IL NUOVO CIMENTO **41 C** (2018) 148
DOI 10.1393/ncc/i2018-18148-x

Colloquia: LaThuile 2018

Top quark physics at the Tevatron

S. Leone for the CDF and D0 Collaborations
INFN, Sezione di Pisa - Pisa, Italy

received 6 September 2018

Summary. — A selection of the most recent CDF and D0 results in the top quark sector is presented. The most recent top quark mass measurements, including the pole mass measurements obtained from cross section measurements, are discussed. The Tevatron combined $t\bar{t}$ charge asymmetry results are shown. The recent top quark polarization measurements are reviewed.

1. – Introduction

The Tevatron Collider provided $p\bar{p}$ collisions at a center of mass energy of $\sqrt{s} = 1.96$ TeV until it ceased operating in September 2011. Data corresponding to approximately $10\,\mathrm{fb}^{-1}$ were recorded by the CDF and D0 experiments. The top quark was first observed at the Tevatron. On 2 March 1995, physicists at CDF and D0 announced the discovery of the top quark [1]. Since then, the top sector has been actively explored by the Tevatron and LHC experiments.

At the Tevatron center of mass energy top quarks are primarily produced in $t\bar{t}$ pairs, with $q\bar{q} \to t\bar{t}$ being the dominant process. This is distinct from the production at the LHC, where the dominant process is gluon fusion $gg \to t\bar{t}$. Therefore the Tevatron is the right place to study the $t\bar{t}$ production via $q\bar{q}$ annihilation.

However, the production cross section is small: the top quark discovery happened with a few hundred of top quarks produced per experiment, and even in $10\,\mathrm{fb}^{-1}$ the number of produced events is much smaller than at the LHC, which can be considered a top factory.

The standard model of elementary particles (SM) predicts that each top quark decays almost exclusively into a real W and a b quark. Each W subsequently decays into either a charged lepton and a neutrino or two quarks. For top quark pair production, events can thus be identified by means of different combinations of leptons (e or μ) and jets. Two decay modes are used in the analyses described in this report: the dilepton mode, where both W's decay to a charged lepton and a neutrino, and the lepton plus jets mode, where one W decays leptonically and the other one decays hadronically to a pair of quarks.

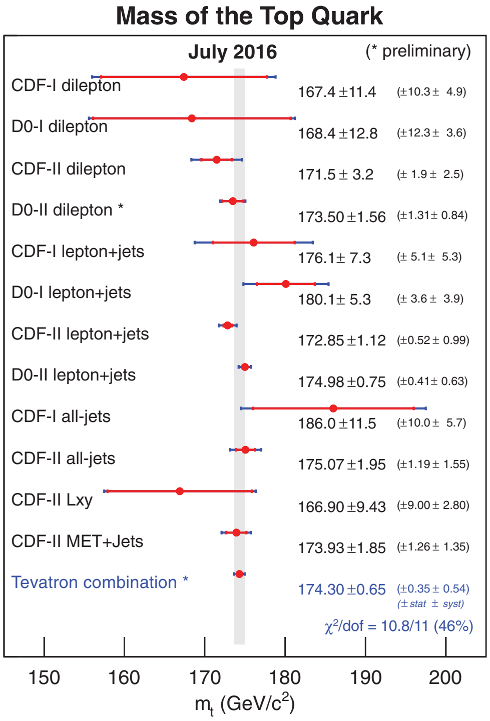

Fig. 1. – Summary of the CDF and D0 top quark mass measurements used for the 2016 Tevatron top mass combination.

The top quark is the most massive of the known elementary particles. As a consequence of its large mass it is the only quark that decays before hadronizing, thus offering a chance to study a bare quark. The top quark properties can be inferred from the kinematic distributions of its decay products. More than 20 years ago CDF and D0 assembled all the pieces needed to discover the quark top. The standard strategy to study the top quark properties remains the same today.

All the analyses described in the following are based on the full Tevatron Run 2 dataset.

