IL NUOVO CIMENTO Vol. 37 C, N. 2 Marzo-Aprile 2014
DOI 10.1393/ncc/i2014-11734-2

Colloquia: LC13

Top quark physics at the Tevatron

S. Leone on behalf of the CDF and D0 Collaborations
INFN, Sezione di Pisa - Pisa, Italy

ricevuto il 22 Gennaio 2014

Summary. — In this paper I summarize some of the most recent top quark physics results obtained by the CDF and D0 Collaborations, analysing data collected during Run II of the Tevatron Collider. The top pair production cross section has been measured with a precision comparable to the theoretical one (5.4%). A precision of 0.5% on the measurement of the top quark mass has been achieved. The single top production in the s channel has been measured. The top quark production mechanism, decay vertex and kinematic distributions have been investigated to test many aspects of the Standard Model. Most of the results shown here are already based on the full Run II dataset.

PACS `14.65.Ha` – Top quarks.

1. – Introduction

CDF II and D0 are multipurpose detectors which collected data at the Tevatron Collider. During the so-called Run II, the Tevatron provided proton-antiproton collisions at a center of mass energy $\sqrt{s} = 1.96\,\text{TeV}$ until its shutdown in September 2011. Data corresponding to an integrated luminosity of approximately $10\,\text{fb}^{-1}$ were collected by each experiment. The analyses described in the following are based on up to the full Run II dataset.

The top quark was first observed at the Tevatron by CDF and D0 in 1995 [1]. The top quark has a very special property: it is the most massive of the known elementary particles. A consequence of its large mass is that it is the only quark that decays before hadronizing, therefore its properties, such as spin, can be inferred from the kinematic distributions of the top decay products. With a Yukawa coupling near one, the top quark could play a special role in electroweak symmetry breaking, and its large mass could potentially lead to enhanced couplings to new physics.

2. – Top-quark pair production

At $\sqrt{s} = 1.96\,\text{TeV}$, top quarks are produced primarily in $t\bar{t}$ pairs with the strong process $q\bar{q} \rightarrow t\bar{t}$ being the dominant one. At the LHC the dominant $t\bar{t}$ production

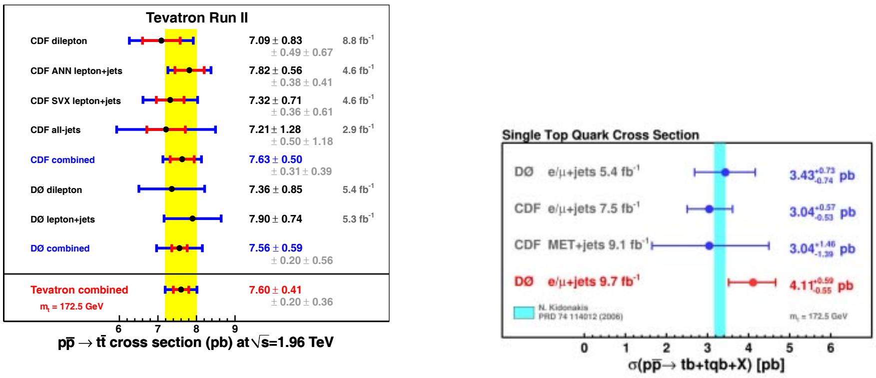

Fig. 1. – Left: Summary of Tevatron $t\bar{t}$ cross section measurements. Right: Summary of single-top $s + t$ Tevatron cross section measurements.

process is through gluon-gluon fusion. Therefore the Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production.

In the Standard Model (SM) each top quark decays through charged-current weak interaction almost exclusively into a real W and a b quark ($t \rightarrow Wb$). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. The $t\bar{t} \rightarrow W^+bW^-\bar{b}$ events can thus be identified by means of different combinations of energetic leptons (e or μ) and jets and are labeled as *dilepton*, *single lepton plus jets* or *all-hadronic*, depending on whether a leptonic decay has occurred in both, only one, or none of the two final–state W bosons, respectively.

