Top quark properties at the Tevatron

G. Compostella
(on behalf of the CDF and DØ Collaborations)
INFN and University of Padova,
via Marzolo 8, 35131 Padova, ITALY
compostella@pd.infn.it

Summary. — Precise determination of the top quark properties allows for stringent tests of the Standard Model. In this paper we report the latest results from the CDF and DØ collaborations on a data sample of $p\bar{p}$ collisions at 1.96 TeV collected at the Fermilab Tevatron up to an integrated luminosity of 4.8 fb^{-1}.

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1. – Introduction

In the Standard Model of Particle Physics, the top quark is the "up-type" quark of the third generation, weak isospin partner of the bottom quark, with charge $Q = +2/3$.

After the top quark discovery in 1995 at the Tevatron by both the CDF and DØ collaborations [1, 2], many measurements have been performed to map its properties. Being the most massive fundamental particle known up to date, it is the dominant contributor to radiative corrections for many Standard Model processes. The top quark has also very large coupling to the not yet observed Higgs boson and may be related to the electroweak symmetry breaking mechanism, and thus sensitive to new physics, which could be constrained by measuring its production and decay properties. Thanks to the increasing quantity of data delivered by the Tevatron, amounting to more than 5 fb^{-1} to date, precision measurements on top quark physics can be performed, allowing to improve the understanding of the observed particle and its role within the Standard Model.

This paper reports the most recent results of measurements of top quark properties performed by both the CDF and DØ collaborations, in particular in the areas of top intrinsic properties and decay, providing a short summary of a few of them.

In $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV top quarks are mainly produced in pairs through quark-antiquark annihilation (85%) or gluon fusion (15%). Since within the Standard Model the top quark decays almost exclusively to a W boson and a b quark, the top pair production signatures can be classified with respect to the decay modes of the W boson. In 6% of all the $t\bar{t}$ decays, when both W's decay into electrons or muons, we have the so called dilepton channel; in 38% of the decays, when only one W decays into electrons or muons, the lepton plus jets channel. In the remaining 56% of the cases, when no electron or muon from the W decay are present in the event, we have the so called all-hadronic channel.

The presence of a b-quark in its decay can also be exploited to identify the top quark: b-quarks give rise to jets containing long lived b-hadrons, and those jets can be identified by looking for the presence of tracks in the detector compatible with a secondary decay vertex distinct from the primary interaction point. Such jets are called b-tagged, and the requirement of at least one b-tagged jet in the event is a powerful tool to increase the signal-to-background ratio in data.

2. – Top quark Mass

The top quark mass m_{top} is a fundamental parameter of the Standard Model, and its precise knowledge is necessary to calculate physics observables involving top quark quantum loops to high precision. Additionally, the determination of m_{top} can also give valuable indirect information on the Higgs boson mass m_H. The dominant radiative corrections to the W boson mass m_W come from loops containing top and bottom quarks, which are proportional to m_{top}^2, and from loops containing Higgs bosons, which are proportional to $log(m_H)$. Thus for each value of m_H, a unique line in the m_{top} and m_W parameter space is defined within the Standard Model. By measuring precisely the W boson and top quark masses, we can limit the range of values for m_H allowed by the Standard Model, as shown in fig. 1.

The measurement of the top quark mass relies on the precise reconstruction of the energy of its decay products. This is a major experimental challenge: while electrons and muons energies can be calibrated using well known $Z \to ee$ and $Z \to \mu\mu$ decays, dealing with quarks energies is more complicated. Since quarks manifest themselves as jets in the detector, the energy measurement of the calorimeter in the jet cone must be calibrated to the energy of the particles coming from the hadronization of the original quark in the same cone. Calorimeter response is calibrated by balancing the transverse momentum in events with a photon and a jet, and propagating this calibration to the parton level using Monte Carlo derived corrections. Variations in calorimeter response and gain are determined using dijet events, in order to determine the relative jet energy scale and have a uniform response in the calorimeter at all momenta. This allows to determine the jet energy calibration with a systematically limited precision of about $2-3\%$.
The jet energy scale is one of the dominant contributions to the systematic error in top quark mass measurements, with a relative effect of $3-6\%$. In order to reduce this uncertainty, we can use the hadronic decays of W bosons coming from the top decay to calibrate "in situ" the jet energy scale by constraining the invariant mass of the non b-tagged jets in the event to be equal to the W mass. This procedure provides an additional overall calibration factor for jet energies which is only statistically limited by the number of hadronic W decays in the sample, and allows the overall jet energy systematic on the top quark mass to scale directly with the luminosity.