2. – Top quark mass measurement

The most measured top quark property is its mass, which is a free parameter of the SM. Several methods have been used to obtain precise top quark mass measurements. Most of them are based on the comparison of kinematic observables in data and in Monte Carlo (MC) samples generated at different top quark masses.

Figure 1 shows a summary of the CDF and D0 top quark mass measurements obtained in all the decay channels and used for the latest Tevatron combination $m_{top} = 174.30 \pm 0.35(stat.) \pm 0.54(syst.)$ GeV, which was produced in summer 2016 and has a relative uncertainty of less than 0.4% [2].

D0 recently published a combination of the measurements of the top quark mass in Run 1 and Run 2 in the lepton plus jets and dilepton channels. The systematic uncertainties are grouped into sources of the same or similar origin to form uncertainty

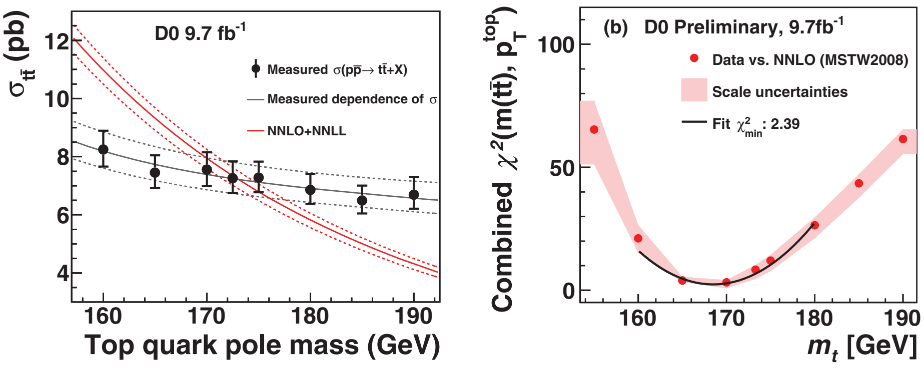

Fig. 2. – (a): D0 measured $t\bar{t}$ production cross section dependence on the top quark mass (points) parametrized by a quartic function (solid black line) and compared to the dependence provided by a NNLO+NNLL calculation (red curves); (b) D0 χ^2 distribution for the differential cross sections in terms of p_T^{top} and $m_{t\bar{t}}$ calculated at NNLO, as a function of the top quark mass.

categories. The dominant sources of uncertainty are the statistical uncertainty, the jet energy scale calibration, which has statistical origin, and the modeling of the signal. The resulting combined value for the top quark mass is: $m_{top} = 174.95 \pm 0.40(stat.) \pm 0.64(syst.)$ GeV. With a relative precision of 0.43% this measurement constitutes the legacy Run 1 and Run 2 measurement of the top quark mass in the D0 experiment [3].

Given the continuous reduction of the experimental error on the top quark mass measurement, in the last few years a lot of theoretical work was devoted to studies aimed to translate the MC top quark mass into a definition of mass in a well defined renormalization scheme [4].

From the experimental point of view, alternative ways of measuring the top quark mass were investigated, with the goal of having less inputs from MC, or depending on different systematic effects, with respect to the standard methods.

In this perspective D0 obtained a top quark pole mass measurement from the inclusive cross section measurement. In this analysis the experimental $t\bar{t}$ cross section measurement is compared to the theory computation.

Figure 2(a) shows the measured and theoretical mass dependence of the inclusive $t\bar{t}$ production cross section. The measured $t\bar{t}$ cross section only changes by 0.7% for a change of 1 GeV in the assumed top quark mass. The experimentally measured dependence is parametrized with a fourth-order polynomial function.

The most probable top quark mass value and uncertainty are extracted by employing a normalized likelihood function, which takes into account the total experimental uncertainty, the theoretical uncertainties on the renormalization and factorization scales, and the PDF uncertainties. Employing the quartic parametrization and the theory predictions at next-to-next-to leading order (NNLO) perturbative QCD $m_{top} = 172.8 \pm 1.1(theo.)^{+3.3}_{-3.1}(exp.)$ GeV is found [5]. The experimental uncertainties dominate the precision of the measurement.