By measuring the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ in many decay channels and comparing it to perturbative QCD calculations, one can test the SM predictions in great detail. $\sigma_{t\bar{t}}$ has been measured in all decay channels: the most precise measurements are those performed in the single lepton plus jets channel. Recently, precise measurements from both experiments have been combined to obtain a Tevatron $\sigma_{t\bar{t}}$ [2]. Assuming a top mass M_{top} of 172.5 GeV/c^2, the Tevatron combined cross section is $\sigma_{t\bar{t}} = 7.60 \pm 0.41$ pb. The experimental uncertainty is 5.4%, dominated by the systematic uncertainties from the luminosity and signal modeling. Figure 1 (left) shows a summary of CDF and D0 $t\bar{t}$ cross section measurements in various decay channels, using various techniques, and includes the most recent Tevatron combination result. Consistent results are found from the different channels, methods and detectors.

3. – Single top-quark production

The SM predicts that top quarks can be produced also singly, through electroweak s-channel or t-channel exchange of a virtual W boson, with a predicted cross section of about half the top-quark pair production. Single-top associated production Wt is also possible, but at the Tevatron the expected cross section for this process is very small and not measurable. Single-top production was observed for the first time at the Tevatron in 2009 [3].

Single-top production is interesting because it provides direct access to the Wtb vertex, therefore allowing a direct measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$. However, this is a challenging measurement, because one has to

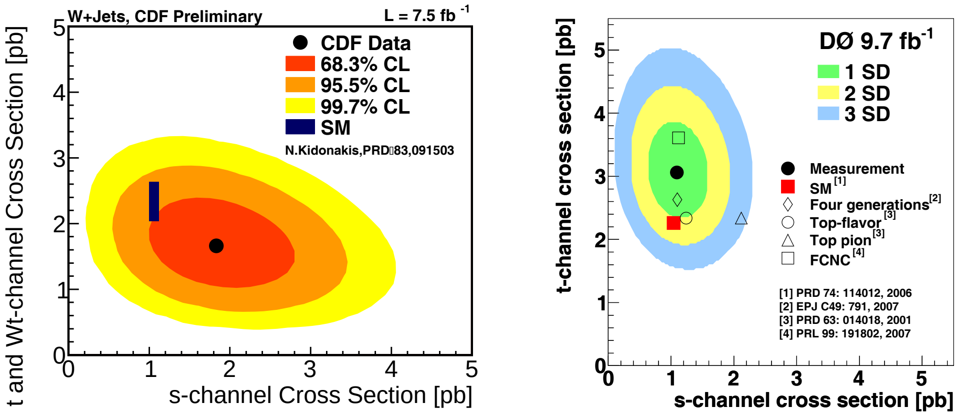

Fig. 2. – 2D posterior density for single-top-quark s-channel and t-channel, with one, two, and three s.d. probability contours, Left: CDF. Right: D0.

extract a small signal out of a large background with large uncertainties: it took 14 years after the top discovery for the single-top-quark production to be observed by the CDF and D0 experiments. No single variable provides sufficient signal-background separation, so the use of multivariate techniques is mandatory. If we compare the expected single-top production cross section at the Tevatron and LHC [4], we immediately notice that the cross section in the s-channel at 8 TeV only increase by a factor of 5 compared to the Tevatron, while the signal/background ratio in the s-channel is lower at the LHC than at the Tevatron. Therefore, the Tevatron is favourite with respect to LHC for the study of single-top quark production in this particular channel.

The most recent CDF analysis of the combined $s+t$ channels is based on $7.5\,\text{fb}^{-1}$ and uses a Neural Network to discriminate signal from background. CDF finds $\sigma(s+t) = 3.0^{+0.6}_{-0.5}\,\text{pb}$ [5]. D0 recently performed a new analysis based on the full Run II dataset and optimized to look for the s-channel production. From this analysis the $s+t$ cross section was measured as well: $\sigma(s+t) = 4.1 \pm 0.6\,\text{pb}$ [6]. Figure 1 (right) shows a summary of the most recent CDF and D0 single-top $s+t$ results. From the single-top-quark cross section measurement one can extract the CKM matrix element $|V_{tb}|$, assuming SM top-quark decay, V-A and CP conserving Wtb vertex. CDF measures $|V_{tb}| = 0.92^{+0.10}_{-0.08}(\text{stat}+\text{syst}) \pm 0.05(\text{theory})$. D0 measures the strength of the V-A coupling, maintaining the possibility for an anomalous strength of the left-handed Wtb coupling (f_1^L), which could rescale the single-top-quark cross section: $|V_{tb}f_1^L| = 1.12^{+0.09}_{-0.08}$.