Top mass measurements are currently performed following two basic classes of algorithms, that will be briefly described. In the template method a set of observables sensitive to m_{top} are reconstructed and used as estimators of the top quark mass. Their distributions for a range of top quark masses are derived from Monte Carlo simulations

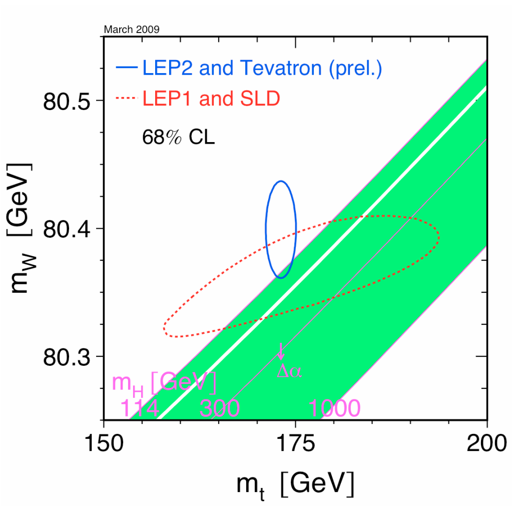

Fig. 1. – W boson mass versus top quark mass plane. The green band is consistent with the Standard Model for a Higgs mass in the range 114 GeV $< m_H <$ 1 TeV.

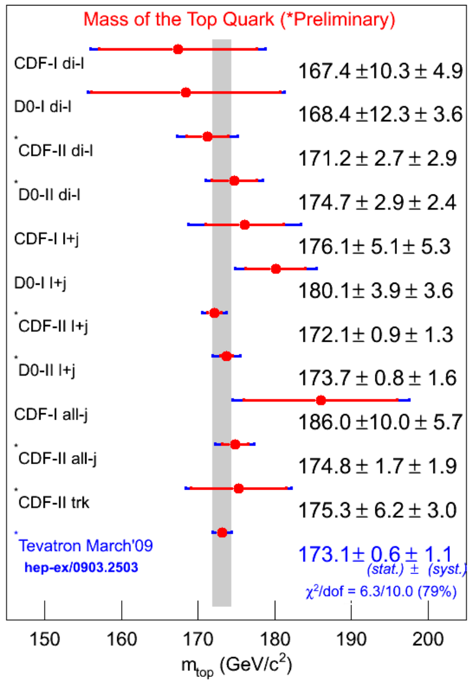

Fig. 2. – Summary of top quark mass measurements from the two Tevatron experiments CDF and DØ in the different channels, compared with the world-average determination. The summary is updated to March 2009.

and the shape of these distributions determine the so called templates. The behaviour of the chosen observables in data are compared to template expectations for different values of m_{top} and fractions of top signal in the sample, performing a likelihood maximization. Since the shape of a template depends both on the top quark mass and on the jet energy scale, which are free parameters in the likelihood, this technique can provide a determination of both of them. The CDF collaboration has recently used this method to measure the top quark mass in a data sample of dilepton and lepton plus jets events corresponding to an integrated luminosity of 4.8 fb^{-1}. Due to the presence of neutrinos in the final state, the kinematics of dilepton events is underconstrained, so that estimators of m_{top} must be calculated integrating over some unknown quantities. This analysis uses the Neutrino Weighting Algorithm: the unknown pseudorapidities of the two neutrinos are integrated over, and different solutions for a given top quark mass are weighted by the agreement with the missing transverse energy in the detector. The most probable value of the top quark mass is used as estimator for the true value of m_{top}. On the contrary, in lepton plus jets channel, the kinematic of the event is overconstrained. By using a kinematic fitter it is possible to select the single best assignment of jets to quarks in the hypothesis of a top pair decay, and determine the top quark mass in the selected configuration. The results of the first and second best assignment are used as estimators of the true value of the top quark mass. By combining the two template based measurements

