STUDIES OF TOP QUARK PROPERTIES AT THE TEVATRON

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An overview of the recent measurements of the top quark properties in proton antiproton collisions at $\sqrt{s} = 1.96$ TeV is presented. These measurements are based on 5.4 – 8.7 fb^{-1} of data collected with the D0 and CDF experiments at the Fermilab Tevatron collider. The top quark mass and width measurements, studies of the spin correlation in top quark pair production, W boson helicity measurement, searches for anomalous top quark couplings and Lorentz invariance violation are discussed.

1 Introduction

Top quark plays a special role in the modern particle physics. Its large mass, close to 173 GeV, extremely short lifetime of about $5 \cdot 10^{-25}$ sec, large coupling to the Higgs boson and potentially large couplings to the beyond-standard-model particles make the top quark an unique laboratory to test predictions of the standard model (SM) and search for phenomena beyond SM. In this article the recent measurements of the top quark properties are reported, based on the 5.4 – 8.7 fb^{-1} of data collected with the D0 [1] and CDF [2] experiments at the Fermilab Tevatron collider.

2 Top Quark Mass Measurement

Top quark mass is a free parameters in the SM. It is measured at the Tevatron collider mainly with a matrix element or template based methods. A significant reduction of the jet energy scale (JES) related uncertainties is achieved by using the W boson mass as a constrain for the invariant mass of two jets, produced by the W boson decay in the lepton+jet final state. Recently the CDF collaboration measured the top quark mass using the full available statistics of 8.7 fb^{-1} in the lepton + jet final state [3]. In each events the reconstructed top mass is found by minimizing a χ^2 function describing the overconstrained kinematics of the $t\bar{t}$ system for the combination with minimal χ^2. The improvement in precision could be reached by using a reconstructed top quark mass from 2nd best χ^2 combination. Templates for the dijet mass of the hadronically decaying W boson are used to constrain the JES in situ. The 3D probability density functions for different top quark masses are constructed using a kernel density estimation to the simulation. Comparison of the simulation templates with data ones allows to extract the top quark mass. This measurement results to the most precise determination of the top quark mass in a single channel: $M_{top} = 172.85 \pm 0.71\ (stat.) \pm 0.84\ (syst.)\ GeV$. The precision of the measurement is limited mainly by the signal simulation uncertainties and residual JES uncertainty.

The D0 collaboration produced the new measurement in the dilepton channel using 5.4 fb^{-1}

of data using the neutrino weighting technique to reconstruct the underconstrained kinematic in this channel [4]. This measurement has slightly less statistical precision than the previous matrix element measurement [5], but improved systematic uncertainty. The improvement has been achieved by propagating the in situ JES correction factor from the lepton+jet top quark mass measurement [6] to the dilepton channel. Additionally the uncertainty on the b quark JES has been reduced by applying the specific JES corrections for the different type of partons in the simulation. These corrections reflect the difference in the signal particle response between data and MC for the gluon, light quark or b-quark jets. The result of this measurement is $M_{top} = 174.0 \pm 2.4\ (stat.) \pm 1.4\ (syst.)\ GeV$.

The most recent combination of the top quark mass measurements at the Tevatron [7] doesn't include these two measurements yet, but has a remarkable precision of 0.54% and yield the top quark mass $M_{top} = 173.18 \pm 0.94\ GeV$ (Fig. 1). The further improvement in the top quark mass uncertainty requires better understanding of the model uncertainties in the $t\bar{t}$ production simulation.

3 Top Quark Width

The top quark decay width (Γ_t) is a difficult parameter for the direct measurement. CDF collaboration made an attempt to measure the top quark width by comparing the reconstructed top mass distributions in simulation and data. Unfortunately the precision of this method allows only to establish the upper limit of about $\Gamma_t < 7.6$ GeV at 95% C.L. [8] using luminosity of 4.3 fb^{-1}.

The D0 collaboration use the indirect determination of the top quark decay width using the partial decay width $\Gamma(t \to Wb)$ and the branching fraction $B(t \to Wb)$. The partial decay width is obtained from the t-channel single top quark production cross section as $\Gamma(t \to Wb) = \sigma(t-channel)\frac{\Gamma(t \to Wb)_{SM}}{\sigma(t-channel)_{SM}}$. The total decay width can be written in terms of the partial decay width and the branching fraction as $\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$. Combining these two equations, the total decay width becomes $\Gamma_t = \frac{\sigma(t-channel)\Gamma(t \to Wb)_{SM}}{B(t \to Wb)\sigma(t-channel)_{SM}}$. Using the $B(t \to Wb)$ measured value [9] and t-channel cross section measurement [10], the resulting width is found to be $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV for the top quark mass 172.5 GeV [11]. This value could be reinterpret as a top quark lifetime $\tau_t = \hbar/\Gamma_t = 3.29^{+0.90}_{-0.63} \times 10^{-25}$ s.