D0 also measured the top quark pole mass from a comparison of the differential $t\bar{t}$ cross sections measured as a function of the transverse momentum of the top quark p_T^{top} and the invariant mass of the $t\bar{t}$ system $m_{t\bar{t}}$ with the differential distributions predicted by perturbative QCD. This measurement was made possible thanks to the recent availability of NNLO differential predictions [6]. The measured top quark pole mass is

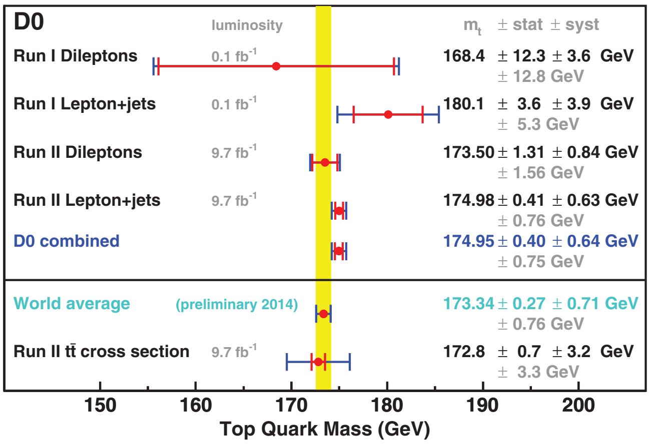

Fig. 3. – Summary of the D0 top quark mass measurements.

$m_{top} = 169.1 \pm 2.5(total)$GeV [7]. Figure 2(b) shows the combined χ^2 distribution for the differential cross sections in terms of p_T^{top} and $m_{t\bar{t}}$ calculated at NNLO, as a function of the top quark mass. The shaded band indicates the theoretical scale uncertainties.

Figure 3 shows a summary of the top quark mass measurements used in the recent D0 combination along with the D0 final result and the top quark pole mass extracted from the D0 inclusive cross section measurement. The latter is not used in the combination.

3. – $t\bar{t}$ charge asymmetry

The $t\bar{t}$ production mechanism has been investigated in detail by studying the charge production asymmetry. The forward-backward asymmetry is such that the top quark is preferentially emitted in the direction of the incoming light quark, while the antitop quark follows the direction of the incoming antiquark, and it is due to the $q\bar{q}$ annihilation process. A recent QCD NNLO calculation evaluates an asymmetry of 9.5% [8]. The gg initial state does not contribute to the asymmetry but dilutes the average value. On the other hand, new physics could give rise to an enhanced asymmetry.

Experimentally the asymmetry is defined relying either on the fully reconstructed top quarks, or on leptons from the W decay. In the first case it uses the rapidity difference Δy of the top (antitop) quark decaying semileptonically $t \rightarrow l\nu b$ and the antitop (top) decaying hadronically $\bar{t} \rightarrow jjb$. It requires reconstruction of top and antitop quarks using all the available information associated with the final-state particles. Background contributions are subtracted from the yield of selected candidates, thereby providing the $t\bar{t}$ signal, which is then corrected for detector effects, to unfold from the reconstructed top and antitop to the parton level.

In the second case the lepton asymmetry in $t\bar{t}$ decay is parametrized as a function of qy_ℓ where q is the charge and y_ℓ is the pseudorapidity of the charged lepton from the W decay. This asymmetry, while smaller in magnitude, does not need unfolding but must be corrected for acceptance effects, and it is insensitive to biases from the top quark reconstruction procedure.