Since s- and t-channels are sensitive to different physics beyond the SM, it is important to measure the two production processes separately. This is done by forming the posterior in the two-dimensional plane σ_s *versus* σ_t, relaxing the requirement on the ratio s/t being equal to the SM prediction in the posterior, and extracting the s-channel and t-channel cross sections separately. Figure 2 left (right) shows the CDF (D0) result. CDF measures $\sigma_s = 1.81 \pm 0.63\,\text{pb}$ and $\sigma_t = 1.49 \pm 0.47\,\text{pb}$ [5]. D0 finds $\sigma_s = 1.10 \pm 0.33\,\text{pb}$ and $\sigma_t = 3.07 \pm 0.53\,\text{pb}$ [6]. The s-channel result from D0 is the first evidence for single-top s-channel production, with a significance of the measured cross section corresponding to 3.7 standard deviations (s.d.). CDF performed two new analyses optimized to search for single-top s-channel production using the full Run II dataset, one in the lepton plus

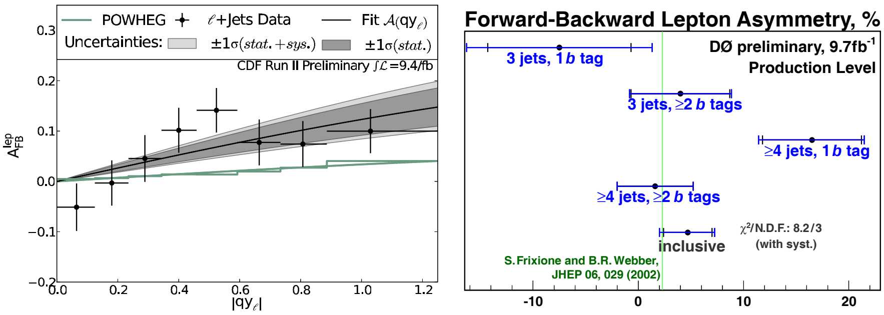

Fig. 3. – Left: CDF leptonic asymmetry as a function of lepton charge times lepton rapidity. Right: D0 summary of leptonic asymmetry.

jets channel, one in the complementary missing E_T plus jets dataset. The s-channel cross section combining these two measurements is $\sigma_s = 1.38^{+0.38}_{-0.37}$, with a significance corresponding to 4.2 s.d. [7].

4. – Forward-backward asymmetry

The $t\bar{t}$ production mechanism has been investigated in detail studying the forward/backward production asymmetry. Quantum chromodynamics at NLO predicts a small asymmetry from the process $q\bar{q} \to t\bar{t}$ [8]. The asymmetry is defined after reconstructing the top direction, in terms of the rapidity difference between the top and antitop quarks. The gg initial state does not contribute to the asymmetry but it shifts the average value. New physics could give rise to an enhanced asymmetry. We measure the rapidity difference in data, subtract the non-$t\bar{t}$ background, correct for acceptance and detector resolution effects, and obtain the parton-level rapidity difference distribution. Using the full Run II dataset CDF measures in the single-lepton plus jets channel a parton-level asymmetry $A_{FB} = (16.4 \pm 4.7)\%$ [9]. Using 5.4 fb^{-1} D0 measures in the single-lepton plus jets channel $A_{FB} = (19.6 \pm 6.5)\%$ [10].

