Recent results on top-quark physics from the Tevatron

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Summary. — Seventeen years after the discovery of the top quark at the Fermilab Tevatron collider, many aspects of the top-quark sector are now well known. Besides the measurement of basics properties, such as the production cross section, the top-quark mass, width and charge, many new aspects, such as spin correlation in top-quark decays, have been explored for the first time. Due to their well-understood and clean signatures, top-quark events have also been applied to investigate important properties of quantum chromodynamics (QCD) such as the color flow between partons. This review summarizes the latest results from the Tevatron.

PACS `14.65.Ha` – Top quarks.
PACS `12.38.Qk` – Experimental tests.
PACS `13.85.Qk` – Inclusive production with identified leptons, photons, or other nonhadronic particles.

1. – Top quarks in a nutshell

With a mass of 173.2 ± 0.9 GeV [1], the top quark is the heaviest of all known elementary particles. From a theoretical point of view, top quarks are of special interest, as their coupling to the Higgs boson is close to unity, suggesting that the top quark may play a special role in electroweak symmetry breaking. From an experimental point of view, its short lifetime of about 10^{-25} sec is of particular interest as top quarks decay before hadronization and thereby provide an opportunity for studying bare quarks. At the Tevatron $p\bar{p}$ collider, with a center-of-mass energy of 1.96 TeV, 85% of the $t\bar{t}$ pairs are produced through quark-antiquark annihilation and 15% originate from gluon-gluon fusion. In next-to-next-to leading order in pertubative QCD, the rate of pair production is predicted to be 7.46 pb [2], which is a factor of about 2 larger than the electroweak production cross section of single top quarks [3]. In the standard model (SM), top quarks decay almost exclusively to a W boson and a bottom quark, such that $t\bar{t}$ events can be classified into all $-$ jets, ℓ+jets and dilepton events, depending on the modes of the two W decays. The $\ell+$jets channel is characterized by four jets, one isolated, energetic charged lepton, and an imbalance in transverse momentum. The irreducible background comes mainly from W+jets events. Instrumental background arises from events in which a jet is misidentified as a lepton, and from events with heavy quarks that decay into leptons that pass isolation requirements. The topology of the dilepton channel is defined by two jets, two isolated, energetic charged leptons, and a significant imbalance in transverse momentum from the undetected neutrinos. Here, the main background processes are from Z+jets and diboson events (WW, WZ and ZZ with associated jets), as well as the kind of instrumental background characterized above.

2. – Probing top-quark production at $\sqrt{s}$ =1.96 TeV

One of the basic analyses involves the measurement of the $t\bar{t}$ production cross section. This requires a well-modeled background as well as a clean and large signal fraction. A good separation between signal and background can be achieved either through b-jet identification or by using multivariate statistical techniques or both, to achieve greater precision. To reduce the main systematic uncertainty from the integrated luminosity, the CDF experiment explored the possibility of using the ratio of the measured $t\bar{t}$ to $Z \to \ell\ell$ cross sections and multiplying this by the theoretical cross section for $Z \to \ell\ell$ production. Such analyses [4, 5] yield:

$$\text{CDF in 4.6 fb}^{-1} \text{ of } \ell + \text{jets data} : \sigma_{t\bar{t}} = 7.82 \pm 0.55 \text{ (stat + syst) pb}\,,$$
$$\text{DØ in 5.3 fb}^{-1} \text{ of } \ell + \text{jets data} : \sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64} \text{ (stat + syst) pb}\,.$$

Both measurements are limited by systematic uncertainties, specifically, in the modeling of $t\bar{t}$ production at CDF, and on the luminosity at DØ. The total uncertainties are comparable to the theoretical uncertainties. As new physics may affect different final states in different ways, and to probe different parts of the phase space as well as the effect of different backgrounds, $t\bar{t}$ production is measured in many different channels, such as dilepton [6, 7], hadronically decaying τ+lepton [8] and τ+jets [9, 10], as well as all $-$ jets [11, 12] final states. So far, all results are consistent among channels and theoretical predictions. A future combination based on the full data of the CDF and DØ experiments, will achieve a precision of better than 5%, and go beyond the theoretical uncertainty, which is dominated by the uncertainty on parton distribution functions (PDF).

