_{\text{reco}}/2)$ in Eq. 2. The value of $\overline{M}_t$ is set to 172.5 GeV/$c^2$.

The measurement uses the template method and define two sensitive variables $\Delta m^{\text{reco}}$ and $\Delta m^{\text{reco}(2)}$ by lepton charge ($Q(l)$) and $dm_{\text{reco}}$ obtained from the minimum and 2$^{nd}$ minimum $\chi^2$ combination as follows:

\[
\Delta m^{\text{reco}} = -Q(l).dm_{\text{reco}}^{\text{min}}
\]

\[
\Delta m^{\text{reco}(2)} = -Q(l).dm_{\text{reco}}^{2\text{nd min}}
\]
There are 20 MC samples generated with different top-quark-mass difference. The final result is obtained by unbinned maximum likelihood fit, where the likelihood is defined by two-dimensional probability density functions obtained by KDE method. We measure top anti-top mass difference of $\Delta M_{\text{top}} = -1.95 \pm 1.11 \text{(stat.)} \pm 0.59 \text{(syst.)} \text{GeV}/c^2$ or $\Delta M_{\text{top}} = -1.95 \pm 1.26 \text{GeV}/c^2$. This result is consistent with CPT-symmetry expectation ($\Delta M_{\text{top}} = 0 \text{GeV}/c^2$). [17]

6. Conclusions
We present several new CDF and DØ measurements. CDF Collaboration comes with the results obtained using full statistics of collected data. The most precise measurement is still the Tevatron combination, which does not include the CDF full statistics measurements, yet. The combination using the collected data with integrated luminosity of up to 5.8 fb$^{-1}$ and determines the mass value of 173.18$^{+0.56\text{(stat)}}_{-0.75\text{(syst)}}$ GeV or 173.18$\pm 0.94$ GeV, what gives a precision of 0.54% and makes this result the most precise measurement. In addition, the measurement of the mass difference of top and anti-top quarks is present showing the mass difference of 1.95$\pm 1.26$ GeV.

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