When the $t\bar{t}$ forward-backward asymmetry measurements were first performed in Tevatron Run 2 in the lepton plus jets channel, a small departure from the SM expectations was observed, which brought a lot of excitement in the field [9]. Both CDF

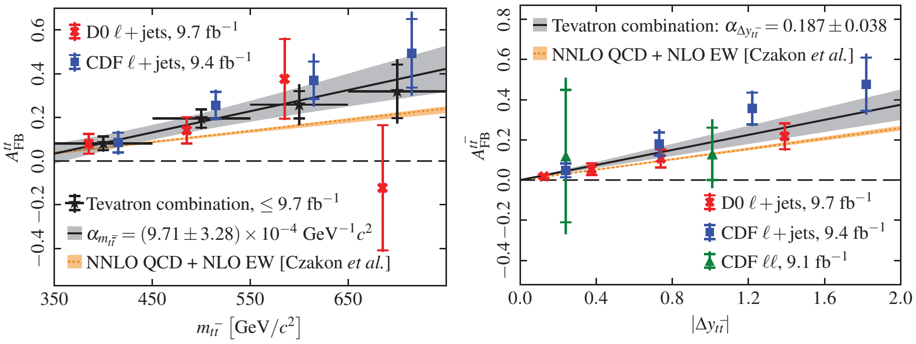

Fig. 4. – (a): Results for $A_{FB}^{t\bar{t}}$ *vs.* $m_{t\bar{t}}$ for the individual CDF and D0 measurements and for their combination. (b) Measurements of the differential asymmetries $A_{FB}^{t\bar{t}}$ *vs.* $|\Delta y_{t\bar{t}}|$. In both plots the inner error bar indicates the statistical uncertainty, while the outer error bar corresponds to the total uncertainty. The linear dependence of the combined result is given by the solid black line, with the 1 SD total uncertainty of the two-parameter (one-parameter) fit given by the shaded gray area. The dashed orange area shows the NNLO QCD + NLO EW prediction with its 1 SD uncertainty.

and D0 then completed their measurements program on the full Run 2 dataset, and with a more refined analysis they found, in some cases, lower values of the asymmetry [10]. Furthermore, the theory predictions were improved by including higher-order QCD and electro-weak (EW) corrections, and, as a result, the new expectations are higher than they were before [8].

Recently CDF and D0 published the combination of their asymmetry measurements obtained with the BLUE method accounting for all uncertainties and their correlations [11]. The combination is performed for the three asymmetries, based either on the reconstructed rapidities of the top and antitop, or on the lepton pseudorapidities, or on the difference between lepton pseudorapidities for the dilepton channel. The combined inclusive asymmetry is $A_{FB}^{t\bar{t}} = 0.128 \pm 0.021(stat.) \pm 0.014(syst.)$, consistent with the NNLO QCD + next-to-leading order (NLO) EW prediction of 0.095 ± 0.007 within 1.3 standard deviations (SD).

The values of $A_{FB}^{t\bar{t}}$ as a function of $m_{t\bar{t}}$ for each experiment and their combination are shown in fig. 4(a), together with the NNLO QCD + NLO EW predictions. The predicted slope parameter agrees with the combined experimental results to within 1.3 SD. The linear dependence of the combined result is given by the solid black line together with the 1 SD total uncertainty of the two-parameter fit given by the shaded gray area.

The differential $t\bar{t}$ asymmetry as a function of $|\Delta y_{t\bar{t}}|$ is available from CDF for both the lepton plus jets and the dilepton channels, and from D0 for the lepton plus jets channel. The choice of binning differs for these measurements. A simultaneous least-squares fit to a linear function for all available measurements is performed. The prediction and the combined result differ by 1.5 SD. Figure 4(b) shows the individual measurements and the result of the linear fit.

The combined fit to the CDF and D0 inclusive single-lepton asymmetry gives $A_{FB}^{\ell} = 0.073 \pm 0.016(stat.) \pm 0.012(syst.)$ and is consistent with the NLO QCD + NLO EW prediction of 0.038 ± 0.003 to within 1.6 SD.

