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Measurement of top quark properties at Tevatron

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This article presents the most recent Fermilab Tevatron Collider results on the top quark properties measured in proton-antiproton collisions at $\sqrt{s} = 1.96\,TeV$ by the CDF and DØ collaborations. The top quark mass were measured in different final states, some of these results already use all Tevatron RunII data corresponding to integrated luminosity up to $10\,fb^{-1}$. Precise mesurement of the top quark width can be used to determine the top quark lifetime and limits on the CKM matrix element $|V_{tb}|$. Short lifetime of the top quark and its decay before hadronization allows measurement of the spin correlation between quark and antiquark. The top quark decays almost exclusively in the W boson and b–quark and W boson helicity fractions from $t\bar{t}$ decays were also measured. All these precise measurements can be used to probe standard model predictions.

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1. Introduction

The top quark was discovered by CDF and DØ collaborations in 1995 at the Tevatron proton anti-proton accelerator with center of mass energy $1.8\,TeV$ in so called RunI. In September 2011 Tevatron was shut down after ten years of data taking during so called RunII with $\sqrt{s} = 1.96\,TeV$. Data available now for physic analysis are two order of magnitude bigger than at the time of the top quark discovery (more then $10fb^{-1}$ were recorded by each experiment) and this makes possible to precisely measure different top quark properties.

There are only two places in the world, Fermilab Tevatron Collider and CERN Large Hadron Collider (LHC), that have sufficient energy to produce the top quarks and to measure directly their properties. Even thought Tevatron has much smaller center-of-mass energy and as a consequence much smaller top quark production rate, they can still produce competitive precise measurements of the top quark properties, because some analysis are no longer limited by statistical uncertainties and good understanding of CDF and DØ detectors leads to smaller systematic uncertainties. At the Tevatron proton-antiproton collider the top quark pairs are mostly produced by quark-antiquark anhilation (85%) where at the LHC they are mostly produced by gluon-gluon fusion and different production mechanism also leads to complementary results.

The top quark has unique position between quarks because of its high mass and short lifetime. It decays before hadronization that allows us to study directly bare quark properties. Precise measurement of the top quark properties and their deviations from standard model (SM) could reveal signs of physics beyond the SM. The top quark has very high mass and that's why it is expected to have strong coupling with the SM higgs. Precise measurement of the top quark mass and the W boson mass provides limits on the SM higgs mass.

2. Mass

The top quark mass is a free parameter of SM and that's why it is important to measure experimentally as precise as possible. The top quark decay almost exclusively in $t \rightarrow Wb$, W boson later decays to the lepton plus undetected neutrino or hadronize to quarks (detected as jets) and this give us experimental signature observed in our detector. CDF and DØ measure the top quark properties in all three different final states given by the W boson decay modes — 35% *lepton+jets* (one W boson decays leptonically), 2% *dilepton* (both W bosons decays leptonically), 46% all jets (both W bosons hadronize).

Lepton+jets is usually the best final state for the top quark studies, because it is relatively easy to select events with lepton in final state and experimental signature provides good means for signal and background separation, the top quark kinematics can be fully reconstructed (no undetected neutrino in this final state) and branching fraction for this decay channel is pretty high. CDF collaboration already used all RunII data corresponding to the $8.7fb^{-1}$ of integrated luminosity and measured the top quark mass $172.85 \pm 0.71(stat.) \pm 0.84(syst.)$ GeV/c^2 [1] using template method with in–situ jet energy scale (JES) that use known W boson mass as a JES calibration constraint. This is the most precise mass measurement using data from one decay channel. The precision in *lepton+jets* channel is no longer limited by statistical but systematical uncertainties. DØ collaboration measured the top quark mass in *lepton+jets* using matrix element method [2]. This method usually provides most precise results in *lepton+jets* channel and with less than $1/2$ of collected data ($3.6 fb^{-1}$) DØ was able to measure the top quark mass $174.94 \pm 0.83(stat) \pm 0.78(JES) \pm 0.96(syst)$ GeV/c^2 [3]. The largest systematical uncertainties comes from JES and both collaborations devote special effort to minimize them, CDF is using special JES for jets coming from b–quark and DØ is using flavor dependent JES correction.

