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Top quark properties studies at the Tevatron

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In this paper I report a selection of the most recent CDF and D0 results on top quark properties, based on the analysis of Tevatron Run II data. The top quark is being studied in great detail by the CDF and D0 experiments. The production mechanism, decay vertex and kinematic distributions have been investigated to test many aspects of the Standard Model. Searches for new physics have been performed using the top quark candidates sample. All results shown here are in agreement with Standard Model predictions.

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1. Introduction

CDF II and D0 are multipurpose detectors which were taking 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 TeV until its shutdown in September 2011. Data corresponding to an integrated luminosity of approximately 10 fb^{-1} were collected by each experiment. The analyses described in the following are based on up to the full Run II dataset.

2. Top Quark Physics

The top quark was discovered in 1995 at the Tevatron [1]. At $\sqrt{s}$ = 1.96 TeV, top quarks are produced primarily in $t\bar{t}$ pairs with the strong process $q\bar{q} \to t\bar{t}$ being the dominant one [2].

In the standard model (SM) each top quark decays through charged current weak interaction almost exclusively into a real W and a b quark ($t \to Wb$). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. The $t\bar{t} \to W^+bW^-\bar{b}$ 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.

SM predicts that top quarks can be produced also singly, through s–channel or t–channel exchange of a virtual W boson [3]. Single top production was observed at the Tevatron in 2009 [4].

The production mechanism mostly used to study top quark properties is the $t\bar{t}$ pair production.

The top quark is a very special particle: it is the most massive of the known elementary particles [5]. A consequence of its large mass is that the top quark 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. Precision measurements of top properties are important both as tests of the standard model and as potential signal for the discovery of new physics.

Top–quark mass, production cross section and forward–backward asymmetry [6] measurements from the Tevatron experiments have been already presented in this conference. In this paper we concentrate on some other top–quark related measurements made by the CDF and D0 collaborations.

3. Ratio of branching fractions R

The SM prediction that top quarks almost always decay to Wb has been tested by CDF and D0 by measuring the ratio of branching fractions R:

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

with q being a d, s or b quark (the second equality only holds in the case of unitarity of the Cabibbo Kobayashi Maskawa CKM matrix). SM predicts that R is very close to one. A value for R significantly less than one could indicate the presence of new physics (like the existence of additional quark families). D0 has performed a simultaneous measurement of R and the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ using dilepton and single lepton plus jets events in 5.4 fb^{-1} of data [7]. D0 finds: $\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57}$ pb and $R = 0.90 \pm 0.04$, from which a lower limit on the CKM matrix element $|V_{tb}|$ is extracted: $|V_{tb}| > 0.88$ at 99.7% confidence level (CL). CDF has recently published a measurement based on the full Run II dataset (8.7 fb^{-1}), obtained using single lepton plus jets events with either one or two identified b–jets. The CDF simultaneous measurement of $\sigma_{t\bar{t}}$ and R yields: $\sigma_{t\bar{t}} = 7.5 \pm 1.0$ pb, $R = 0.94 \pm 0.09$ and $|V_{tb}| = 0.97 \pm 0.05$ [8]. Figure 1 (left) shows the contour for the two–dimensional CDF fit.

4. Top quark total decay width

In the SM the top quark total decay width $\Gamma_{\rm top}$ is expected to be approximately 1.3 GeV. A deviation from the SM prediction could indicate the presence of non–SM decay channels, such as decays through a charged Higgs, the supersymmetric top quark partner, or a flavor–changing neutral current [9]. CDF has performed a direct model–independent measurement in the lepton plus jets decay channel with the full Run II dataset. The analysis exploits the reconstructed top quark mass distribution, and makes a likelihood fit based on template samples obtained with different input top quark widths. CDF obtains a two–sided limit of $1.10 < \Gamma_{\rm top} < 4.05$ GeV at 68% CL, which corresponds to a top quark lifetime of $1.6 \times 10^{-25} < \tau_{\rm top} < 6.0 \times 10^{-25}$ s. For a typical quark hadronization time scale of 3.3×10^{-24} s [10], this result supports the assertion that top-quark decay occurs before hadronization. This is the most precise direct determination of the top–quark width and lifetime.

Using data corresponding to an integrated luminosity of 5.4 fb^{-1} D0 has performed an indirect measurement of $\Gamma_{\rm top}$ that assumes SM couplings and requires input from several other measurements [11]. D0 measures $\Gamma_{\rm top} = 2.00^{+0.47}_{-0.43}$ GeV, which is the most precise indirect measurement of $\Gamma_{\rm top}$, and corresponds to a top–quark lifetime of $\tau_{\rm top} = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ s.

