IL NUOVO CIMENTO Vol. 35 C, N. 1 Gennaio-Febbraio 2012
DOI 10.1393/ncc/i2012-11142-8

Colloquia: LaThuile11

Top physics at Tevatron

Hyun Su Lee on behalf of the CDF and D0 Collaborations
University of Chicago - Chicago, IL, USA

(ricevuto il 29 Settembre 2011; pubblicato online il 25 Gennaio 2012)

Summary. — The top quark, discovered in 1995 at the Fermilab Tevatron collider from CDF and D0 experiments, remains by far the most interesting particle to test standard model. Having data collected more than $7\,\text{fb}^{-1}$ of integrated luminosity of $p\bar{p}$ collision, both experiments have been studied the top quark in all the possible directions. In this article, we present the recent measurements of the top quark properties including the mass, width, spin correlation, and W helicity as well as new particle searches using $t\bar{t}$ signature.

PACS 14.65.Ha – Top quarks.

1. – Introduction

The top quark, observed by both the CDF and D0 experiments in 1995 [1], is by far the heaviest known elementary particle and its mass is almost 40 times heavier than its isospin partner, the bottom (b) quark [2]. Due to the heavy mass, the top quark plays an important role in electroweak radiative corrections relating the top quark mass (M_{top}) and the W boson mass to the mass of the predicted Higgs boson [3,4]. The lifetime of top quark is about 20 times shorter than the timescale for strong interactions, and therefore it does not form hadrons, giving us a unique opportunity to study a "bare" quark.

Top quarks at the Tevatron are predominantly produced in pairs, and decay almost always to a W boson and a b quark in the standard model (SM). The topology of $t\bar{t}$ events depends on the different decay of the two W bosons. In the dilepton channel, each W boson decay to charged lepton (electron and muon) and neutrino. Events in this channel thus contain two leptons, two b-quark jets, and two undetected neutrinos. Because of the presence of two leptons, this channel has the lowest background. However the dilepton channel has the smallest branching fraction. In the all-jets channel, each W boson decays to two jets so that this channel contains two b quark jets and four light quark jets. This channel has the largest branching fraction but also the largest background from QCD multijet production. The lepton+jets channel has one W boson decaying leptonically and the other hadronically so that we have one charged lepton, two b-quark jets, two light quark jets, and one undetected neutrino. Because of the relatively large branching fraction with manageable backgrounds, lepton+jets channel is considered as the "golden

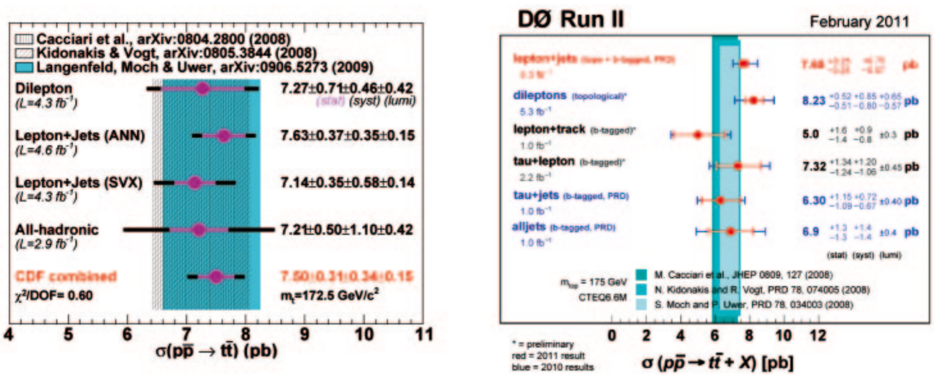

Fig. 1. – Summary of the top quark pair production cross section measurement from CDF (left) and D0 (right) are shown. The results are compared with various NLO calculations.

channel" in the top quark studies. By this reason, the most results presented here use the lepton+jets final state.

2. – Top quark pair production cross section measurement

The top quark pair production cross section at the Tevatron is calculated within the SM to be $7.5^{+0.72}_{-0.63}$ pb for $M_{\mathrm{top}} = 172.5\,\mathrm{GeV}/c^2$ in the next leading order (NLO) calculation [5]. Deviations of the measurements from this value indicate non-perturbative effects, or new production mechanism beyond the SM. Both CDF and D0 have very precise measurements in the lepton+jets channel using neural network technique [6, 7] taking advantages of the different kinematics between the signal and backgrounds. Since a large uncertainty of the luminosity determination (about 6%), CDF Collaboration employed the ratio measurement of $t\bar{t}$ to Z-boson ($\sigma_{t\bar{t}}/\sigma_Z$) converting to $t\bar{t}$ cross section with the theoretical Z boson cross section. With this approach, we obtained the most accurate $t\bar{t}$ cross section measurement at the Tevatron as 7.70 ± 0.52 pb [6] which is less than 7% relative precision. Figure 1 shows a summary of CDF and D0 $t\bar{t}$ cross section measurements obtained using various different decay channels and techniques. All measurements are excellently agreed with the SM predictions.

