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Top Physics at CDF

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Abstract. Top quark physics is one of the most important successes of the concluding Tevatron program. In this paper, a summary of the most recent measurements of top quark properties, including the mass and its 2011 average, will be presented. Some common techniques and discussion of major systematic uncertainties for top measurements will also be presented.

1. Introduction

With the conclusion of the Tevatron Run II colliding operation in the fall of 2011, top quark physics still reminds one of the most important priorities of the CDF program. Since the first evidence in 1994 [1] and the discovery of the top quark in 1995 [2][3], CDF invested a lot of effort to determine the top quark properties, especially the top quark mass. This effort combined with the newly collected data samples gave the collaboration the ability to produce, for the first time, analyses with results which are systematically dominated, e.g. the recent top mass and $t\bar{t}$ cross-section measurements.

In the past several years, the Fermilab accelerator complex performed extremely well averaging approximately 2.25 fb^{-1} per year. Until May 2011, the Tevatron delivered more than 11 fb^{-1}. The Run II-upgraded collider detectors continued to work with a high efficiency and collected more than 9 fb^{-1}. At the end of Run II, the delivered luminosity is expected to reach 12 fb^{-1}. The current plot with integrated luminosity delivered by the Tevatron and acquired by CDF is shown at Fig. 1.

This paper reports on the latest CDF top quark results which are based on about 6 fb^{-1} acquired data until the summer of 2009. It is expected about 4 more fb^{-1}will be collected by the end of the Run II.

At the Tevatron energy of $\sqrt{s}$=1.96 TeV, top quarks are produced generally in pairs from the process $q\bar{q} \rightarrow t\bar{t}$ in ∼85% of the cases. In the remaining ∼15%, $t\bar{t}$ pairs are produced via gluon fusion ($gg \rightarrow t\bar{t}$). Additionally, top can be produced as a single quark by electroweak interactions, by W-gluon fusion or virtual W* production in the s-channel [4], but with a smaller cross section. This paper will not discuss the results from the single top analyses [5].

In the Standard Model the branching ratio of the decay $t \rightarrow bW$ is almost 100%. When a $t\bar{t}$ pair is produced, each of the W-bosons can decay into either a charged lepton and a neutrino (BR = 1/3) or into a $q\bar{q}'$ quark pair (BR = 2/3). This allows us to classify the final states as:

- Dilepton final state (DL), when both W bosons from the $t\bar{t}$ pair decay leptonically. This

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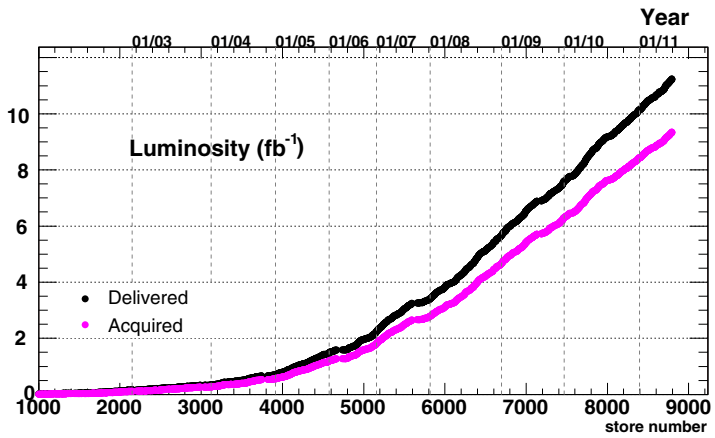

Figure 1. The Tevatron integrated luminosity and the CDF acquired luminosity until May 2011.

state is characterized by two energetic (high P_T) charged leptons, two jets from $b\bar{b}$ quarks [1] and significant missing transverse energy ($\not\!\!E_T$) from the neutrinos.

- Lepton plus jets final state ($L + J$), when one W boson decays leptonically and the other one hadronically. This state contains one high P_T charged lepton, four jets and significant $\not\!\!E_T$.
- All-hadronic final state (ALH), when both W bosons decay hadronically. This state is characterized by 6 jets, two of which are from b-quarks.
- $\not\!\!E_T$ +Jets final state ($\not\!\!E_T + j$), this is a sample of events comming mostly from $L + J$ when the high enrgy lepton is not detected due to limited detector coverage.

In Run II, CDF uses all of these signatures to measure the top quark properties, including the top quark mass.

2. Measurements of the top quark mass

As it was pointed in many previous papers and conference talks, top quark mass is a fundamental parameter of the Standard Model (SM). In the SM, the value of its mass cannot be predicted from the global electroweak fit with accuracy better than ~ 8 GeV/c^2. Thus, since the 1995 discovery, both the CDF and DØ experiments have been improving the top mass measurement accuracy.

The current understating of the origin of the non-zero masses in the SM is explained by spontaneous breaking of the electroweak symmetry induced by the Higgs field [6]. The top quark, which is the heaviest known fundamental particle in the SM with a mass value comparable to the electroweak scale, magnifies the suspect that this quark may play a special role in the mechanism of electroweak symmetry breaking. In addition, because of its mass, the top quark gives the largest contribution to loop corrections in the W propagator. Within the SM, the correlation between the top mass and the W mass induced by these corrections gives us the ability to set limits on the mass of the Higgs boson favoring a relatively light Higgs [7]. A more accurate measurement of the top quark mass will tighten the SM predicted region for the Higgs mass. Moreover, a precise measurement can be used as an additional constraint on the supersymmetric models beyond the SM [8].