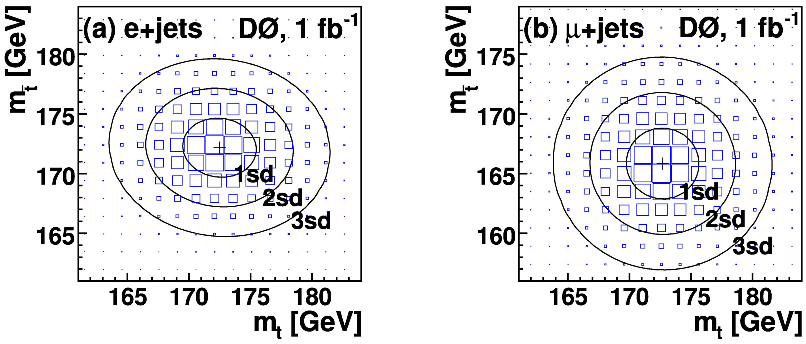

Fig. 3. – Direct measurement of the top antitop mass difference performed by the DØ collaboration in 1 fb^{-1} of data in the lepton plus jets channel. The lines show fitted contours of equal probability for the two-dimensional likelihoods as a function of m_t and $m_{\bar{t}}$ for electron (left) and muon (right) plus jets events. The blue boxes have areas proportional to the value of the likelihood evaluated at the bin center.

into the same likelihood, the result $m_{top} = 171.9 \pm 1.1$ (stat+JES) $\pm$ 0.9 (syst) GeV/c^2 is obtained [3].

Another algorithm used for the top quark mass measurement is the so called Matrix Element method, which tries to extract the most possible information from every event by constructing a per-event likelihood as a function of the top quark mass. The likelihood uses leading order theoretical predictions for the production and decay of the $t\bar{t}$ pairs, considering the matrix element of the process. In order to turn parton level predictions coming from the matrix element calculation into indications on the observed physics, it's necessary to take into account transfer functions: those functions depend on the jet energy scale and map the probability to observe a particular kinematics in the detector given an event configuration at the parton level. This way every observed event can be weighted according to its probability to come from a $t\bar{t}$ decay as a function of the top quark mass and the jet energy scale, which can be constrained through a likelihood maximization. The DØ collaboration has performed a top quark mass measurement in the lepton plus jets channel using the Matrix Element technique with an integrated luminosity of 3.6 fb^{-1}, obtaining the result $m_{top} = 173.7 \pm 0.8$ (stat) $\pm$ 0.8 (JES)$\pm$ 1.4 (syst) GeV/c^2 [4].

The CDF collaboration has recently approved a new measurement of the top quark mass in the lepton plus jets channel in 4.8 fb^{-1} of data where the Matrix Element method was combined with an additional per event discriminant based on the output of a Neural Network trained to discriminate between top events and W+jets and QCD backgrounds [5]. Thanks to this improvement, this analysis measures the top quark mass with an unprecedented precision, with a result of $m_{top} = 172.8 \pm 0.7$ (stat) $\pm$ 0.6 (JES) $\pm$ 0.8 (syst) GeV/c^2. It's interesting to note that total relative error on this measurement is even lower than the error on the world average for m_{top}, shown in fig. 2 along with the summary of the different measurements performed by the Tevatron experiments in the various top pair decay channels [6].