Dilepton decay channel is kinematically underconstrainted and that makes mass measurements more complex, but on the other hand two leptons in final state makes signal selection very pure. Both collaboration use neutrino weighting method which integrates over η distribution of both neutrinos and assign weight to each kinematic solution comparing measured and calculated energy imbalance (MET). To get the best signal and background separation each lepton combination in the top decay final state (ee, $e\mu$, $\mu\mu$) is analyzed separately and DØ in addition use in–situ JES calibration derived in *lepton+jets* channel (this calibration can't be extracted directly because of incomplete kinematic reconstruction in *dilepton* channel). Individual results for ee, $e\mu$, $\mu\mu$ in final state are combined with best linear unbiased estimator (BLUE) method and DØ measured the top mass $174.0 \pm 2.4(stat) \pm 1.4(syst)$ GeV/c^2 [4] and CDF $170.3 \pm 2.0(stat) \pm 3.1(syst)$ GeV/c^2 [5]. These results were obtained using $1/2$ of collected data ($\approx 5 fb^{-1}$) and that means there are still room for future improvements, because small branching ratio in *dilepton* channel makes this analysis statistically limited.

All–jet channel has very large branching ratio, but also overhelming QCD background. Moreover these kind of multijet background can't be reliably modeled by any current MC generator and that's why CDF used data driven background based on b–tag rate parametrization with small b–quark probability (negligible signal contribution in background sample). Events with 1 and 2 b–tags and 6–8 jets were separated by 13 parameter neural network (NN) discriminator to increase signal to background ratio. Selected events still have huge number of possible jet–parton assignment and the best χ^2 for event kinematics is used to choose best combination which is later used as an input for template method. Largest systematic uncertainty that comes from JES is reduced by in–situ calibration using known W boson mass. CDF top mass result in *all–jet* channel with $5.8 fb^{-1}$ of data is $172.5 \pm 1.4(stat) \pm 1.0(JES) \pm 1.1(syst)$ GeV/c^2 [6]. Main systematic uncertainty of this measurement comes from signal and background modeling.

Last CDF top quark mass measurement using whole $8.7 fb^{-1}$ RunII data sample is done on events with significant energy imbalance (MET) that was missed by previous $lepton + jet$ and *dilepton* data preselection. This analysis use almost same approach as *all–jet* analysis (data driven background, NN discriminant, template method, in–situ calibration, ...) and measure $173.9 \pm 1.6(stat. + JES) \pm 0.9(syst.)$ GeV/c^2 [7].

All Tevatron top quark mass measurements published by the DØ and CDF collaborations using RunI and RunII data were included in the Tevatron top mass combination. Current combination was done with results that use up to $5.8 fb^{-1}$ (July 2011 combination). Each collaboration used different method, χ^2 was used by CDF and DØ used best linear unbiased estimator (BLUE). Both methods give consistent result $173.2 \pm 0.6(stat) \pm 0.8(syst)$ GeV/c^2 [8]. As it was mentioned earlier single measurement that use all RunII data can reach similar ≈ 1 GeV/c^2 precision and further improvements can be expected with the final legacy Tevatron top quark mass combination.

3. Mass difference

The standard model (SM) is a local gauge–invariant quantum field theory (QFT) which is invariant under CPT (charge, parity and time reversal). CPT conservation is fundamental principle in SM however it is important to examine possibility of CPT violation as there are extension of the SM allowing CPT symmetry breaking. The mass difference between particle and antiparticle would indicate a violation of CPT and it was tested for many elementary particles. Quarks carry color charge and that's why they can't be observed directly, because they hadronize first via QCD with exception of the top quark. The top quark is most massive quark and with very short lifetime it decays before hadronization. This provide us opportunity to measure directly the mass difference between quark and its antiquark.

CDF measured mass difference with all RunII data using same selection as in the $lepton+jets$ top quark mass measurement. They choose same template method, but templates for this measurement were created with different top and antitop masses. Measured mass difference $\Delta m_{t\bar{t}} = -1.95 \pm 1.11(stat) \pm 0.59(syst)$ GeV/c^2 [9] is most precise measurement to date. DØ used matrix element technique and signal samples generated by modified version of PYTHIA that not only produces data with different top and antitop quark masses but also adjust dependent variables (e.g. decay width Γ_t). With only $3.6 fb^{-1}$ of data collected by DØ this method lead to $\Delta m_{t\bar{t}} = -0.8 \pm 1.8(stat) \pm 0.5(syst)$ GeV/c^2 [10]. Both results are in agreement with SM expectation of no mass difference.