We can also use the measured value of Γ_t to probe the Wtb interaction and directly determine the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix element $|V_{tb}|$. Similar to the determination of $|V_{tb}|$ using the single top cross section, this determination does not assume the unitarity of the CKM matrix or three generations of quarks. Additionally, using the measured branching fraction $B(t \to Wb)$ and t-channel as a single top cross section, allows to avoid an assumption that the top quark decays exclusively to Wb and an assumption that the relative production rate of s and t single top channels is the same as predicted by the SM. Restricting the $|V_{tb}|$ values to the physically allowed region $0 \le |Vtb|^2 \le 1$, a lower limit on $|V_{tb}|$ matrix element could be establish: $|Vtb| > 0.81$ at 95% C.L. [11].

4 Spin Correlation in $t\bar{t}$ Production

The unique feature of the top quark that it decays before depolarization or hadronization. This peculiarity allows to study the spin related quantities via the top quark decay products, W boson and b quark. Although top and antitop quarks are produced unpolarized at hadron colliders, they have a significant correlation between the orientation of theirs spins. The strength of spin correlation depends on the production mechanism and on the calculation basis and could be measured via the angular distributions of top quark products. The $t\bar{t}$ spin correlation strength

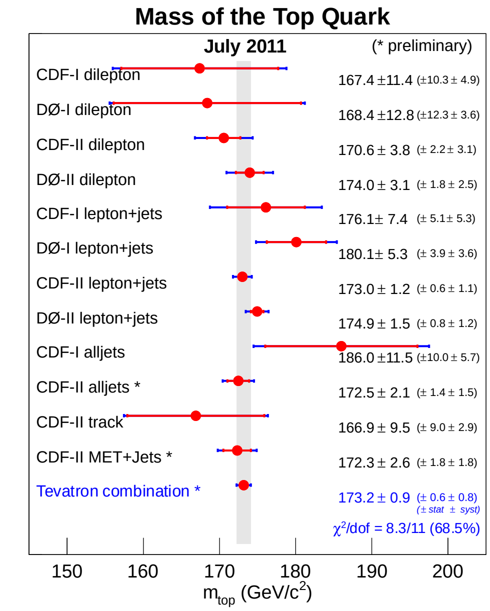

Figure 1: Top quark mass combined result from D0 and CDF collaborations and results used in the combination.

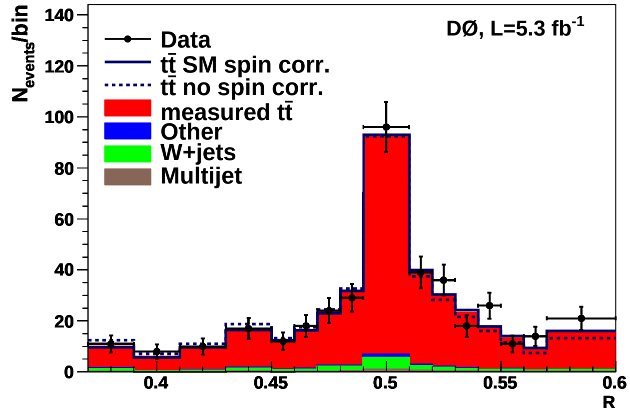

Figure 2: The distribution of the discriminant R of the l+jets events with four jets. The expectation (including background) for complete spin correlation as predicted by the SM and the case of no spin correlation. The measured $t\bar{t}$ distribution is shown with the spin correlation strength measured in the dilepton and lepton+jet channels.

C is defined by $d\sigma^2_{t\bar{t}}/(d\cos\theta_1 d\cos\theta_2) = \sigma_{t\bar{t}}(1 - C\cos\theta_1\cos\theta_2)/4$, where $\sigma_{t\bar{t}}$ is a production cross section, θ_1, θ_2 are the angles between the spin-quantization axis and the direction of flight of the down-type fermion from the W boson decay in the respective parent t or $\bar{t}$ rest frame. Using the beam momentum vector as the quantization axis, the SM predicts $C = 0.78^{+0.03}_{-0.04}$ at NLO QCD for the proton antiproton collision with the center-of-mass energy 1.96 TeV [12].

Two approaches have been developed at the Tevatron for this measurement. The first one is the template based measurement, which consist in the comparing the angular distributions templates with different spin correlation strength in simulation with data distribution. With this approach D0 measured in the dilepton channel $C = 0.10 \pm 0.45(stat. + syst.)$ [13]. CDF measured in the dilepton channel $C = 0.04 \pm 0.56(stat. + syst.)$ [14] and in the lepton+jet channel $C = 0.72 \pm 0.69(stat. + syst.)$ [15]. All these results are compatible with SM prediction, but have the limited statistical precision and can't distinguish between "no spin correlation" and "spin correlation" cases.