2·1. *Boosted top search.* – If the top quark is highly boosted, it would appear as a jet with structure. CDF Collaboration has studied very high p_T ($p_T > 400\,\mathrm{GeV}/c$) jets and isolates the top quark signal region using jet mass ($130\,\mathrm{GeV}/c^2 < m_{\mathrm{jet}} < 210\,\mathrm{GeV}/c^2$). Because of the dominant QCD multijet production and low cross section of the boosted top production, we just set the upper limit of $\sigma_{t\bar{t}}^{\mathrm{boost}} < 40$ fb at 95% CL [8].

3. – Top quark mass and t-$\bar{t}$ mass difference

The mass of the top quark is very important to estimate the SM Higgs boson because precise top and W boson masses measurements can predict the mass of the Higgs boson either SM or beyond SM. Since the discovery of the top quark, both the CDF and D0 experiments have been improving the precision of the M_{top} measurement [9].

For the M_{top} measurements, two primary techniques have been established. The template method (TM) uses the distributions of variables (templates) which are strongly

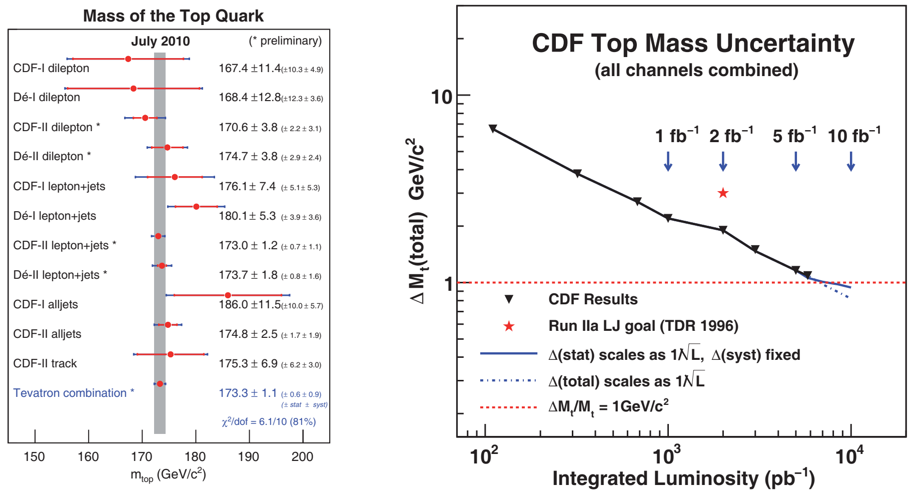

Fig. 2. – Left: Summary of the Tevatron top quark mass measurements and its combination. Right: CDF prediction of $M_{\rm top}$ precision by scaling using increased luminosity (solid line) and plus possible improvement (dashed line).

correlated with the top quark mass and JES. In the building of a probability, only a few variables (usually less than two) are used, for instance reconstructed top quark mass and dijet mass of hardronic decay W boson in the lepton+jets channel. The Matrix Element Method (ME) uses event's probability to be a combinates signals and background. ME exploit all the information in the event by using a leading-order matrix element calculation convoluted with parton distribution function and transfer functions (TFs) making connection between detector response and parton level particle. Because we can use all the information of $t\bar{t}$ production and decay in principle, ME usually provide better precision of $M_{\rm top}$ than TM. Both techniques employ likelihood to compare data to the modeling of signals and background to extract $M_{\rm top}$.