The measurement of the production cross section $\sigma_{t\bar{t}}$ can be extended to a measurement of the ratio R of events in which the top quark decays to Wb divided by the number of events with top quarks decaying to Wq, where q can be any down-type quark. In the SM, this ratio is predicted to be one. Smaller values would provide a direct indication for physics beyond the SM, such as the existence of a 4^{th} generation of quarks. In the ℓ + jets channel, the DØ experiment splits events into three categories: (i) events with no identified b jet, (ii) one b jet and (iii) two b jets. The dilepton final state relies on the continuous output of the b-jet-identification algorithm. Based on 5.4 fb^{-1}, the DØ experiment obtains $R = 0.90 \pm 0.04$ (stat + syst) [13] combining both channels. The main systematic uncertainty is from b-jet identification.

The first measurement of the $t\bar{t} + \gamma$ production cross section was performed by the CDF collaboration. This is particularly challenging, as the production rate is one order of magnitude smaller than that for $t\bar{t}$ production. In addition, the $t\bar{t}+\gamma$ analysis requires a well-developed photon identification and excellent modeling of the background. Based on 6.0 fb^{-1} of data, CDF observes 26.9 ± 3.4 candidate events where 30 are expected. The measured cross section of $\sigma_{t\bar{t}+\gamma} = 0.18 \pm 0.08$ pb [14] is consistent with the predicted value of 0.17 ± 0.03 pb [15]. This represents first evidence for $t\bar{t} + \gamma$ production with a significance of 3.0 standard deviations (SD).

After the observation of the top quark in the $t\bar{t}$ final state, it took another 14 years to observe single top-quark production. The production rate of single top quarks probes directly the electroweak Wtb interaction. Sophisticated, multivariate analysis techniques are needed to extract the small signal from an overwhelming background, mainly from W+jets. Both CDF [16] and DØ [17] extracted the cross section for the combined contribution of s and t channel processes, yielding:

$$\text{CDF in } 3.2 \text{ fb}^{-1} \text{ of data} : \sigma_{s+t} = 2.3 \pm 0.6 \text{ (stat + syst) pb} ,$$
$$\text{DØ in } 5.4 \text{ fb}^{-1} \text{ of data} : \sigma_{s+t} = 3.4 \pm 0.7 \text{ (stat + syst) pb} .$$

Assuming that the production of single top quarks in the s and t channel is directly proportional to $|V_{tb}|^2$, and that $|V_{ts}|^2 + |V_{td}|^2 << |V_{tb}|^2$, the above measurements can be translated into a measurement of $|V_{tb}|$, yielding:

$$|V_{tb}| = 0.91 \pm 0.13 \text{ (stat + syst)} ,$$
$$|V_{tb}| = 1.02 \pm 0.11 \text{ (stat + syst)} ,$$

for CDF and DØ, respectively. As the production of single top quarks in the t and s channel is sensitive to different physics beyond the SM, CDF [18] and DØ [19] measured not only their sum, but both of the processes in a simultaneous fit to the data using separate multivariate techniques for each of the channels. For the t channel results give:

$$\text{CDF in } 3.2 \text{ fb}^{-1} \text{ of data} : \sigma_{t} = 0.8 \pm 0.4 \text{ (stat + syst) pb} ,$$
$$\text{DØ in } 5.4 \text{ fb}^{-1} \text{ of data} : \sigma_{t} = 2.9 \pm 0.6 \text{ (stat + syst) pb} .$$

DØ claims first observation of this process with a significance of 5.5 SD. The main systematic uncertainty comes from the modeling of background. The analysis of the s channel is not yet sensitive enough to claim evidence for s channel production. This will only be reached using the full set of data. However, this channel is especially important, as it is the only production mode that is not very enhanced at the LHC, while the contamination from background is significantly larger than at the Tevatron.