The direction of the charged lepton from top-quark decay is kinematically correlated with the direction of the parent top quark. A similar asymmetry A^{ℓ}_{FB} can be defined also in terms of the rapidity of the charged lepton from top decay. Because the reconstructed direction of the charged lepton does not depend on the $t\bar{t}$ reconstruction procedure, a measurement of the leptonic forward-backward asymmetry allows to verify that the observed top-quark pair A_{FB} is not an artifact of the reconstruction procedure. In the single-lepton plus jets channel CDF measures $A^{\ell}_{FB} = (9.4^{+0.032}_{-0.029}(\text{stat} + \text{syst}))\%$ [11]. Figure 3 (left) shows the CDF distribution for the lepton rapidity multiplied by the lepton charge, used to measure the A^{ℓ}_{FB}. D0 recently presented its updated results for the A^{ℓ}_{FB}, based on full Run II dataset. In the single lepton plus jets channel D0 measures $A^{\ell}_{FB} = (4.7 \pm 2.3(\text{stat})^{+1.1}_{-1.4}(\text{syst}))\%$ [12]. Figure 3 (right) summarizes the D0 results.

5. – Top-quark mass

The top-quark mass M_{top} is a fundamental parameter of the SM. CDF and D0 performed many determinations of M_{top} in all top-decay final states, using different methods. Many clever techniques have been developed to improve sensitivity, such as in

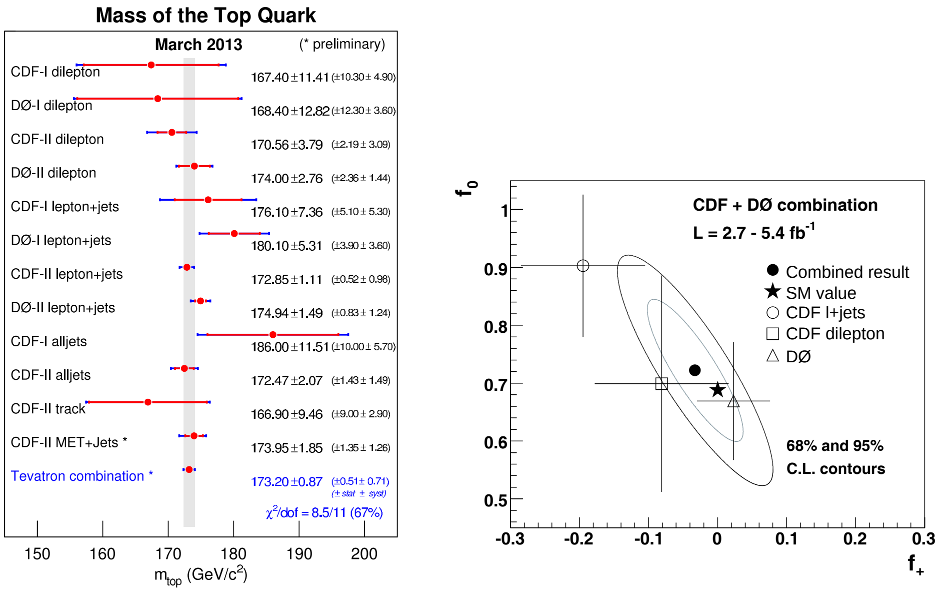

Fig. 4. – Left: Summary of top-quark mass measurements used for the Tevatron top-mass combination. Right: Contours for the Tevatron combination of the 2D helicity measurements. The ellipses indicate the 68% and 95% CL contours, the dot shows the best-fit value, and the star marks the expectation from the SM. The input measurements in the combination are represented by the open circle, square, and triangle.

situ constraints on the jet energy scale systematic uncertainties [13]. Most sensitive analyses from both experiments have been performed in the single-lepton plus jets channel [14]. Figure 4 (left) summarizes the CDF and D0 top mass measurements used for the most recent Tevatron combination. The combined Tevatron top-quark mass is $M_{top} = 173.20 \pm 0.51(\mathrm{stat}) \pm 0.71(\mathrm{syst})\ \mathrm{GeV}/c^2$. It is limited by systematic uncertainties, the dominant ones being signal modeling and jet energy scale uncertainties [15].