Another interesting measurement related to the top quark mass has been performed by the DØ collaboration in [7]. Using the Matrix Element method and a sample of 1 fb^{-1} of electron plus jets and muon plus jets events, and using the charge of the lepton to tag the presence of a top or antitop in the event, the first direct measurement of the mass difference between a quark and its antiquark partner has been carried out. This measurement is a direct test of the CPT theorem, fundamental to any local Lorentz-invariant quantum field theory, that requires that the mass of a particle and that of its antiparticle be identical. The result of the measurement for the two different samples is shown in fig. 3. The measured mass difference is $3.8 \pm 3.7\ GeV/c^2$, consistent with the equality of top and antitop masses.

3. – Top quark decay width

Using a template based method very similar to those employed to measure the top quark mass, the CDF collaboration has performed a measurement of the top quark decay width in the lepton plus jets channel using 4.3 fb^{-1} of data[8]. In the Standard Model the theoretical top quark lifetime is very short, of the order of $5 \cdot 10^{-25} s$, making the top quark decay before top-flavored hadrons or $t\bar{t}$-quarkonium bound states can form. The predicted top quark decay width is 1.5 GeV which is out of reach of current experiments. Deviations of the top quark decay width from the Standard Model predicted value could indicate the presence of additional top decay modes and would result in a change of the reconstructed top mass line shape. Using Monte Carlo simulations for different input top quark widths ranging from 0.1 GeV to 30 GeV with a fixed input top quark mass $m_{top} = 172.5\ GeV/c^2$, templates for the distributions of the invariant top quark mass and dijet mass of W boson in the lepton plus jets topology are reconstructed, forming a two-dimensional template for each sample. By comparing the shapes of these two observables with that of the events in the data, the top quark width can be extracted using a maximum likelihood fit. A Feldman-Cousins construction is used to build 95% confidence intervals and an upper limit is set on the top quark width of $\Gamma_{top} < 7.5\ GeV$ at 95% confidence level.

4. – Top antitop spin correlations

The fact that due to its short lifetime, top quark decays weakly before any hadronization processes take effect, enables the top spin information to be transmitted to the top quark decay products. Standard Model top pair production produces a characteristic spin correlation which can be modified by new production mechanisms such as Z' bosons or Kaluza-Klein gluons. The spin correlation coefficient k can be defined as $k = (N^S - N^O)/(N^S + N^O)$ where N^S and N^O are the number of $t\bar{t}$ pairs with parallel and antiparallel spin respectively.

CDF has performed a measurement of the top antitop spin correlations in the lepton plus jets channel with 4.3 fb^{-1} of data in the helicity basis [9]. The analysis uses the helicity angles of the lepton, the down quark, and the bottom quark which come from the hadronically decaying top. The helicity angle, defined as the angle between the decay product momentum (in the top rest frame) and the top quark momentum (in the top quark pair rest frame) carries information about the spin of the parent top quark. The top and top pair rest frames are determined using a kinematic fitter with constrained top quark mass. Monte Carlo samples for $t\bar{t}$ signal and for the various backgrounds are used to derive templates for the helicity angles of the top pair decay products in the two cases of t and $\bar{t}$ having either the same or opposite helicity. Finally a fit of the data to the sum of opposite helicity, same helicity and background templates is performed and the correlation factor is measured to be $k = 0.60 \pm 0.50$ (stat) $\pm\ 0.16$ (syst) to be compared

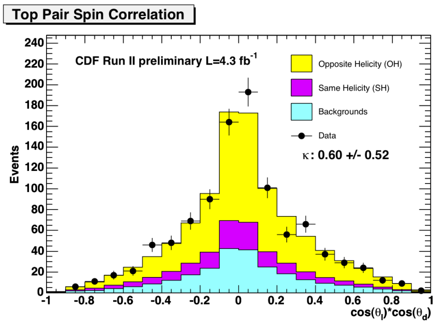

Fig. 4. – CDF measurement of the top antitop spin correlation factor in the lepton plus jets channel. The plot shows the distribution of $cos(\theta_l) \cdot cos(\theta_d)$, where θ_l and θ_d are the helicity angles of the lepton and the down type quark from the top decay, for $t\bar{t}$ signal samples with same and opposite helicity and backgrounds.