[1] Errors in jet reconstruction and gluon radiation in the event may increase or decrease the observed number of jets. This statement is valid for all final states.

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2.1. Top kinematics and mass reconstruction methods

The $t\bar{t}$ kinematics and reconstruction methods depends on the final states. Historically, it was shown that the lepton plus jets final state provides the best mass measurement sensitivity. This channel combines signatures with high signal-to-background ratio (S/B), especially in the silicon vertices tagged events, with over-constrained kinematics. This means, that the number of measured quantities in the $L + J$ channel and the number of applicable energy-conservation equations, from five production and decay vertexes, are larger than the number of non-measured kinematical parameters in an event. This feature allows for a complete reconstruction of the four-momenta of the final state particles in the event, for example using the two constraint kinematical fit (2 CF) - a reconstruction of the top mass event-by-event.

In this type of analysis there is an ambiguity in how to assign the four leading jets to the two b and two light quarks coming from the $t\bar{t}$ system, so-called combinatorial uncertainty. If none of these jets is tagged by b taggers[2], there are 12 different ways of assigning jets to the 4 partons. Combining with the ambiguity from solving of a quadratic equation on P_z^ν of the neutrino, there are 24 different values of M_{top} returned by the kinematical fit. The combinations are reduced to 12 or to 4 if one or two of the jets are selected from b-taggers.

In contrast to the lepton plus jets mode, the di-lepton case, due to the presence of two neutrinos, has unconstrained kinematics. For this channel, the number of non-measured kinematical variables is larger by one than the number of kinematic constraints (-1 CF). Obviously, it is impossible to find only one solution for the mass value per event. Typical approaches to solve the unconstrained problem is to integrate over several of the event kinematic variables. Another way to approach the problem is to assume some kinamatical event parameters ($\vec{C}$) as known in order to constrain the kinematics and then vary $\vec{C}$ to determine a set of solutions. In this case, to determine a preferred mass, one may average all of the mass solutions or select the the most probable one.

The minimal requirement in the case of -1 CF kinematics is to use a two dimensional vector as $\vec{C}$. In DL analyses, we chose the pseudo-rapidities or the azimuthal angles of the two neutrino momenta ($\vec{C} = (\eta_{\nu 1}, \eta_{\nu 2})$ or $\vec{C} = (\phi_{\nu 1}, \phi_{\nu 2})$) to create a net of solutions in the $\vec{C}$ plane.

In case of the all-hadronic final state, a 3 CF kinematic fit[3] can be applied. This channel is kinematically easy to reconstruct but suffer from a very low S/B ratio, due to the large QCD multi-jet background which dominates the $t\bar{t}$ signal by 3 orders of magnitude after the application of the online trigger selection only. To improve S/B, requirements based on the kinematical and topological characteristics of standard model $t\bar{t}$ events are expressed in terms of a neural network and applied to the data. The neural network selection is followed by the requirement of jets to be b-tagged from the silicon vertex detector. This allows us to achieve a S/B of $\sim$ 1:2.

Table 1 summarizes the S/B in case of different finals states and after applying the b-jet tagging identification. Additional improvement of the S/B could be achieved if soft lepton b-jet tagger is applied [11] (it is not represented in the table).

The variety of the CDF analyses in different final states is relatively large. However, all analyses can be separated in three major categories:

(i) Template type analyses, where the reconstructed data distributions are compared with expected distributions from Monte Carlo generated signal (mass-dependent) and background. In these types of analyses, all events are weighted equally. By doing so one neglects the additional information coming from a different mass resolution in single events.

[2] CDF uses taggers based on either displaced vertices (Secondary Vertex Tagging, SVX, for example see [10]) or on low P_T electrons or muons from the b-quark semileptonic decays (Soft Lepton Tagging, SLT [11])

[3] If the conservation of the transverse momentum in the $p\bar{p}$ interaction point is applied, 5 CF is possible to be performed

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Table 1. Signal-to-background ratio for different final states.

Sample	Di-lepton S/B (e,μ)	Lepton plus Jets S/B (e,μ)	All-hadronic S/B after NN kin. selection	$\not\!\!E_T$ plus Jets S/B after NN kin. selection
0 b-tags	1:1	1:3	1:20	1;10
1 b-tags	4:1	3:1	1:3	3:2
2 b-tags	20:1	10:1	1:1	6:1
Top Events in 1 fb^{-1} ($\geq$ 1 b-tags)	25	180	300	150

(ii) Matrix Element type analyses, originally proposed by Dalitz and Goldstein [12] and independently by Kondo [13]. These methods calculate the posterior probability, given the known production cross section, for every event with measured kinematic properties, to originate from a $p\bar{p} \rightarrow t\bar{t}$ process.