6. – Top-quark properties

Precision measurements of the top-quark properties are important both as tests of the SM and as potential signal for the discovery of new physics. Many aspects of the top-quark properties were investigated at the Tevatron, trying to answer the question if the observed top quark is the SM top quark. CDF and D0 directly measured the top-quark width Γ_{top}. CDF set a 95% confidence level (CL) upper limit of $\Gamma_{top} < 6.38\,\mathrm{GeV}$ and a two-sided limit $1.10\,\mathrm{GeV} < \Gamma_{top} < 4.05\,\mathrm{GeV}$ at 68% CL [16]. They also measured the $t\bar{t}$ spin correlation. D0, combining measurements in the dilepton and single-lepton plus jets channels, finds that the fraction of events which contain the SM spin correlation is $f = 0.85 \pm 0.29$. This result provides the first 3 s.d. evidence for the existence of the spin correlation in the $t\bar{t}$ system [17].

The SM predicts that the fractions of longitudinal f_0, left-handed f and right-handed f_+ W bosons in $t\bar{t}$ events are 0.7, 0.3, and 0, respectively. Both D0 and CDF have performed measurements of these helicity fractions by studying angular distributions of the W-decay products, particularly the leptons in $t\bar{t}$ candidate events. A combination of the W-helicity results from the two experiments has recently been published and it is the first Tevatron combination of W-helicity measurements. Assuming $f_0 + f + f_+ = 1$, the combined measurement is $f_0 = 0.722 \pm 0.081$ and $f_+ = 0.033 \pm 0.046$ [18].

Figure 4 (right) shows the result of the fit for the Tevatron combined W-helicity fractions.

7. – Conclusion

Both CDF and D0 Collaborations continue to investigate the top-quark sector, exploiting the Tevatron unique dataset, and are in the process of making Tevatron legacy measurements. They are concentrating mainly on the measurements complementary to the ones performed at the LHC, given the different center-of-mass energy and initial state, where the Tevatron can still produce some interesting results. The single-top-quark production in the s-channel (challenging at the LHC) was recently observed. The forward-backward asymmetry results show some tension between the D0 leptonic asymmetry and the CDF and D0 asymmetry measured after reconstructing the $t\bar{t}$ system. Many CDF and D0 measurements, such as the $t\bar{t}$ production cross section, top-quark mass and W helicity fractions, have been combined to obtain Tevatron-wide results. The Tevatron data-taking has been over since more than two years now, but there is still a lot to be learned from the Tevatron's unique top-quark sample.

REFERENCES

[1] Abe F. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **74** (1995) 2626; Abachi S. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **74** (1995) 2632.
[2] Aaltonen T. *et al.* (CDF and D0 Collaborations), arXiv:1309.7570, submitted to *Phys. Rev. D.*
[3] Abazov V. M. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **103** (2009) 092001; Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **103** (2009) 092002.
[4] Kidonakis N., arXiv:1311.0283.
[5] Aaltonen T. *et al.*, CDF conference note 10793.
[6] Abazov V. M. *et al.* (D0 Collaboration), *Phys. Lett. B*, **726** (2013) 656.
[7] Aaltonen T. *et al.*, CDF conference note 11045.
[8] Kuhn J. H. and Rodrigo G., *Phys. Rev. D*, **59** (1999) 054017.
[9] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. D*, **87** (2013) 092002.
[10] Abazov V. M. *et al.* (D0 Collaboration), *Phys. Rev. D*, **84** (2011) 112005.
[11] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. D*, **88** (2013) 072003.
[12] Abazov V. M. *et al.*, D0 conference note 6381.
[13] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **109** (2012) 152003.
[14] Abazov V. M. *et al.* (D0 Collaboration), *Phys. Rev. D*, **84** (2011) 032004.
[15] Aaltonen T. *et al.* (CDF and D0 Collaborations), arXiv:1305.3929.
[16] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **111** (2013) 202001.
[17] Abazov V. M. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **108** (2012) 032004.
[18] Aaltonen T. *et al.* (CDF and D0 Collaborations), *Phys. Rev. D*, **85** (2012) 091104.