CDF and D0 experiments have performed the $M_{\rm top}$ measurements in the various final states with different techniques. In the lepton+jets and all-jets channels the uncertainty from jet energy scale (JES) can be reduced by using the reconstructed dijet mass from hadronically decaying W boson with *in situ* calibration of JES. To date the most precise measurement has been performed by CDF Collaboration using lepton+jets channel with ME. We found $M_{\rm top} = 173.0 \pm 1.2\,{\rm GeV}/c^2$ using $5.6\,{\rm fb}^{-1}$ of the data [10]. D0 carried out the most precise $M_{\rm top}$ measurement in the dilepton channel using TM. We built templates of the reconstructed top quark mass distributions and extract $M_{\rm top} = 173.3 \pm 3.2\,{\rm GeV}/c^2$ using $5.3\,{\rm fb}^{-1}$ data [11]. Figure 2 (left) shows the summary of the $M_{\rm top}$ measurements and the combination of the Tevatron $M_{\rm top}$ measurements [9]. The precision, $\Delta M_{\rm top}/M_{\rm top} \sim 0.6\%$, is already surpassed the prediction of RunII experiments and close to the $1\,{\rm GeV}/c^2$. We predict to reach less than $1\,{\rm GeV}/c^2$ precision by end of RunII with approximately $10\,{\rm fb}^{-1}$ data as shown in fig. 2 (right).

The precision determination of $M_{\rm top}$ allows us to measure the mass difference between top quark and anti-top quark to a few GeV. In the CPT theorem, which is fundamental to any local Lorentz-invariant quantum field theory, the quark mass should be same as its anti-quark partner. Despite the fact that no violations have ever been observed in the meson and baryon sectors, it is important to test CPT violation in all sectors such as quarks and high mass particles.

D0 Collaboration has a first direct measurement of top quark and antitop quark mass difference ($\delta M_{\rm top}$) in the lepton+jets channel using the ME. In the matrix element calculation, one assumes SM-like $t\bar{t}$ production and decay, where identical particle and antiparticle masses are assumed for b quarks and W bosons but not for top quarks. Using $1\,{\rm fb}^{-1}$ of $p\bar{p}$ collision data, we measure $\delta M_{\rm top} = 3.8 \pm 3.7\,{\rm GeV}/c^2$ [12]. CDF Collaboration measures the mass difference using the TM. We reconstruct the mass difference using modified kinematic fitter allowing mass difference between hadronic top quark and leptonic top quark. Using $5.6\,{\rm fb}^{-1}$ of $p\bar{p}$ collisions, we measure $\delta M_{\rm top} = -3.3 \pm 1.7\,{\rm GeV}/c^2$ [13]. It is consistent with CPT symmetry at a 2σ level. This is the most precise measurement of a quark and anti-quark mass difference.

4. – Study of other top properties

We have studied the top quark properties in various different ways using its unique characteristics. Since top quarks decay before hadronization, information of the top quarks is carried by the decay products. Therefore, we can directly determine the properties of the top quark.

Because of the short lifetime, a direct determination of the top quark lifetime is extremely hard. However, we can calculate it from the decay width. CDF Collaboration has a direct measurement of the top quark width ($\Gamma_{\rm top}$) using $4.3\,{\rm fb}^{-1}$ of $p\bar{p}$ collision. The $M_{\rm top}$ and the mass of W boson that decays hadronically are reconstructed for each event and compared with templates of different $\Gamma_{\rm top}$ and deviations from nominal jet energy scale ($\Delta_{\rm JES}$) to perform a simultaneous fit for both parameters, where $\Delta_{\rm JES}$ is used for the *in situ* calibration of the jet energy scale. By applying a Feldman-Cousins approach, we establish an upper limit at 95% confidence level of $\Gamma_{\rm top} < 7.6\,{\rm GeV}$ and a two-sided 68% CL interval of $0.3\,{\rm GeV} < \Gamma_{\rm top} < 4.4\,{\rm GeV}$ [14]. D0 Collaboration has an indirect determination of $\Gamma_{\rm top}$ using single top t-channel cross section and $t \to Wb/t \to Wq$ fraction measurements. The $\Gamma_{\rm top}$ is calculated with quantum mechanical relation, $\Gamma_{\rm top} = \frac{\sigma(t-ch)}{Br(t\to bW)} \cdot \frac{Br(t\to bW)_{\rm SM}}{\sigma(t-ch)_{\rm SM}}$. The result, $\Gamma_{\rm top} = 1.99^{+0.65}_{-0.55}\,{\rm GeV}$, is the most precise determination of the top quark width using experimental data sample and consistent with SM [15].

The $t\bar{t}$ spin correlation is predicted by the SM and a potentially sensitive discriminant of new physics coupled to the top quark. The spin state is observable in angular correlations among the quark decay products. In the dilepton channel, we used the angular correlation between two leptons and measured consistent results with SM from both CDF [16] and D0 [17] Collaborations. CDF Collaboration has a new measurement using lepton+jets channel by introducing new technique which separate the down-type (d or s) quark of hadronic decay W boson. Using the correlation between lepton and down-type quark we measure the spin correlation coefficient $\kappa = 0.72 \pm 0.62 \pm 0.26$ using $5.3\,{\rm fb}^{-1}$ data. It is consistent with SM ($\kappa_{\rm SM} = 0.78$) [18].