3. – Measuring the mass of the top quark

There are two fundamentally different approaches to measure the mass of the top quark. One is based on mass-dependent distributions of templates, e.g., the mass of the top quark, m_t, reconstructed from the decay products, or the degree of consistency $w_{\nu,\not{p}_T}$ of the reconstructed neutrino momenta and the measured imbalance in transverse momentum. Monte Carlo (MC) simulated events for different top-quark masses are used to form mass-dependent templates. The top-quark mass is extracted through a comparison of templates to data. All measurements are calibrated using pseudo-experiments, making sure that the measurement is bias-free and that the statistical uncertainty is properly estimated. To reduce the main systematic uncertainty from the jet energy, a global jet energy scale (JES) correction is extracted simultaneously with the mass of the top quark. This correction relies on the fact that the mass of the W boson, m_W, is well measured, and can therefore be used to constrain the energies of the jets. In dilepton events, however, this procedure is not possible, and the JES correction from ℓ+jets events

TABLE I. – *Latest results from Tevatron on the mass of the top quark.*

Experiment	L (fb^{-1})	Final state	Method	m_t (GeV)	stat (GeV)	syst (GeV)
CDF	8.7	$\ell+$jets	m_t, m_{jj}	172.8	0.7	0.8
CDF	5.8	all $-$ jets	m_t, m_W	172.5	1.7	1.1
CDF	5.6	dilepton	m_t	170.3	2.0	3.1
DØ	5.4	dilepton	$w_{\nu,\not p_T}$	174.0	2.4	1.4
DØ	5.4	dilepton	ME	174.0	1.8	2.4
DØ	3.6	$\ell+$jets	ME	174.9	1.1	1.0
CDF	3.6	$\ell+$jets	ME	172.4	1.4	1.3

is transferred directly to the jets in the dilepton channels. Any remaining difference is accounted for as a systematic uncertainty.

The most precise measurements of m_t, are obtained using the Matrix-Element (ME) method, where for each final state y, the probability to originate from $q\bar{q} \to t\bar{t}$ is calculated as a function of m_t:

$$(1)\quad P_{t\bar{t}}(x;m_t) = \frac{1}{\sigma_{\mathrm{obs}}(m_t)} \int \mathrm{d}\epsilon_1 \mathrm{d}\epsilon_2 f_{\mathrm{PDF}}(\epsilon_1) f_{\mathrm{PDF}}(\epsilon_2)\, \frac{(2\pi)^4\,|M(y)|^2}{\epsilon_1\epsilon_2 s}\, \mathrm{d}\Phi_6\; W(x,y)\,,$$

where ϵ_1, ϵ_2 denote the energy fraction of the incoming quarks from the protons and antiprotons, f_{PDF} represent the parton distribution function, s is the square of the energy in the $p\bar{p}$ center of mass, $M(y)$ is the leading-order (LO) matrix element for $t\bar{t}$ production and decay [20] and $\mathrm{d}\Phi_6$ is an element of the 6-body phase space. The resolution of the detector is taken into account through a transfer function $W(x,y)$ that describes the probability of a partonic final state y to be measured as x in the detector. The signal probability is normalized by the observable cross section σ_{obs} for the specific ME.

An overview of the latest results from template and ME methods is given in Table I. For template based results, the variables used to construct the templates are given in the appropriate row under "Method". All results are consistent with each other. Almost all results are limited by systematic uncertainties, where the remaining jet uncertainties and the modeling of $t\bar{t}$, i.e., hadronization and the underlying event, NLO effects, initial and final-state radiation, as well as color reconnection, dominate. The latest combination of all measurements yields an average value of $m_t = 173.2 \pm 0.6$ (stat) $\pm\, 0.8$ (syst) GeV, with a total uncertainty of less than 1 GeV.

Besides systematic effects, another particular challenge in mass measurements is the theoretical interpretation, i.e. the question of how close the measured mass, which relies on MC simulation, is to the pole mass of the top quark. To bypass this problem, DØ pioneered a different approach [21], where the measured $t\bar{t}$ cross section is compared to higher order QCD predictions performed using either the pole mass or the $\overline{\mathrm{MS}}$ mass definition. Based on 5.3 fb^{-1} of $\ell+$jets events, the pole mass is extracted to be $m_t^{\mathrm{pole}} = 167.5^{+5.2}_{-4.7}$ GeV, while the mass for the $\overline{\mathrm{MS}}$ scheme is $m_t^{\overline{\mathrm{MS}}} = 160.0^{+4.8}_{-4.3}$ GeV. Both results are smaller than the direct measurements, but the pole mass agrees better within its uncertainties with the combination of the direct measurements.