4. Width

The top quark is the heaviest known elementary particle whose large mass results in the largest decay width (Γ_t) and hence shortest lifetime ($t = \hbar/\Gamma_t$). Lifetime is expected to be shorter than QCD scale typical of the formation of the hadronic bound state. Assuming $|V_{tb}| = 1$ and $m_t = 172.5$ GeV/c^2) the next-to-leading order calculation with QCD electroweak corrections predict $\Gamma_t = 1.3 GeV (\tau_t \approx 5.10^{-25} s)$. Deviation from this SM prediction would indicate contribution of beyond SM (BSM) physics (anomalous Wtb couplings, hadronically decaying charged Higgs bosons, top quark decay to its supersymmetric scalar partner stop plus neutralinos, ...).

DØ determined indirectly the total width of the top quark based on two prior DØ measurements using $5.4 fb^{-1}$ of integrated luminosity. The single top quark t-channel cross section $\sigma(p\overline{p} \to tqb + X) = 2.90 \pm 0.59(stat+syst) pb$ [11] and the ratio $R = B(t \to Wb)/B(t \to Wq) = 0.90 \pm 0.04(stat+syst)$ [12]. The total decay width Γ_t can be expressed in terms of the t-channel single top quark production cross section and the branching fraction $\Gamma_t = (\sigma(t-channel)\Gamma(t \to Wb)_{SM})/(B(t \to Wb)\sigma(t-channel)_{SM})$. The total top quark width found using this indirect method is $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV [13] and it can be expressed as a top quark lifetime of $\tau_t = (3.29^{+0.90}_{-0.63} \times 10^{-25} s$.

Direct measurement of the top quark width were done by the CDF collaboration using $l + jets$ decay channel of $t\bar{t}$ events and data sample corresponding $4.3 fb^{-1}$ of integrated luminosity. They built templates for a fixed top quark mass $m_t = 172.5$ GeV/c^2 with simulated MC $t\bar{t}$ signal with different Γ_t and Δ_{JES} (deviation from nominal jet energy scale). These signal and background templates were compared with data distributions using unbinned maximum likelihood fit and simultaneous fit were performed in Γ_t and Δ_{JES}. Δ_{JES} was used for the in–situ calibration of the jet energy scale to reduce systematic uncertainties. By applying a Feldman-Cousins approach they established an upper limit at 95% confidence level (CF) of $\Gamma_t < 7.6$ GeV [14] and two sided 68% CL interval 0.3 GeV $< \Gamma_t <$ 4.4 GeV. Both DØ and CDF top quark width measurements are consistent with the standard model prediction.

5. Spin Correlations

As it was pointed out in the top quark width measurement, CDF and DØ results confirms very short lifetime of the top quark, even shorter then the timescale for hadronization. This means that original polarization of the top quark at production is preserved and because of its decay via weak interaction it is also transferred to its decay products. $t\bar{t}$ spin correlation can be measured by looking at the angular distribution of its decay products, because the spin orientation is reflected in the angular distribution of the final state particles. The amount of spin correlation is given by $t\bar{t}$ production mechanism — quark-antiquark anhilation ($q\bar{q}$) with spin 1 and gluon-gluon (gg) fusion producing $t\bar{t}$ pair in spin 0. At Tevatron dominant process in $t\bar{t}$ production is $q\bar{q}$ anhilation and it is expected to measure significant correlation between top and anti-top quark spins.

Both CDF and DØ collaborations measure spin correlation strength coefficient C of the doubly differential cross section $(1/\sigma_{t\bar{t}}) * (d^2\sigma_{t\bar{t}}/d\cos\theta_1\cos\theta_2)$ which can be written as $\frac{1}{4}C\cos\theta_1\cos\theta_2$, where θ_1 (θ_2) are angles between spin-quantization axes and the direction of flight of the down-type fermion from W boson decay in the $t\bar{t}$ rest frame. This coefficient C is related to the difference of $t\bar{t}$ with aligned and antialigned spins normalized by the total number of $t\bar{t}$ events and multiplied by analyzing power of the final state fermion ($t \rightarrow l^+\nu_l b \approx 1$, $t \rightarrow \bar{d}ub \approx 0.97$ in NLO QCD). This means that the best sensitivity at Tevatron can be expected in *dilepton* channel. The spin correlation coefficient C depends also on the quantization bases and all measurements were done using beam basis corresponding to the direction of the incident colliding particles.