(iii) A mixture between methods 1) and 2). For example the $t\bar{t}$ event is reconstructed using the kinematic algorithms similar to the template analyses but an event-by-event probability of each kinematic reconstruction is exploited as a weight (e.g. $exp(-\frac{\chi 2}{2})$). A typical example of this category is the CDF all-hadronic ideogram analysis [14].

2.2. Jet Energy Scale

In Run I, the uncertainty coming from the calorimeter jet energy scale was dominating the total systematic error. This uncertainty, commonly named *a priori* uncertainty, was determined from different calibration samples like photon plus jet, Z plus jet and di-jet events [15]. There are many sources of uncertainties related to jet energy scale at CDF, but the major ones can be summarized as:

- Relative response of the calorimeters as a function of pseudorapidity.
- Single particle response linearity in the calorimeters.
- Jet Fragmentation.
- Modeling of the underlying event energy.
- Correction for the energy deposited out of the jet cone.

The upper uncertainties are evaluated separately as a function of the jet p_T and η. The summary contributions are shown in Fig.2 for the η region of $0.2 < \eta < 06$. The black lines show the total $\pm$ 1σ total uncertainty which is taken as a unit of jet energy scale miscalibration in the analyses.

In Run II, CDF takes advantage of the larger $t\bar{t}$ samples available and employ new analysis techniques to reduce the JES uncertainty. In particular, the Run II analyses in the lepton plus jets, all hadronic and $\not\!\!E_T$ +Jets channels constrain the response of light-quark jets using the kinematic information from $W \rightarrow qq'$ decays (*in situ* calibration). Residual JES uncertainties associated with p_T and η dependencies as well as uncertainties specific to the response of b-jets are treated separately. This method decreased in the order of magnitude the systematic uncertainty on the top quark mass associated with JES. Moreover, in analyses where W decays only leptonically, a JES scale determined from external data samples can be used to decrease top mass uncertainty.

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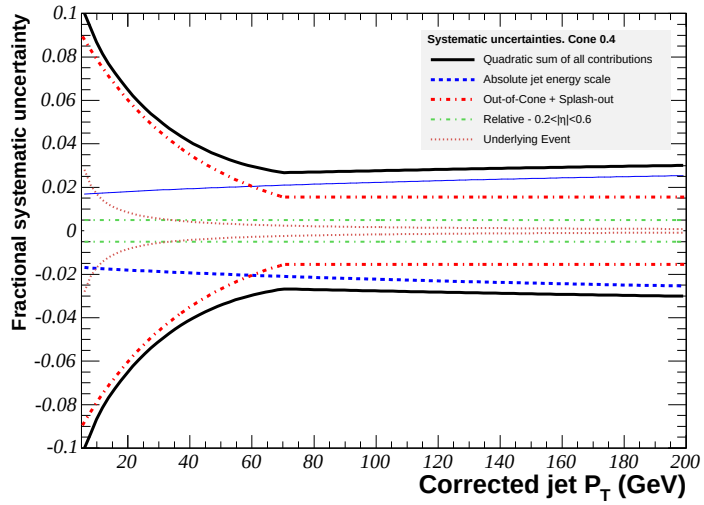

Figure 2. Jet energy scale (JES) uncertainty as a function of the corrected jet p_T for the underlying event (dotted red), relative response (dashed green), out-of-cone energy (dashed red) and absolute response (dashed blue). The contribution of all sources are added in quadrature (solid black line) and shows the total JES systematic uncertainty.

2.3. Lepton plus jets final state

The most accurate top quark mass measurement comes from the lepton plus jets final state. As it was mentioned earlier, this final state combines the benefits of good S/B ratio, the possibility to reconstruct the top quark mass event by event with a relatively small combinatorial effect, and a large branching fraction. In brief, we summarize below the main selection criteria for this channel. The events have the signature $p\bar{p} \to t\bar{t}X \to \ell\nu bq\bar{q}'\bar{b}X$. The characteristics of this final state begins with the identification of one isolated central high energy lepton (e with $E_T >$ 20 GeV or μ with $P_T >$ 20 GeV) and $|\eta| < 1$[4]. In recent analyses, CDF included the samples with forward muons $|\eta| > 1$ which are collected with a dedicated trigger on missing transverse energy [17] with a muon p_T >20 GeV/c. Assuming that the lepton is coming from W boson decay, a companion neutrino should exist. As the neutrino energy is not detected, we require $\not{E}_T$ >20 GeV in the event.

In order to fully reconstruct the $t\bar{t}$ system, at least four central jets $|\eta| \leq 2$ are required in the system. The SVX tagging algorithm is run over the leading jets (E_T >15 GeV). To obtain maximum statistical benefit from the event sample it is helpful to decompose it into two classes of events (1-SVX tag and 2-SVX tag) which are expected to have different S/B ratios and therefore different top mass resolutions.

The recent most accurate CDF $L + J$ analysis is based only on the sample with four tight jets [18] and integrated luminosity of 5.6 fb^{-1}, and uses the Matrix element methodology.

The dominant backgrounds in all samples are direct W plus multi-jet production, including heavy flavor production, and QCD multi-jet events where one jet is misidentified as a lepton. Additional small backgrounds are due to WW/WZ and single top production, Table 2.