4. – Unique top-quark properties at the Tevatron

Due to the fact that at the Tevatron about 85% of the $t\bar{t}$ production arises from quark-antiquark annihilation, while at the LHC 90% is from gluon-gluon fusion, some features of production differ between the two colliders. One of these is the correlation expected for the spins of the two top quarks. Although the t and $\bar{t}$ are not produced polarized, their spins are correlated if angular momentum is conserved in the process. At the Tevatron, near the production threshold, all top-quark spins are expected to point in the same direction at LO for $q\bar{q}$ induced processes only. This fraction is reduced to 78% [22] taking account of effects from NLO corrections and gluon-gluon fusion using the beam momentum vector as quantization axis. Due to the short lifetime of the top quark, the top-quark spin does not flip, and its orientation is reflected in the angular distribution of the decay products: The spin-correlation coefficient C can therefore be measured by studying, e.g, the doubly-differential cross section:

$$\frac{\mathrm{d}^2\sigma_{t\bar{t}}}{\mathrm{d}\cos\theta_1 \mathrm{d}\cos\theta_2} = \frac{\sigma_{t\bar{t}}}{4}(1 - C\cos\theta_1\cos\theta_2) \tag{2}$$

where θ_1 and θ_2 denote the angle between the spin-quantization axis and the direction of flight of the down-type fermion from W-boson decay in the respective parent t or $\bar{t}$ rest frame. At both CDF and DØ, the spin correlation has been measured using templates in angular distributions. The DØ experiment uses the product of the lepton angles [23], while the CDF experiment considers two two-dimensional templates, one based on lepton angles, and one on the angles of the b quarks [24]. In the $\ell+$ jets channel, the CDF collaboration uses the product of the cosines of the leptons and of the down-type quarks as well as the product of the cosines of the leptons and the b quarks [25]. A particular challenge in the $\ell+$ jets final state is the identification of the down-type quark from W-boson decay. The small efficiency of slightly more than 60% leads to a large dilution of the measurement. Based on about 5 fb^{-1}, the template based measurements yield the following correlation coefficients in the beam frame:

$$\begin{aligned}
\text{CDF in 5.3 fb}^{-1}\text{ of }\ell+\text{jets data}: C_{\text{beam}} &= 0.72 \pm 0.69\ (\text{stat}+\text{syst}),\\
\text{CDF in 5.1 fb}^{-1}\text{ of dilepton data}: C_{\text{beam}} &= 0.04 \pm 0.56\ (\text{stat}+\text{syst}),\\
\text{DØ in 5.4 fb}^{-1}\text{ of dilepton data}: C_{\text{beam}} &= 0.10 \pm 0.45\ (\text{stat}+\text{syst}).
\end{aligned}$$

All these measurements are consistent with the SM expectation of $C_{\text{beam}} = 0.78 \pm 0.04$ at NLO QCD. However, none of these is sensitive enough to distinguish between the case of SM spin correlation and no spin correlation. A significant improvement, can be achieved making use of matrix-element information [27].

The event probability for $q\bar{q} \to t\bar{t}$ production can also be written as a function of spin correlation. Two hypotheses H are considered in the analysis: spins correlated according to the SM ($H = c$) and uncorrelated spins ($H = u$). Using the above notation, the probabilities can be written as:

$$P_{t\bar{t}}(x;H) \propto \int d\epsilon_1 d\epsilon_2 f_{PDF}(\epsilon_1) f_{PDF}(\epsilon_2) \frac{|M(y;H)|^2}{\epsilon_1\epsilon_2 s} W(x,y) d\Phi_6\,. \tag{3}$$

Based on these probabilities, a powerful variable R can be defined:

$$R = \frac{P_{t\bar{t}}(H = c)}{P_{t\bar{t}}(H = c) + P_{t\bar{t}}(H = u)}\,, \quad (4)$$

that discriminates between $t\bar{t}$ events with (c) and without (u) SM spin correlation [26]. Using 5.4 fb^{-1} of dilepton $t\bar{t}$ events, DØ obtained $C_{\text{beam}} = 0.57 \pm 0.31$ (stat + syst). Compared to the measurements based on angular templates, this improves the sensitivity by about 30%. The largest systematic uncertainty of ± 0.07 is from limited statistics of forming the MC templates.