CDF performed spin correlation analysis with integrated luminosity $5.1 fb^{-1}$ and $t\bar{t}$ candidates in *dilepton* channel. Template method and unbinned likelihood was used to measure $C = 0.042^{+0.563}_{-0.562}(stat+syst)$ [15]. DØ performed spin correlation measurement with data sample $5.3 fb^{-1}$ in $l+jets$ channel and $5.4 fb^{-1}$ in *dilepton* channel. Both analysis used matrix-element method and measured $C = 0.89 \pm 0.33(stat+syst)$ [16] resp. $C = 0.57 \pm 0.31(stat+syst)$ [17]. Combining these two DØ results they obtained significant evidence for presence of spin correlation in $t\bar{t}$ events with 3.1 standard deviation and $C = 0.66 \pm 0.23(stat+syst)$ [17] . All spin correlation measurements are in agreement with NLO SM value $C \approx 0.777$.

6. *W* boson helicity

In the standard model (SM) the branching ratio $t \rightarrow Wb$ is $> 99.8\%$ and produced on-shell W boson have three different helicity states — f_0 (longitudial), f_- (left-handed) and f_+ (right-handed). SM top quark decays via the $V-A$ weak charged-current interaction, which strongly suppress right-handed W^+ bosons or left-handed W^- bosons. For the $m_t = 173.3 \pm 1.1$ GeV/c^2 and $M_W = 80.399 \pm 0.023$ GeV/c^2 the SM predicts a longitudially polarized fraction to be $f_0 = 0.688 \pm 0.004$, left-handed $f_- = 0.310 \pm 0.004$ and right-handed $f_+ = 0.0017 \pm 0.0001$.

CDF and DØ measured W boson helicity fractions from the angular distribution given by $\omega(\theta^*) \propto 2(1-\cos^2\theta^*)f_0 + (1-\cos\theta^*)^2 f_- + (1+\cos\theta^*)^2 f_+$, where θ^* is the angle between direction of flight of the top quark and the down type fermion decay product of the W boson in the W boson rest frame. CDF performed W boson helicity measurement using all RunII $t\bar{t}$ candidates in $l + jets$ final state and integrated luminosity $8.7 fb^{-1}$. For the best sensitivity matrix-element (ME) method was used to simultaneously (to be as model independent as possible) extract longitudial $f_0 = 0.026 \pm 0.066(stat) \pm 0.067(syst)$ and right-handed $f_+ = -0.025 \pm 0.024(stat) \pm 0.040(syst)$ [18]. DØ measurement was done with $t\bar{t}$ candidates in $l + jets$ and *dilepton* final states and data sample that corresponds an integrated luminosity $5.4 fb^{-1}$. Measured $\cos\theta^*$ distribution was used to simultaneously extract the value of the $f_0 = 0.669 \pm 0.078(stat) \pm 0.065(syst)$ and $f_+ = 0.033 \pm 0.041(stat) \pm 0.034(syst)$ [19] W boson helicity fractions with a binned Poisson likelihood fit to the data.

To improve statistical and systematical uncertainties CDF and DØ combined W boson helicity measurements using $5.4 fb^{-1}$ CDF result measured using with template method in *dilepton* final state [20], $2.7 fb^{-1}$ CDF result measured with ME method in $l + jets$ final state [21] and DØ $l + jets$ and *dilepton* result [19]. This combination lead to measured value of $f_0 = 0.722 \pm 0.062(stat) \pm 0.052(syst)$ and $f_+ = -0.033 \pm 0.034(stat) \pm 0.031(syst)$ [22]. All individual measured W helicity fractions and also their combination are consistent with SM prediction.

7. Conclusion

We have presented the latest results of the various top quark properties measured at Tevatron proton-antiproton ($p\bar{p}$) collider at a center-of-mass energy $\sqrt{s} = 1.96 TeV$. Several measurements already used all RunII data but there are still a lot of analyses in the top quark sector that will benefit from additional data (up to integrated luminosity $10 fb^{-1}$), better understanding of detector performance, improved analysis techniques and combination of the CDF and DØ results.

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