For each event, a likelihood function depending on of the true top mass M_{top} and deviation from the true detector energy scale ΔJES is constructed as:

$$L_{ev}(\vec{y} \mid \mathrm{M}_{top}, \Delta\mathrm{JES}) = \frac{1}{N}\sum_{1}^{24}\int \frac{PDF(z_p, z_{\bar{p}})}{Flux}\ \mathrm{TF}(\vec{y} \mid \vec{x}, \Delta\mathrm{JES})\ |\mathrm{ME}(\mathrm{M}_{top}, \vec{x})|^2\ \Phi(\vec{x}) \qquad (2.1)$$

[4] A complete description of the lepton selection, including all cuts used, can be found elsewhere [16]

Table 2. Expected sample composition for an integrated luminosity of 5.6 fb^{-1}. The $t\bar{t}$ contribution is estimated using a cross section of 7.4 pb [19] and M_{top} = 172.5 GeV/c^2.

Event	1 b-tag	2 b-tag	Source/Generator
$W + Heavyflavor$	129.5±42.2	15.7±5.5	Alpgen[20]
Non-W (QCD)	50.1±25.5	5.5±3.8	Data[21]
$W + Lightflavor$ (Mistag)	48.5±17.1	1.0±0.4	Alpgen
Diboson (WW,WZ,ZZ)	10.5±1.1	1.0±0.1	Pythia[22]
Single top	13.5±0.9	4.0±0.4	Madgraph[23]
$Z \to ll$ + jets	9.9±1.2	0.8±0.1	Pythia
Total background	261.8±60.6	28.0±9.6	-
$t\bar{t}$ signal	767.3±97.2	276.5±42.0	Pythia
Total expected	1029.1±114.5	304.5±44.1	-
Total observed	1016	247	Data

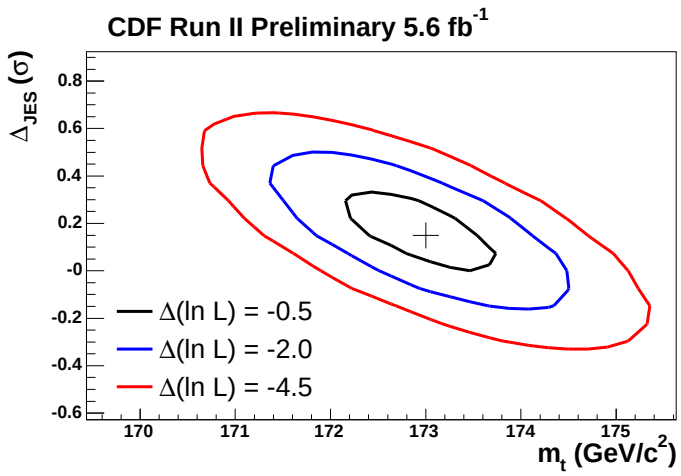

Figure 3. 2D likelihood on the 1087 data events: the contours corresponding to 1σ, 2σ, and 3σ uncertainty in the M_{top} measurement are shown.

where $\vec{y}$ are the kinematical quantities measured in the detector (e.g. jets and lepton momenta), $\vec{x}$ is the parton level variables which define the event kinematics, N is a normalization factor including the event acceptance, PDF are the parton distribution functions for incoming $p\bar{p}$ with momentum fractions z_p and $z_{\bar{p}}$, $Flux$ is the relativistic flux factor, and $\mathrm{TF}(\vec{y} \mid \vec{x}, \Delta\mathrm{JES})$ are the transfer functions that estimates the probability specific parton kinematic to produce measured jets. $\mathrm{ME}(M_{top}, \vec{x})$ is the leading order matrix element and it includes both $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ production processes with appropriate spin correlations. All 24 possible permutations are summed with weight corresponding to the probability jet to originate from b or light quark.

The total likelihood L_{total} for all candidate events are calculated under the assumption that all events are signal. In reality, L_{total} contains contributions from both signal and background events. To correct for the background events, an average background contribution to L_{total} is calculated and subtracted.

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Fig. 3 shows the L_{total} 2D likelihood contours for 1σ, 2σ and 3σ. The next step is to treat ΔJES as a nuisance parameter and eliminate it using the profile likelihood method, taking the maximum value of L_{total} along the ΔJES axis for each M_{top}. This procedure gives us ability to extract the top mass value of 173.0 ± 0.9 GeV/c^2. Two effects are contribution to the error of 0.9 GeV/c^2. The first part is the statistical uncertainty on M_{top} and the second part is the uncertainty due to ΔJES. By fixing the ΔJES to correspond to the maximum value of L_{total}, one can separate these contributions: 173.0 ± 0.7 $(stat.) + 0.6$ (JES) GeV/c^2.

Table 3 shows typical systematic categories for top mass analyses. These categories and how they are evaluated are the outcome of many years of effort of the CDF and DØ collaborations [24]. Many of the systematic uncertainties decreased significantly with time due to increasing knowledge of the source of the data versus MC discrepancies, adding improved particle generators, and new calibration samples. For CDF mass analyses, even after applying of the *in situ* calibration, the residual JES uncertainty associated with the p_T and η dependencies still dominates in the systematic tables. This fact stresses the importance of better calorimeter calibrations in wide p_T and η regions.