This approach is also applied to 5.3 fb^{-1} of $\ell +$ jets events [28]. Requiring at least two jets to be identified as coming from b quarks, the signal purity is increased to about 90%. To increase the sensitivity, and to reduce the dilution from initial and final state radiation, events are split into four subsamples by dividing the data into two groups of events, one with four jets and the other with more than four jets. To reduce the contamination from events in which a b jet is mistakenly taken to emerge from W boson decay, these two groups are again separated according to whether the invariant mass of the two light-flavor jets is within 25 GeV of the accepted mass of the W boson. From a total of 729 $t\bar{t}$ candidate events, C_{beam} is extracted to be $C_{\text{beam}} = 0.89 \pm 0.33$ (stat + syst). Combining results from the dilepton and $\ell +$ jets channel yields

$$\begin{aligned} C_{\text{beam}} &= 0.66 \pm 0.23 \text{ (stat + syst)}\,, \\ C_{\text{beam}} &> 0.04 \text{ at } 99.7\% \text{ CL}\,, \end{aligned}$$

providing first evidence for a non-vanishing spin correlation in $t\bar{t}$ events.

Another important property of top-quark production that is different between LHC and the Tevatron, is the angular asymmetry in the t and $\bar{t}$ production, i.e., the question whether top (anti top) quarks are produced more often in the direction of the proton (antiproton) at the Tevatron. At LO, $t\bar{t}$ production is supposed to be symmetric in the collision center of mass, however, at NLO interferences from contributions symmetric and asymmetric under $t\bar{t}$ exchange yield asymmetries. Thus, the SM predicts an enhanced production of t ($\bar{t}$) quarks in the direction of the proton (antiproton) of 5%. Extension of the SM with Z' bosons or warped extra dimensions, increase the expected asymmetry, while e.g., axi-gluons would decrease it. Depending on the quantization axis and the objects considered, this asymmetry can be defined and checked in multiple ways. One possibility is the direction of the reconstructed t and $\bar{t}$ in the laboratory frame. Based on their rapidity $y = \frac{1}{2} ln(\frac{E+p}{E-p})$, one can define the forward/backward (FB) asymmetry:

$$A_{\text{FB}}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}\,. \quad (5)$$

However, due the relatively large energy resolution of jets and the challenge of reconstructing the neutrinos, an improved definition makes use of the lepton direction, which can be very well measured. It is given by:

$$A_{\text{FB}}^{\ell} = \frac{N(q_\ell y_\ell > 0) - N(q_\ell y_\ell < 0)}{N(q_\ell y_\ell > 0) + N(q_\ell y_\ell < 0)}\,, \quad (6)$$

where y_ℓ is the rapidity and q_ℓ the charge of the lepton.

To calculate the asymmetry defined in Eq.(5), the full $t\bar{t}$ event must be reconstructed. This is done using kinematic fitters, that reconstruct the event under the $t\bar{t}$ hypothesis using mass and resolution constraints [29]-[31]. The background contribution is subtracted from the data and the result is unfolded correcting for the biases of reconstruction and acceptance. CDF uses a matrix-inversion method, while DØ applies a regularized unfolding procedure. These results can be compared directly to asymmetries from MC generators or theoretical calculations. For MC@NLO[32], the asymmetry is predicted to be 5%, Ahrens et al. calculate an asymmetry of 7% at NLO+NNLL [33] and Holik et al. find 9% at NLO that includes corrections from quantum electrodynamics (QED) [34]. The experimental results for Eq.(5) are

$$\begin{aligned} \text{CDF in 5.1 fb}^{-1} \text{ of dilepton data}: A_{\text{FB}}^{t\bar{t}} &= (42.0 \pm 15.0 \text{ (stat)} \pm 5.0 \text{ (syst)})\%\,, \\ \text{CDF in 5.1 fb}^{-1} \text{ of } \ell + \text{jets data}: A_{\text{FB}}^{t\bar{t}} &= (15.8 \pm 7.2 \text{ (stat)} \pm 1.7 \text{ (syst)})\%\,, \\ \text{DØ in 5.4 fb}^{-1} \text{ of } \ell + \text{jets data}: A_{\text{FB}}^{t\bar{t}} &= (19.6 \pm 6.0 \text{ (stat)}^{+1.8}_{-2.6} \text{ (syst)})\%\,. \end{aligned}$$