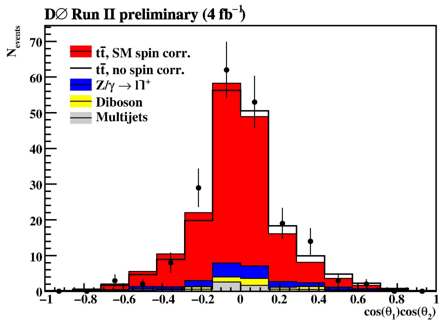

Fig. 5. – DØ measurement of the top antitop spin correlation factor in the dilepton channel. The plot shows the distribution of $cos(\theta_1) \cdot cos(\theta_2)$, where θ_1 and θ_2 are the angles of the leptons with the beam axis in the parent top rest frame for $t\bar{t}$ signal with and without spin correlations and backgrounds.

with a Standard Model expected value of $k^H_{SM} = 0.40$ in the helicity basis. The result of the fit is shown in fig. 4.

The DØ collaboration has also performed a measurement of the top antitop spin correlations in the dilepton decay topology using 4.2 fb^{-1} of data in the beam axis basis [10]. The analysis considers the angles between the direction of flight of each of the two leptons in the rest frame of their parent top quark and the reference direction of the beam axis. Selected dilepton events are reconstructed using the Neutrino Weighting Algorithm to integrate over the unknown neutrinos pseudorapidities and calculate a weight distribution for each event as a function of the lepton angles defined above. The data distributions for the angles are compared with Monte Carlo derived templates for $t\bar{t}$ signal built with different correlation hypotheses and with templates for the backgrounds to obtain the best fit value for the spin correlation factor, that is measured to be $k = -0.17^{+0.65}_{-0.53}$ (stat+syst), to be compared with a Standard Model expected value of $k^{BA}_{SM} = 0.78$ in the beam axis basis. The result of the fit is shown in fig. 5.

5. – Top quark charge

In the Standard Model the top quark is expected to have charge 2/3; due to its fast decay, a direct measurement of the charge is impossible, and only the total charge of the top decay products can be measured. Assuming that top quarks decay to a W boson and a b quark, exotic models have been proposed in literature as part of a fourth generation of quarks and leptons [11], where the top decays to a W^- and a b quark, hence having a charge of 4/3, rather than to a W^+ and a b quark as predicted by the Standard Model. The CDF collaboration has recently performed a measurement in the lepton plus jets channel in 2.7 fb^{-1}. The charge of the two Ws and two b-quarks is determined for each data event, using a kinematic fitter to select the best jet to parton assignment compatible with the top quark decay. The charge of one of the two W's is obtained by identifying the charge of the lepton in the event while the charge of the b-tagged jets is obtained considering the charge of soft leptons in the event compatible with the semileptonic decay of a b quark. Based on the total number of reconstructed top charges in agreement with the Standard Model hypothesis or with the exotic hypothesis, limits can be set on the validity of the two models. With this method, CDF observes 29 events consistent with the Standard Model and 16 events consistent with a 4/3 charge top quark. This results in a 95% confidence level exclusion of the 4/3 charge hypothesis [12].

The DØ collaboration has performed a similar measurement in the past on 0.37 fb^{-1}, using the JetCharge algorithm to determine the charge of the b-quarks in the event. With a similar technique, DØ excluded the 4/3 charge hypothesis with a 92% confidence level [13].