The combined fit to the CDF and D0 inclusive dilepton asymmetry built using the

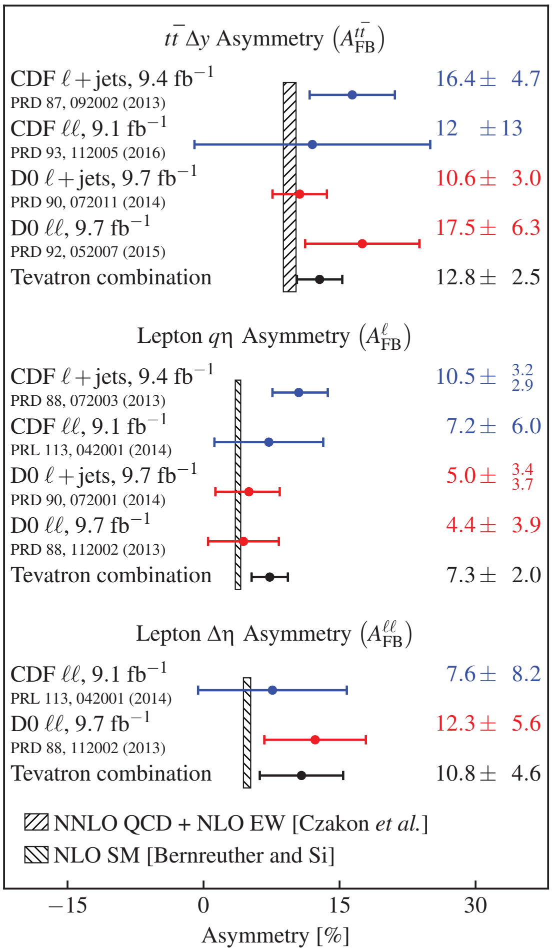

Fig. 5. – Summary of inclusive forward-backward asymmetries in $t\bar{t}$ events in percents at the Tevatron.

rapidity of the 2 leptons yields $A_{FB}^{\ell\ell} = 0.108 \pm 0.043(stat.) \pm 0.016(syst.)$ and is consistent with the NLO QCD + NLO EW prediction of 0.048 ± 0.004 to within 1.3 SD.

All measurements favor somewhat larger positive asymmetries than the predictions, but none of the observed differences are larger than 2 standard deviations. Hence, we conclude that the measurements and their combinations, shown in fig. 5, are consistent with each other and with the SM predictions.

4. – Top quark polarization

The SM predicts that top quarks produced at the Tevatron collider are almost unpolarized, while some models beyond the standard model (BSM) predict enhanced polarization [12]. The top quark polarizations at the Tevatron and LHC are expected to be different because of the different initial states, which motivates the measurement of the top polarization in Tevatron data.

The top quark polarization can be measured in the top quark rest frame through the angular distributions of the top quark decay products relative to some chosen axis. The

TABLE I. – *D0 measured the top quark polarization from the lepton plus jets channel along the beam, helicity, and transverse axes. The total uncertainties are obtained by adding the statistical and systematic uncertainties in quadrature.*

Axis	Measured polarization	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.061	-0.004
Transverse	$+0.040 \pm 0.035$	$+0.011$

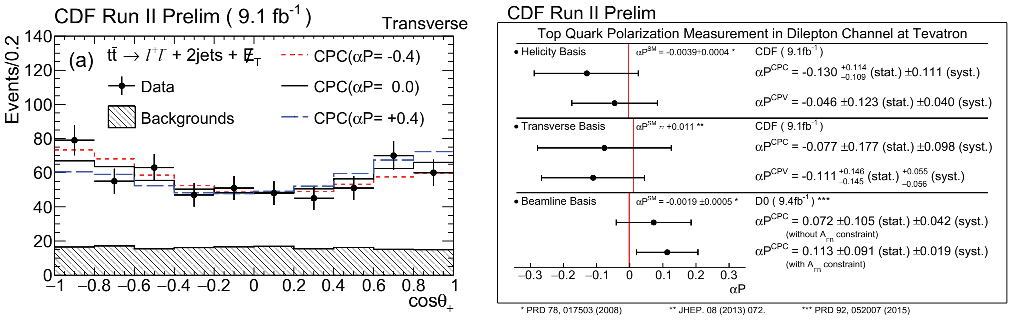

Fig. 6. – (a) $\cos\theta$ data distribution (black dots) for positive leptons in the tranverse basis, compared to expectations for three different polarization values; (b) summary of top quark polarization measurements in the dilepton channel at the Tevatron.

mean polarizations of the top and antitop quarks are expected to be identical because of CP conservation.