The other systematic uncertainties in Table 3 correspond to sources from: the calibration of the method, signal Monte Carlo modeling (differences between PYTHIA and HERWIG [25] generators), tuning the parameters used for initial state radiation and final state radiation to CDF Drell-Yan data, additional uncertainties on JES for b-jets (reflecting to the differences between light and gluon jets versus b-jets), uncertainty on the lepton p_T scale, multiple hadron interactions (we take into account uncertainty on the jet corrections as a function of the number of interactions in the event), uncertainties arising from the PDFs, the background modeling and the systematic uncertainty due to color reconnection effects. The individual systematic uncertainties added in quadrature is 0.88 GeV/c^2. This determines the total top quark mass uncertainty and makes the analysis the most precise single measurement available to date: 173.0 ± 0.9 $(stat. + \text{JES}) \pm 0.9$ $(syst.)$ GeV/c^2

2.4. Dilepton Final State

CDF has a dilepton final state measurement of the top quark using 5.6 fb^{-1} of data. This measurement was performed utilizing the template methodology. The analysis uses two

Table 3. Typical systematic uncertainties on M_{top}. The categories are the same for all top quark mass analyses. The values are from ME $L + J$ analysis.

Systematic source	Systematic uncertainty (GeV/c^2)
Residual JES	0.49
Calibration	0.10
MC generator	0.37
ISR and FSR	0.15
b-JES	0.26
Lepton P_T	0.14
Multiple hadron interactions	0.10
PDFs	0.14
Background modeling	0.34
Gluon fraction	0.03
Color reconnection	0.37
Total	0.88

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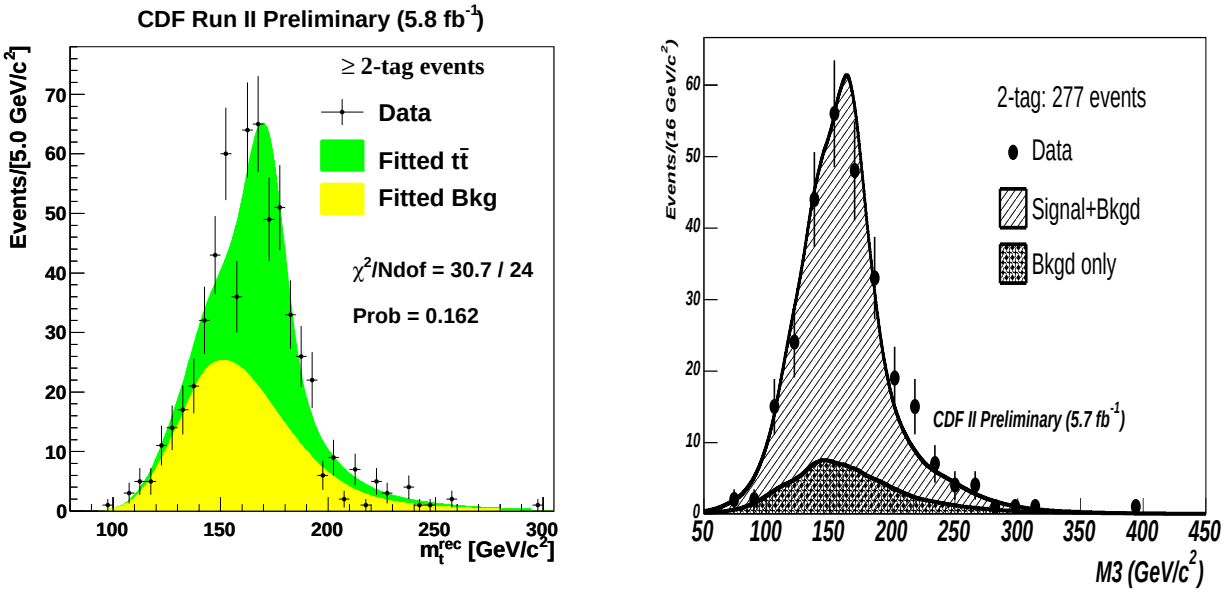

Figure 4. Reconstructed M_{top} in the case of ALH for events with two b-tag jets is shown on the left. The right plot shows the reconstructed invariant mass $M3$, described in the text, for the events with two b-tag jets in the $\not{E}_T$ +Jets final state.

dimensional templates where one of the two variables is M_{top} reconstructed with the neutrino weighting method [26, 27]. The idea of the method is to scan over the unknown pseudorapidities of the two neutrinos and to weight the solutions based on the $\not{E}_T$ event resolution. The second variable is m_{T2} [28, 29] which corresponds the the transverse mass in two missing particles final states, in our case the two neutrinos. A total of 237 events with no tagged jets and 155 with at least one tagged jet are selected with expected background of 82±22 and 9±1 events respectively. One can see that non-tagged and tagged events have very different S/B and using them as statistically independent samples increases the sensitivity of the method. This analysis provides the current most accurate published measurement in DL of 170.3±2.0 ($stat.$)±3.1 ($syst.$) GeV/c^2 [30].