D0 pioneered the matrix element method for the spin correlation measurement. This method consist in the calculating the discriminant R for each event $R = \frac{P(x,H=1)}{P(x,H=c)+P(x,H=u)}$, where P(x) is a probability, calculated as a function of all measured kinematic variables x using the leading order matrix element for the $t\bar{t}$ production for the "spin correlation" hypotheses ($H = c$) and "no spin correlation" hypothesis ($H = u$). The simulated distributions of the discriminant R for the correlation and no correlation hypotheses are used to fit the distribution in data and determine the correlation strength (Fig. 2). Due to the maximal use of kinematic information in the event and optimal use of the statistical weight of each event, this method is 30% more precise than the template based one. Measuring the spin correlation strength in the dilepton and lepton+jet channel and combining them together, D0 obtained $C = 0.66 \pm 0.23(stat. + syst.)$ in agreement with the SM [16]. This measurement has excluded the "no spin correlation" hypothesis for the first time a the level of 3.1σ or $C > 0.26$ at 95% C.L.

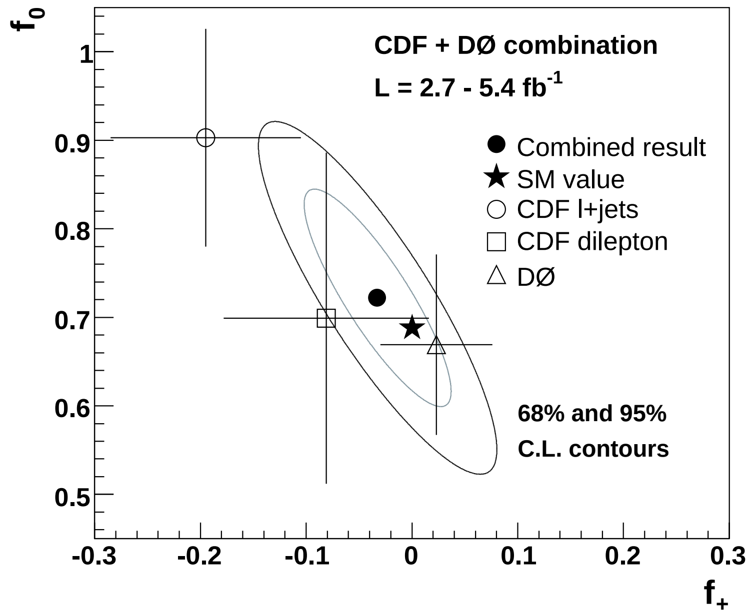

Figure 3: Combination of the 2D W boson helicity measurements. The ellipses indicate the 68% and 95% C.L. contours, the dot shows the best-fit value, and the star marks the expectation from the SM. The input measurements to the combination are represented by the open circle, square, and triangle, with error bars indicating the 1 uncertainties on f_0 and f_+. Each of the input measurements uses a central value of mt = 172.5 GeV.

5 W Helicity Studies and Search for the Anomalous Quark Couplings

In the SM, the top quark decays, almost always, to a W boson and b quark via the $V - A$ charge current interaction. The new physics contribution may alter the fraction of the W boson produced in different polarization states from SM values of 0.688 ± 0.004 for the longitudinal helicity fraction f_0, 0.310 ± 0.004 for the negative helicity fraction f_- and 0.0017 ± 0.0001 for the positive helicity fraction f_+ [17] at the top quark mass of 173.3 GeV. Both D0 and CDF collaborations have measured fractions f_0 and f_+ using the angular distribution of the down-type decay products of the W boson (charged lepton or d, s quarks) in the rest frame of the W boson. Recently all these results with 2.7 – 5.4 fb^{-1} of integrated luminosity have been combined together [18]. The obtained results are $f_0 = 0.722 \pm 0.081$ $[0.062(stat.) \pm 0.052(syst.)]$ $f_+ = -0.033 \pm 0.046$ $[0.034(stat.) \pm 0.031(syst.)]$ for measurements in which both f_0 and f_+ are varied simultaneously (see Fig. 3). These are the most precise measurements of f_0 and f_+ to date. The results are consistent with expectations from the SM and provide no indication of new physics in the tWb coupling.

D0 also make a direct search for the anomalous coupling in tWb vertex. Search for the phenomena beyond the SM done in the form of right-handed vector couplings f_V^R or left- or right-handed tensor couplings f_T^L, f_T^R, described by the effective Lagrangian including operators up to dimension five:

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L + f_V^R P_R)\; tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\;\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_T^L P_L + f_T^R P_R)\; tW_{\mu}^{-} + h.c.\;,$$

where M_W is the mass of the W boson, q_ν is its four-momentum, V_{tb} is the Cabibbo-Kobayashi-Maskawa matrix element, and $P_L = \frac{1}{2}(1-\gamma_5)$ ($P_R = \frac{1}{2}(1+\gamma_5)$) is the left-handed (right-handed) projection operator. It is assumed that CP is conserved at the Wtb vertex, meaning that all form

Table 1: Observed upper limits on anomalous tWb couplings at 95% C.L. from W boson helicity assuming $f_V^L = 1$, from the single top quark analysis, and from their combination, for which no assumption on f_V^L is made.