D0 published a measurement of top quark polarization in $t\bar{t}$ production in the lepton plus jets final state [13]. The polarization is measured along three quantization axes: i) the beam axis, given by the direction of the proton beam; ii) the helicity axis, given by the direction of the parent top or antitop quark; and iii) the transverse axis, given as perpendicular to the production plane defined by the proton and parent top quark directions. The measured polarizations for the three spin-quantization axes are listed in table I. The polarizations are consistent with SM predictions. The transverse polarization is measured for the first time.

Very recently CDF presented a new measurement of the top quark polarization in the dilepton channel [14]. The measurement is performed assuming that the polarization is generated by either a CP-conserving (CPC) or a CP-violating (CPV) production amplitude. The top quark polarization is measured using the two-dimensional angular distributions of leptons with respect to the helicity axis and the transverse axis. Figure 6(a) shows, as an example, the one-dimensional $\cos\theta$ distribution for positive leptons in the transverse basis assuming CPC and comparing data to two extreme polarization values in the allowed physical region. Figure 6(b) shows a summary of the measurements of top quark polarization in the dilepton channel at the Tevatron, compared to SM prediction (red vertical line). The measured polarizations are consistent between CDF and D0 and with the SM predictions.

5. – Conclusions

Several years after the end of Run 2, Tevatron experiments continue to provide valuable top physics results. CDF and D0 are in the process of producing the last Tevatron legacy measurements. D0 evaluated a combined top quark mass and presented pole mass measurements based on the inclusive and differential cross section measurements. The final Tevatron combined production asymmetry A_{FB} was just published. Both experiments measured the top quark polarization in the lepton plus jets and dilepton channels. All measurements are in agreement with the SM predictions.

REFERENCES

[1] CDF Collaboration (Abe F. *et al.*), *Phys. Rev. Lett.*, **74** (1995) 2626; D0 Collaboration (Abachi S. *et al.*), *Phys. Rev. Lett.*, **74** (1995) 2632.
[2] The Tevatron Electroweak Working Group for the CDF and D0 Collaborations, arXiv:1608.01881.
[3] D0 Collaboration (Abazov V. M. *et al.*), *Phys. Rev. D*, **95** (2017) 112004.
[4] Beneke M., Marquard P., Nason P. and Steinhauser M., *Phys. Lett. B*, **775** (2017) 63; Hoang A. H., Lepenik C. and Preisser M., *JHEP*, **09** (2017) 099; Corcella G., *PoS*, **DIS2017** (2018) 134.
[5] D0 Collaboration (Abazov V. M. *et al.*), *Phys. Rev. D*, **94** (2016) 092004.
[6] Czakon M., Fiedler P., Heymes D. and Mitov A., *JHEP*, **05** (2016) 034.
[7] D0 Collaboration and Czakon M., Fiedler P., Heymes D. and Mitov A., FERMILAB-CONF-16-383-PPD.
[8] Czakon M., Fiedler P. and Mitov A., *Phys. Rev. Lett.*, **115** (2015) 052001.
[9] CDF Collaboration (Aaltonen T. *et al.*), *Phys. Rev. D*, **83** (2011) 112003; D0 Collaboration (Abazov V. M. *et al.*), *Phys. Rev. D*, **84** (2011) 112005.
[10] CDF Collaboration (Aaltonen T. *et al.*), *Phys. Rev. D*, **87** (2013) 092002; D0 Collaboration (Abazov V. M. *et al.*), *Phys. Rev. D*, **90** (2014) 072011.
[11] CDF Collaboration, D0 Collaboration (Aaltonen T. *et al.*), *Phys. Rev. Lett.*, **120** (2018) 042001.
[12] Fajfer S., Kamenik J. F. and Melic B., *JHEP*, **08** (2012) 114.
[13] D0 Collaboration (Abazov V. M. *et al.*), *Phys. Rev. D*, **95** (2017) 011101(R).
[14] CDF Collaboration, CDF public note 11232 (2018).