2.5. All-hadronic final state

As it was discussed in 2.1, ALH has the advantages of a large BR, and of a fully reconstructable kinematics - all partons from the $t\bar{t}$ could be detected in the detector. The major downside is the huge background from QCD multi-jet production.

The most recent and precise measurement of M_{top} in this channel has been obtained by the CDF experiment using template methodology with 5.8 fb^{-1} of data [31]. After pre-selection cuts and a requirement of at least one b-tagged jet, a neural net is applied. This neural net includes both kinematical and jet shape variables increasing the S/B ratio to 1:3 for single b-tagged events and 1:1 for the double and more b-tagged events. Then, a kinematic fit is performed to reconstruct, for each event, the top and W masses. These variables are then used as templates to fit the data in order to obtain the M_{top} and JES, simultaneously.

A total of 2256 events with exactly one b-tagged jet and 600 with at least two b-tagged jets are selected, with an expected background of 1712±77 and 305±22 events respectively. The background is estimated directly from the non-tagged events, where the correction for the small amount of signal is applied. The final likelihood fit returns 172.5 ± 1.7 ($stat.$ + JES) ± 1.2 ($syst.$) GeV/c^2 corresponding to an accuracy of 1.2%. The data fit in case of two b-tagged events is shown in Fig. 4, left.

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2.6. $\not\!\!E_T$ +Jets final state

For the first time CDF performed analysis in a final state called $\not\!\!E_T$ +Jets [32] with 5.7 fb^{-1} data. This final state contains events mostly from the lepton plus jets decay mode where the lepton is not reconstructed due to limited detector coverage. To start the selection we use fully hadronic trigger with high jet multiplicities, at least four jets. Additionally, the events are required to have a well measured $\not\!\!E_T$ but no leptons. The last requirement is an important criteria in creating a statistically independent sample. The next step is to apply a neural network selection to improve S/B in this sample. The events with lower probability to be produced by the $t\bar{t}$ interactions are used to estimate the shape of the QCD background.

The fact that this analysis does not identify the lepton from $t\bar{t}$ event makes it impossible to perform a full kinematical reconstruction. However, we can reconstruct the invariant mass called $M3$, which is defined as the invariant mass of three jets that give the largest jet $\not\!\!E_T$. To increase the chance that these three jets come from the same top quark decay, we select two of the three jets without b-tags to have an invariant mass m_{jj} closest to the W mass and use them to constrain JES in the analysis. We also reconstruct a third variable called $M3'$, similar to $M3$ mentioned above, except that the third jet is different from any of the three jets that construct $M3$. A multidimensional likelihood fit with three dimensional templates ($M3$, $M3'$ and m_{jj}) is performed. The final result from the likelihood is 172.3 ± 2.4 $(stat. + \mathrm{JES}) \pm 1.0$ $(syst.)$ GeV/c^2 corresponding to an accuracy of 1.5% in the determination of the top mass. Fig. 4, right, shows the reconstructed $M3$ variable for double b-tagged events at the top mass of 172.5 GeV/c^2.

2.7. Top mass combination

CDF combined the measurements from different channels using the best linear unbiased estimation technique [33]. For CDF measurements, the method returned the most probable mass $\mathrm{M}_{top} = 172.7 \pm 1.1$ GeV/c^2 [34]. By combining with DØ results [35], we obtained the best Tevatron top quark mass of 173.2 ± 0.9 GeV/c^2. For first time the total uncertainty is below 1.0 GeV/c^2 and the relative precision is 0.5%. Fig. 5, left, shows the Run I and Run II measurements included in the latest CDF combination. All of these measurements are statistically independent; the systematic uncertainties are combined according to the correlations. The plot on the right extrapolates how the top mass uncertainty is expected to decrease with increasing of the integrated luminosity starting from the first CDF statistically significant measurement at 680 pb^{-1}. The triangles represent the measurements or averages of M_{top} up to 5.8 fb^{-1}. The solid curve represents the trend which keeps all the systematic uncertainties at level of the 680 pb^{-1} measurement, but scales the statistical and "in-situ" JES uncertainties with the integrated luminosity. The dotted curve scales the total uncertainty with luminosity. It represents the lower bound on how well the top mass could be measured. CDF measurements are close to the dotted curve showing a large improvement of the systematic uncertainty with the integrated luminosity.

3. Measurements of the top quark properties

Additionally to the determination of the top mass, we have studied the top quark properties in various ways using its unique characteristics. Top quark decays before hadronization thus the property information is carried by the its decay products. In this paper we present a selection set of measured top properties. The full set of measurement could be found in the CDF public web-pages [36].