6. – Forward Backward asymmetry

The measurement of the $t\bar{t}$ charge asymmetry is equivalent in the Tevatron system to quantifying the forward backward asymmetry on the top production. Several beyond the Standard Model physics predict a detectable forward backward asymmetry, and in addition QCD at next-to-leading order predicts a non-zero asymmetry in $q\bar{q} \rightarrow t\bar{t}$. While at the LHC the top quark production is dominated by gluon fusion, at the Tevatron top pairs are mostly produced by $q\bar{q}$ annihilation, making it the best place to study these effects. Both the CDF and DØ collaborations have performed similar measurements to determine the forward backward asymmetry in top pair production. Events in the lepton plus jets channel, are fully reconstructed using a kinematic fitter, which fits the final states jets and leptons to the $t\bar{t}$ decay hypothesis, allowing to reconstruct the rapidities of the top and antitop. The asymmetry is defined as $A_{fb} = (N^f - N^b)(N^f + N^b)$ where N^f and N^b are the number of events in which the signed rapidity of the top is larger and smaller than that of the antitop respectively.

Once detector effects, bias and dilution from backgrounds, acceptance and reconstruction are taken into account, a measurement of A_{fb} can be performed that can be directly compared with theoretical values. In 3.2 fb^{-1} of data CDF measures $A_{fb} = 0.19 \pm 0.07$ (stat) $\pm$ 0.02 (syst) and in 1.0 fb^{-1} of data DØ measures $A_{fb} = 0.12 \pm 0.08$ (stat) $\pm$ 0.01 (syst) to be compared with the theoretical value from next-to-leading order QCD calculations of $A^{th}_{fb} = 0.05 \pm 0.015$.

7. – W boson helicity in top quark decays

In the Standard Model the top quark decays almost exclusively to a W boson and b quark through the V-A charged weak current interaction. As a consequence, the top quark is expected to decay around 70% of the times to longitudinal and the rest to left-handed polarized W bosons. A different structure of the Wtb vertex or the presence of any new particle could alter the fractions of W bosons produced in each polarization state, therefore a measurement of this fraction allows to perform a test of the V-A nature of the Wtb vertex. The polarization of the W boson can be described using the angle θ^* between the momenta of the down-type fermion and the top quark in the W boson rest frame for each top. The DØ collaboration has measured the longitudinal and right-handed fractions of the W boson helicity combining the lepton plus jets and dilepton $t\bar{t}$ decay channels using 2.7 fb^{-1} of data [14]. Lepton plus jets events are reconstructed using a kinematic fitter that allows to reconstruct the four vectors of the two top quarks and their decay products, and then calculate $cos\theta^*$. For hadronic W boson decays, since it's impossible to know which of the jets from the W boson arose from a down-type quark, a jet is chosen at random to calculate the variable $|cos\theta^*|$, that does not discriminate between left and right handed W bosons but adds information for determining the fraction of longitudinal W bosons. In the dilepton channel, since there is a four-fold ambiguity in the reconstruction of the event, $cos\theta^*$ is determined for each of the four possible combinations and the average value is taken for the considered jet. These distributions in $cos\theta^*$ are compared with Monte Carlo derived templates for different W boson helicity models, corrected for background and reconstruction effects, using a binned maximum likelihood method. Finally a fit is made simultaneously to the three set of templates measuring the fraction of longitudinal W bosons $f_0 = 0.49 \pm 0.11$ (stat) $\pm$ 0.09 (syst) and the fraction of right-handed W bosons $f_+ = 0.11 \pm 0.06$ (stat) $\pm$ 0.05 (syst).

The CDF collaboration has performed a similar measurement in the lepton plus jets channel using 2.7 fb^{-1} of data [15]. This analysis is based on a matrix element method adapted to include the dependence on the W boson helicity fractions. The likelihood function is calculated for each event from the leading order matrix element expression for $t\bar{t}$ signal and for the dominat background (W plus jets) as a function of longitudinal and right-handed W bosons fractions, and a total joint likelihood is then formed by taking the product of the per event likelihood. By maximizing the joint likelihood of the sample of selected lepton plus jets events CDF measures $f_0 = 0.88 \pm 0.11$ (stat) $\pm$ 0.06 (syst) and $f_+ = -0.15 \pm 0.07$ (stat) $\pm$ 0.06 (syst).

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