5. Top–antitop spin correlation

When top–quark pairs are produced the individual top quarks are unpolarized, but the $t\bar{t}$ system has a definite spin state, and thus the spins of the two quarks are correlated. This correlation depends on the production mechanism. Because top quarks decay before hadronization, information on the top–quark spin is carried by the decay products. The strength of the correlation can be quantified as the fractional difference K between the number of top pairs where the quark spins are aligned and the number of pairs where the spins are oppositely aligned. Assuming the spin quantized along the beam axis, SM predicts $K = 0.78$ [12]. Using 5.3 fb^{-1} of data CDF measures $K = 0.72 \pm 0.69$ in the lepton plus jets final state and $K = 0.042 \pm 0.563$ in the dilepton final state [13]. The CDF results are consistent with each other and with the SM prediction, within large uncertainties.

D0 has used a new matrix element approach (that enhances the sensitivity by approximately 30%) to define a discriminant R (shown in figure 1 (right) for lepton plus jets events) based on the probability that a given event contains the SM spin correlation. Combining measurements in the dilepton and lepton plus jets channels, D0 finds that the fraction f of events which contains the

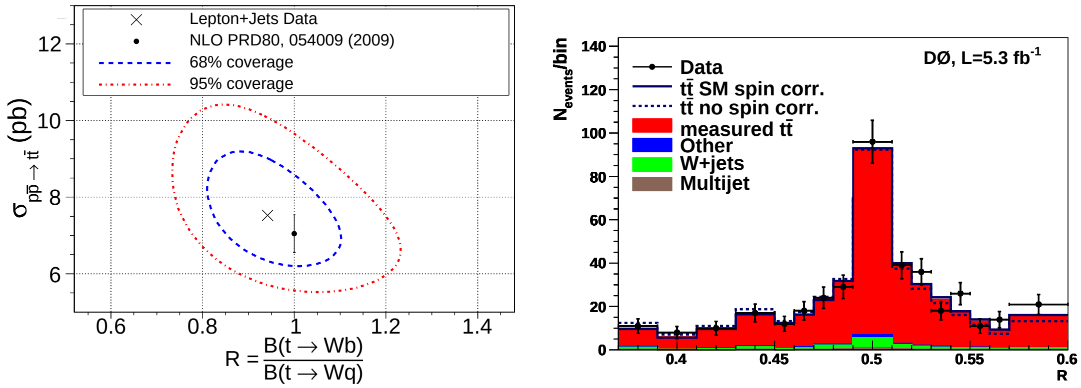

Figure 1: Left: The fit results for the simultaneous measurement of R and $\sigma_{t\bar{t}}$ from CDF data; the X-cross corresponds to the maximum of the likelihood; the point with error bar to the NLO cross section calculation. The two-dimensional confidence regions are shown as well. Right: The D0 discriminant R distribution for lepton plus jet events, used to evaluate the $t\bar{t}$ spin correlation. The expectation (including background) for complete spin correlation as predicted by the SM ($f = 1$) and the case of no spin correlation ($f = 0$) are shown.

SM spin correlation is $f = 0.85 \pm 0.29$. This result provides the first 3σ evidence for the existence of the spin correlation in $t\bar{t}$ production. The fraction f can be converted into a measurement of K giving $K = 0.66 \pm 0.23$ [14].

6. W helicity in top quark decay

In the SM, the helicity states of the W boson coming from the top–quark decay are constrained according to the $V - A$ nature of the Wtb vertex. 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 approximately 0.7, 0.3, and 0.0 respectively. CDF and D0 have both performed measurements of these helicity fractions by studying angular distributions of the W decay products (particularly the charged leptons) in $t\bar{t}$ candidate events. The first CDF–D0 combination of W helicity measurements has been published [15], based on up to 5.4 fb^{-1} of data. Assuming $f_0 + f_- + f_+ = 1$ they find $f_0 = 0.722 \pm 0.081$ and $f_+ = -0.033 \pm 0.046$.

CDF has updated its W helicity measurement using the full Run II data set in the lepton plus jets channel [16], and the result is $f_0 = 0.726 \pm 0.094$ and $f_+ = -0.045 \pm 0.072$.

Figure 2 shows the two–dimensional contours for the Tevatron combined (left) and CDF updated (right) result.

7. Search for resonant top-quark pair production

Several searches for new physics in the top–quark sector have been performed by both CDF and D0. Here we report just an example. Resonant top pair production is predicted by several models of physics beyond the SM. In case of resonant production we expect to see a prominent peak in the $t\bar{t}$ reconstructed mass distribution $M_{t\bar{t}}$. Both experiments have searched for resonant