A recent and intriguing CDF result with 5.3 fb^{-1} of data is the measurement of the forward-backward asymmetry A_{FB} in the $t\bar{t}$ production. This measurements can be done only at the Tevatron and cannot be reproduced at LHC where the initial state is symmetric. In LO QCD, the top production angle is symmetric with respect to the beam direction. In NLO QCD, a small charge asymmetry, $A_{FB} = 0.05 \pm 0.01$, is predicted and it is due to the to

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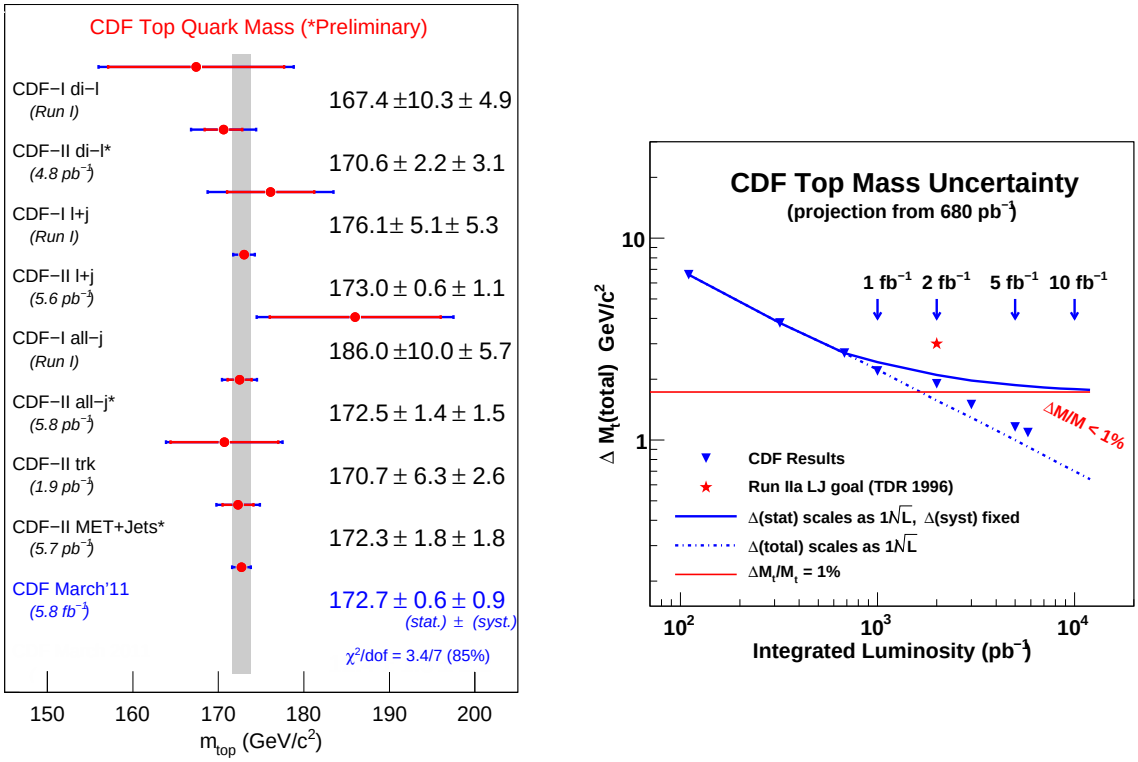

Figure 5. The combination of the top mass is shown in the left plot. The right plot shows the expected uncertainty corridor versus the integrated luminosity and the CDF measurements.

interference between initial-state radiation diagrams with final-state ones [37]. The integral forward-backward asymmetry A_{FB} is defined as $A_{FB} = \frac{N_{top}(p)-N_{top}(\bar{p})}{N_{top}(p)+N_{top}(\bar{p})}$ where $N_{top}(p)$ ($N_{top}(\bar{p})$) is the number of tops observed in the proton (anti-proton) direction. CDF measured A_{FB} in $L+J$ and DL channels. Both results deviate 2σ, $A_{FB}^{LJ} = 0.181 \pm 0.075(stat. + syst.)$ and $A_{FB}^{DL} = 0.42 \pm 0.16(stat. + syst.)$, compared to the SM model prediction. Moreover, for the $L+J$ analysis CDF investigated the dependence of A_{FB} on the rapidity y and the $t\bar{t}$ invariant mass $M_{t\bar{t}}$. If some discrepancy in the dependence of A_{FB} is observed a possible interpretation could be explained with the presence of extra particles decaying to $t\bar{t}$ with a large forward-backward asymmetry. Fig. 6 shows the measured asymmetry dependence on $M_{t\bar{t}}$. While in the low region (< 450 GeV/c^2) measurement A_{FB} is consistent with the SM prediction, a 3σ deviation is observed in the high mass region. The rapidity y dependence of A_{FB} shows a 2σ deviation from the SM prediction.

Top quark is so heavy that it is practically impossible directly to determine its lifetime. However, one can measure the top decay width which is proportional to the top lifetime. CDF has a direct measurement of the top quark width Γ_t based on 4.3 fb^{-1} $p\bar{p}$ collision. This analysis uses template methodology and exploits the dependence of the reconstructed M_{top} width in the $L+J$ channel on Γ_t. Each event is compared to templates created with different Γ_t and the most probable value is extracted. The correct accuracy do not allow us to measure Γ_t but rather to find a limit. By applying a Feldman-Cousins approach, we establish an upper limit of $\Gamma_t < 7.6$ GeV at 95% CL and a two-sided 68% CL interval of 0.3 GeV $< \Gamma_t <$ 4.4 GeV [38].