The SM predicts that the top quark decays almost entirely to a W boson and a bottom quark, and that the Wtb vertex is a $V - A$ charged weak current interaction. A consequence of this is that approximately 70% of the top quark decay longitudinally, 30% of the top quarks have left handed polarization ($f_0 = 70\%$, $f_- = 30\%$, $f_+ = 0\%$) [19]. Any new particles involved in the same decay topologies and non-standard coupling could create a different mixture of polarized W bosons. Therefore, a measurement of this fraction

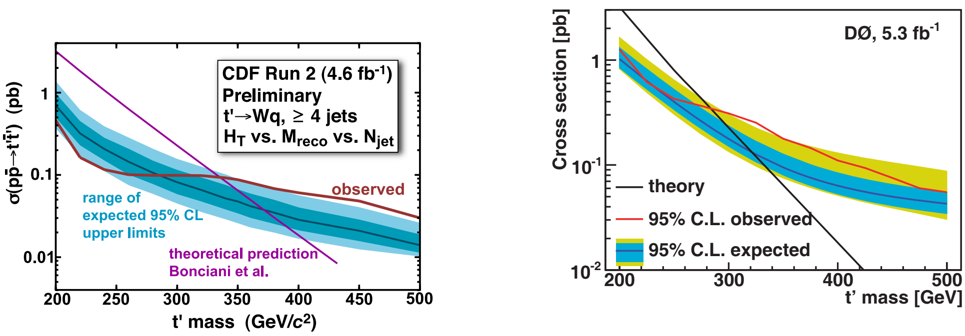

Fig. 3. – 95% CL limits of t' pair production cross section measured by CDF (left) and D0 (right) overlaid predicted cross section.

is a test of the $V - A$ nature of the Wtb vertex. D0 Collaboration uses both lepton+jets and dilepton channel simultaneously with 4.3 fb^{-1} data and extracts $f_+ = 0.02 \pm 0.05$ and $f_0 = 0.06 \pm 0.01$ with the simultaneous fit of the two variables [20]. This is consistent with SM at the 98% CL. CDF Collaboration has results in both lepton+jets [21] and dilepton channels [22] which are also consistent with SM.

Several exotic physics models, such as SUSY and two Higgs doublet, predict flavor-changing neutral current (FCNC) in the top decay. In the SM, this decay mode is highly suppressed so, any signals from FCNC decay chain indicate an evidence of new physics. FCNC decay of top quark ($t \to Zq$) predict different final state of $t\bar{t}$ with SM decays. D0 Collaboration uses trilepton final state ($Z \to ll$ and $W \to l\nu$) using 4.1 fb^{-1} data. Based on the data which is consistent with null signal of FCNC decay, we set the upper limit of FCNC branching fraction as $Br(t \to Zq) < 3.3\%$ at 95% CL [23]. CDF Collaboration has a dilepton channel ($Z \to ll$ and $W \to qq$) analysis using 1.9 fb^{-1} and set the 95% CL upper limit of 3.7% [24].

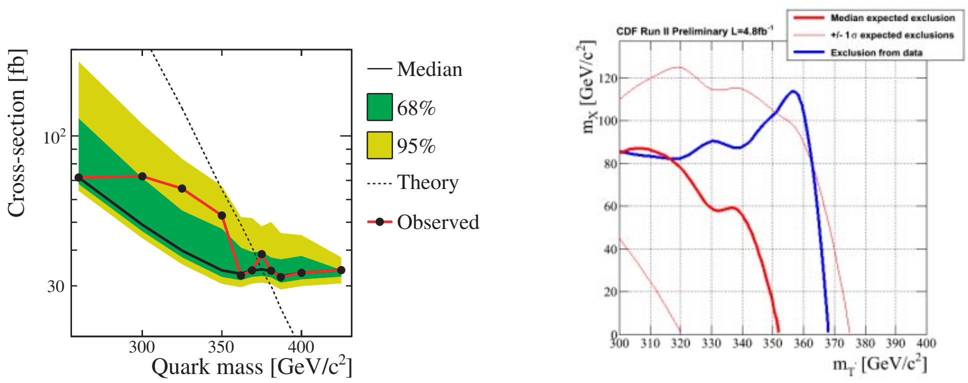

Fig. 4. – 95% CL limits of b' pair production cross section as a function of b' masses (left) and of t' pair production cross section in the two dimensional space of t' and invisible particle masses (right).