	W helicity only	Single top only	Combination
$\|f_V^R\|^2$	0.62	0.89	0.30
$\|f_T^L\|^2$	0.14	0.07	0.05
$\|f_T^R\|^2$	0.18	0.18	0.12

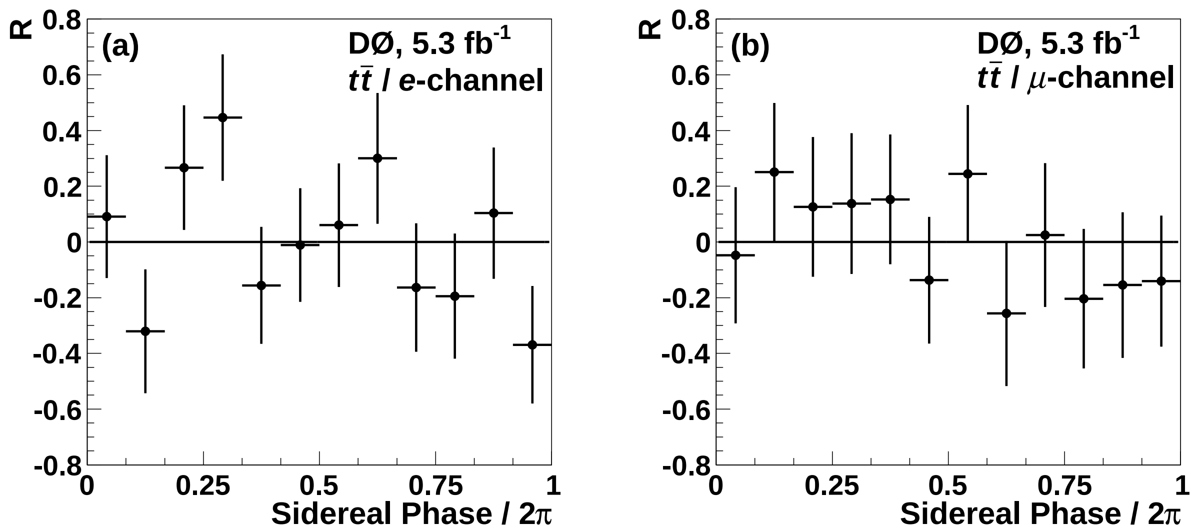

Figure 4: The dependence of the normalized $t\bar{t}$ cross section R, on the sidereal phase for e+jets candidates (left plot) and μ+jets candidates (right plot).

factors $f_i^{L,R}$ are taken to be real. It is also assumed that the top quark has spin $\frac{1}{2}$. Variations in the coupling form factors would mainly manifest themselves in two distinct ways: by changing the rate and kinematic distributions of electroweak single top quark production, and by altering the fractions of W bosons from top quark decay produced in each of the three possible helicity states. D0 combines information from the measurement of W boson helicity fractions [19] with information from measurement of single top quark production [20]. No indication of the beyond SM phenomena are found, so upper limits on on anomalous tWb couplings have been set, see Table 1.

6 Search for violation of Lorentz invariance

D0 collaboration has searched for the violation of the Lorentz invariance in the $t\bar{t}$ production and decay using $5.3 fb^{-1}$ of data in lepton+jet final state. The standard model extension framework provides an effective field theoretical treatment for violation of Lorentz and CPT symmetry in particle interactions by introducing Lorentz-violating terms to the Lagrangian density of the SM [22]. Rotation of the Earth about its axis and about the Sun, leads to the time dependence in the $t\bar{t}$ production cross section. The relevant time scale is the sidereal day, which has a period of 23 hr 56 min 4.1 s. Study of the $t\bar{t}$ cross section didn't reveal any time dependence with the sidereal period, see Fig. 4. In the absence of the any observed violation, the upper limit on the standard model extension has been set in the publication [23].

7 Conclusion

The data collection at the Tevatron has been stop at September 30, 2011. D0 and CDF collaborations accumulated about 10 fb^{-1} of data. Current results of the top quark properties measurement are based on the half of the available statistics mainly. Both collaborations continue studies in the top quark sector, concentrating mainly on the measurement competitive with LHC (like a top quark mass measurement) or complementary to the LHC (like top quark production cross section and asymmetry measurement, spin correlation studies). More details about recent top quark results could be found on the collaborations web pages [24,25].

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