The $t\bar{t}$ spin correlation is well predicted by the SM and any deviation is a sign for new physics coupled to the top quark. The spin state can be observed in the angular correlations in the DL channel where the two leptons are well measured. In this channel, CDF found $k = -0.086^{+0.59}_{-0.57}$ which is consistent with standard model prediction of $k \sim 0.78$ within 95% CL interval [39]. This measurement is currently limited by the statistics of the data sample.

The SM predicts that the W→tb vertex is a 100% V-A coupling. As a consequence, ∼

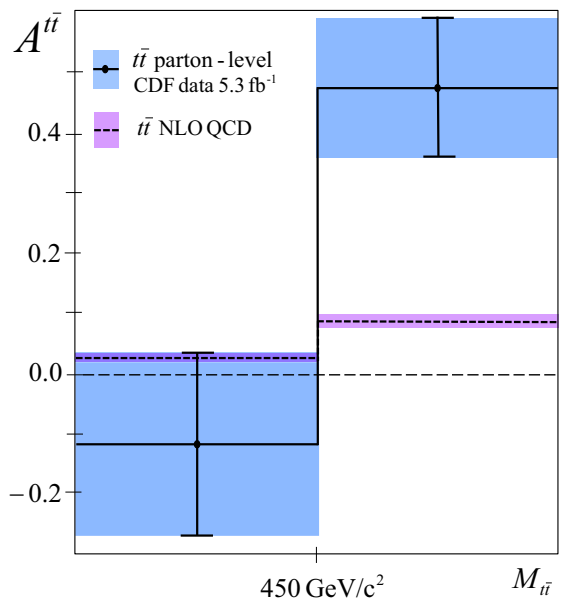

Figure 6. Measured forward-backward asymmetry A_{FB} for two regions of the $t\bar{t}$ invariant mass $M_{t\bar{t}}$

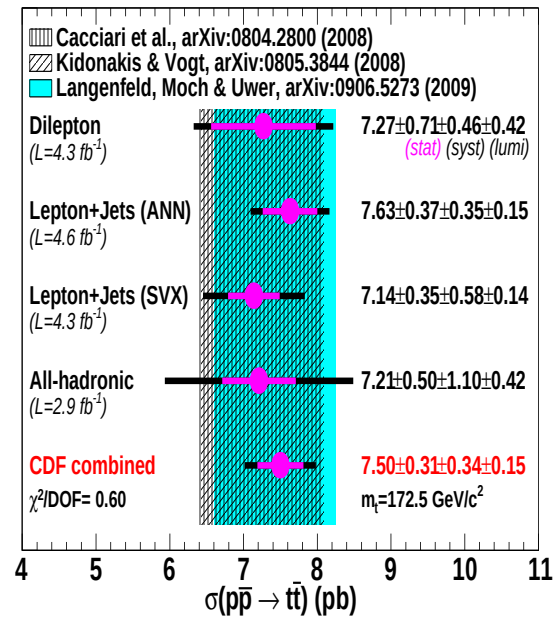

Figure 7. Summary of the CDF $t\bar{t}$ cross section measurements and the combined value.

70% of W bosons are longitudinally (f_0) polarized and in the other 30% of the cases they have a left handed polarization (f_-). Any new particles, which may be involved in the same decay topologies and having non-standard couplings could create a different ratio of polarized W bosons, even producing a few right-handed (f_+) ones. CDF has measurements for the W polarization in the $L + J$ [40] and DL [41] final states. In the most recent one, a model independent simultaneous measurement of f_0 and f_+ yields $f_0 = 0.78 \pm 0.20(stat.) \pm 0.06(syst.)$ and $f_+ = -0.12 \pm 0.11(stat.) \pm 0.04(syst.)$ which are also in good agreement with the SM.

Flavor changing neutral current (FCNC) are predicted in SUSY and other exotic physics models. In the SM, top FVNC decay modes are highly suppressed; in CDF any measurable signal from FCNC decays will indicate an evidence of new physics. FCNC decay of top quark (e.g. $t \to Zq$) predict different final states comparing to the $t\bar{t}$ event where $t \to Wb$. For example, if $Z \to l^+l^-$ and $W \to q\bar{q}'$ one could expect a dilepton final state without large $\not{E}_T$. CDF performed this type of analysis and set the 95% CL upper limit at 3.7% [42].

Finally, CDF measured $t\bar{t}$ cross section in all possible channels. The summary of these measurements and combined cross section value of $\sigma = 7.50 \pm 0.31(stat.) \pm 0.34(syst.) \pm 0.15(lum.)$ are shown in Fig. 7.

4. Conclusion

We presented the current status of the CDF top quark analyses. Due to the excellent performance of the Tevatron collider and the CDF detector, and many improvements in the analysis techniques, the collaboration has been performed many challenging measurements revealing the top quark properties [36]. Some of the measurements started to be systematically dominated. For first time, the Tevatron combined top quark mass has a precision less than 1 GeV/c^2 or $\frac{\Delta M_{top}}{M_{top}}$ =0.5% and the $t\bar{t}$ cross section with a precision of 6.5%. By the end of Run II, September 2011, we expect to have 12 fb^{-1} delivered to the CDF experiment, which approximately doubles our data analysis set. New and improved measurements are expected

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and the possibility of surprising results is not excluded.

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