5. – New physics particle searches

The electroweak precision measurements did not prohibit the fourth generation of quarks such as t' (top-like quark) and b' (bottom like quark). CDF and D0 Collaborations have been searching the fourth generation t' in a decay mode of $t' \to Wq$ which was preferred in case of a small mass splitting between t' and b'. We use the reconstructed t' mass and H_T to isolate signals. As one can see in fig. 3, both experiments have approximately 2σ access in the t' mass around $350\,\mathrm{GeV}/c^2$ [25, 26]. This is interesting access of signal and might be figured out with larger data sample of $10\,\mathrm{fb}^{-1}$ at the end of Run II in both experiments.

CDF Collaboration has searched the b' in a decay mode of $b' \to tW$. We expect very energetic and large jet multiplicity signature from $b'\bar{b}'$ decay. We use H_T categorized by jet multiplicity to extract signal. Data consisted with null signal set the lower limit of $M_{b'} > 385\,\mathrm{GeV}/c^2$ as one can see in fig. 4 (left) [27].

A more exotic model predicts t' decay into tX where X is invisible particle of the dark matter candidate. CDF Collaborations has searched pair productions of t' decaying into t and invisible. Taking advantage of large missing energy from signal, we extract the exotic t' signal from data which is consistent with null signal. We then set the 95% CL limit of parameter space as shown in fig. 4 (right) [28].

6. – Conclusion

The CDF and D0 Collaborations have performed a robust set of analyses using many techniques and improvements to have better understand the top quark nature. As a result, we determine the M_{top} with $\Delta M_{\mathrm{top}}/M_{\mathrm{top}}$ less than 0.7% and $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ less than 7% precisions. By end of Run II, we expect $\sim 12\,\mathrm{fb}^{-1}$ of data delivered to both experiments by the Tevatron which could be almost a double the data sample used in this report. An ultimate precision of about M_{top} less than $1\,\mathrm{GeV}/c^2$ will be possible. The other top properties and new particle searches, which are mostly limited by statistics, have been significantly improved and we may have surprising results.

* * *

I would like to thank for the CDF and D0 colleagues for their efforts to carry out these challenging physics analyses. I also thank for the conference organizers for a very rich week of physics.

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] Nakamura K. *et al.* (Particle Data Group), *J. Phys. G*, **37** (2010) 075021.
[3] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD, the LEP Electroweak Working Group, the Tevatron Electroweak Working Group, and the SLD Electroweak and Heavy Flavor Working Groups, arXiv:1012.2367v2.
[4] Flächer H. *et al.*, *Eur. Phys. J. C*, **60** (2009) 543.
[5] Moch S. and Uwer P., *Nucl. Phys. Proc. Suppl.*, **183** (2008) 75.
[6] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **105** (2010) 012001.
[7] Abazov V. *et al.* (D0 Collaboration), arXiv:1101.0124.
[8] (CDF Collaboration), CDF conference note 10234.

[9] The Tevatron Electroweak Working Group (CDF and D0 Collaborations), FERMILAB-TM-2466-E, arXiv:1007.3178.
[10] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **105** (2010) 252001.
[11] (D0 Collaboration), D0 conference note 6104.
[12] Abazov V. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **103** (2009) 132001.
[13] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **106** (2011) 152001.
[14] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **105** (2010) 232003.
[15] Abazov V. *et al.* (D0 Collaboration), *Phys. Rev. Lett.*, **106** (2010) 022001.
[16] (CDF Collaboration), CDF conference note 9824.
[17] Abazov V. *et al.* (D0 Collaboration), arXiv:1103.1871.
[18] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. D*, **83** (2011) 031104.
[19] Aguilar-Saavedra J. *et al.*, *Eur. Phys. J. C*, **50** (2007) 519.
[20] Abazov V. *et al.* (D0 Collaboration), *Phys. Rev. D*, **83** (2011) 032009.
[21] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **105** (2010) 042002.
[22] (CDF Collaboration), CDF conference note 10333.
[23] Abazov V. *et al.* (D0 Collaboration), arXiv:1103.4574.
[24] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **101** (2008) 192002.
[25] (CDF Collaboration), CDF conference note 10110.
[26] Abazov V. *et al.* (D0 Collaboration), arXiv:1104.4522.
[27] Aaltonen T. *et al.* (CDF Collaboration), *Phys. Rev. Lett.*, **106** (2011) 141803.
[28] Aaltonen T. *et al.* (CDF Collaboration), arXiv:1103.2482.