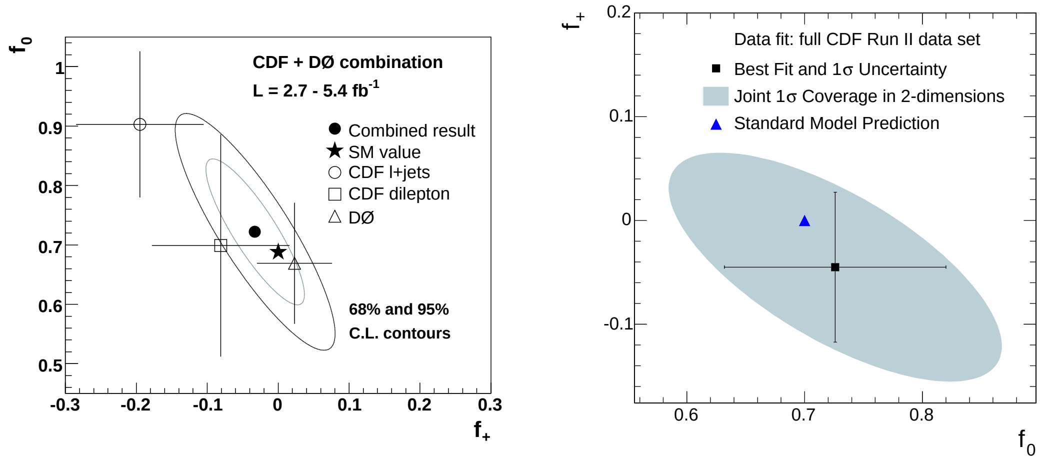

Figure 2: The results for the simultaneous measurement of f_0 and f_+. Left: Tevatron combined result (with partial data); the measurements input to the combination are represented by the open circle, square, and triangle. The ellipses indicate the 68% and 95% CL contours, the dot shows the best-fit value. Right: updated CDF measurement based on full Run II dataset; the square marker with error bars shows the point of maximum likelihood; the shaded ellipse corresponds to the two-dimensional 68% CL contour. In both plots the SM prediction is shown as well.

production of $t\bar{t}$ in the single lepton plus jets decay channel. CDF analysed the full Run II dataset and found no evidence for significant narrow $t\bar{t}$ resonances [17]. Assuming a leptophobic Z' as a benchmark, CDF excluded such hypothetical particle for masses $M_{Z'} < 915$ GeV/c^2 at 95% CL. D0 analysed 5.3 fb^{-1} of data and set an upper limit of $M_{Z'} < 835$ GeV/c^2 at 95% CL [18].

Figure 3 (left) shows the CDF $M_{t\bar{t}}$ distribution obtained for events with four or more jets. Figure 3 (right) shows the D0 limits on a narrow resonance decaying to $t\bar{t}$.

8. 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. Many CDF and D0 analyses, such as the W helicity measurement in $t\bar{t}$ decays described here, are now being combined to obtain Tevatron–wide results. The Tevatron data–taking is over since more than two years now, but there is still a lot to be learned from the Tevatron's unique top quark sample.

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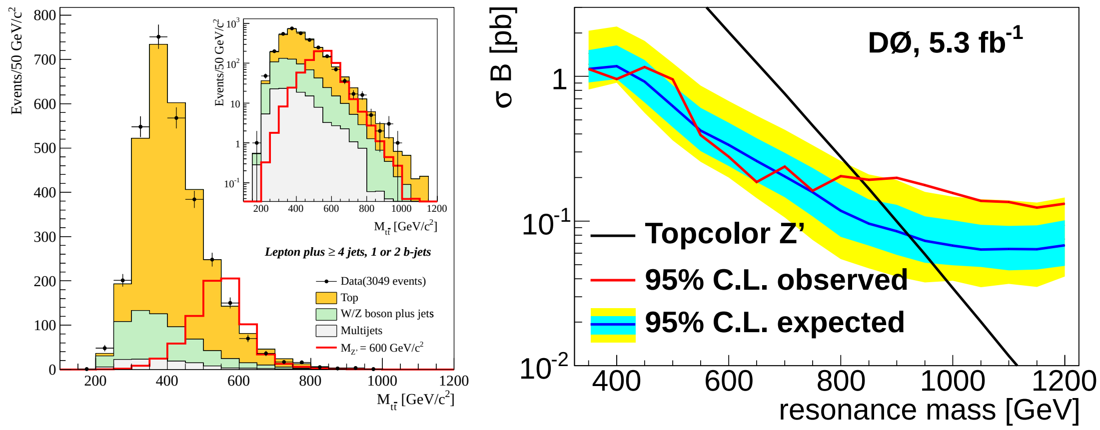

Figure 3: Left: Reconstructed $M_{t\bar{t}}$ for lepton plus four or more jet events in CDF data. The inset shows the same distribution on a logarithmic scale. The red histogram shows the expectation for a 600 GeV/c^2 mass hypothesis for the leptophobic top-color resonance Z' normalized to the predicted cross section. Right: Observed and expected upper limits on cross section times branching fraction for a narrow $t\bar{t}$ resonance as a function of the resonance mass, from D0 data. The solid line shows the predicted Z' cross section.

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