Similarly, the leptonic asymmetry defined in Eq.(6) is measured by the DØ collaboration in the $\ell+$jets channel using 5.4 fb^{-1} of data, with the extracted value of A_{FB}^{ℓ} being $(15.2 \pm 4.0)\%$, which exceeds the predicted value of $A_{\text{FB}}^{\ell} = (2.1 \pm 0.1)\%$ from MC@NLO. As new physics could lead to a different mass dependence, both experiments also studied the dependence of the asymmetry on the mass of the $t\bar{t}$ system and the rapidity difference in t and $\bar{t}$. The largest deviation of more than 3 SD was observed by the CDF collaboration in the mass bin above 450 GeV. However, to get a full understanding of the observed discrepancies, it is not only sufficient to reduce the statistical uncertainty on these results, but one also has to address remaining questions such as the modeling of the transverse momentum of the $t\bar{t}$ system. To rule out models that try to accommodate the observed asymmetries, it is also desirable to examine any polarization of top quarks, as certain models may lead to polarized top quarks [35].

The well-understood and clean environment of $t\bar{t}$ events makes this channel important also for exploring effects of soft QCD and developing new tools, such as the color flow. The color connection between particles depends on the nature of the decaying particle. For color singlets, such as the W or Higgs bosons, the color string connects the decay particles, while for octets, such as gluons, it connects the decay particles to the beam remnants. Color flow can be used to discriminate e.g., $ZH \to Zbb$ from $Z+$jets. The so-called jet-pull variable can be used to describe color flow [36]. This variable is defined by the vectorial sum of all calorimeter cells within a given jet, i.e.

$$\vec{p} = \sum_{i}^{cells} \frac{E_T^i |r_i|}{E_T^{\text{jet}}} \vec{r}_i\,, \tag{7}$$

where E_T^i is the transverse energy deposited in cell i with respect to the nominal center of the detector, $\vec{r}_i$, the location of the cell and E_T^{jet}, the transverse energy of the jet. For jets from color singlets, the jet pulls point towards each other, while for color octets, they have opposite directions. As a first test, DØ used this variable to measure the fraction of events in $t\bar{t}$ in which the $W \to q\bar{q}$ decay is identified as a color singlet. Based on 5.3 fb^{-1} of $\ell+$jets data, the fraction is extracted to be $f_{\text{Singlet}} = 0.56 \pm 0.42$ (stat + syst). Based on MC pseudo-experiments, the hypothesis that the W boson is a color octet can be excluded at the 99% CL, however, in data, this hypothesis can only be ruled out at 95% CL [37] .

5. – Conclusion and Prospects

Seventeen years after the observation of top quarks at the Tevatron collider, many aspects of this massive quark have been measured precisely. By now, the top-quark mass is known to less than 1 GeV. In addition, the well understood detectors at the Tevatron pioneered studies of many new aspects of the top quark, such as spin correlation in $t\bar{t}$ decays, and applications of the so-called jet-pull variable to study color flow in top-quark events. So far, all measurements are consistent with the SM predictions. Nevertheless, discrepancies between data and theory are observed in the forward-backward asymmetry. However, as the statistical uncertainties are still large, more data are needed to learn whether these differences are due to an underestimated effect in modeling $t\bar{t}$ and background or whether this is caused by new physics beyond the SM. Thus far, most analyses make use of half of the total data. Hence, the Tevatron legacy on this and other issues still needs to be resolved. Many aspects of the physics differ between the LHC top factory and the Tevatron- the discovery machine of the top quark. Additional interesting results can still be expected from the full data sample at the Tevatron.

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