Tevatron: Top quark production and properties

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The measurements of top quark properties and the top pair production cross section at the Tevatron constitute important tests of the Standard Model predictions and could potentially be sensitive to new physics. I present in this report the latest results from the CDF and DØ collaborations in a Run II data sample of integrated luminosity up to 1.1 fb^{-1}.

1 Introduction

Since the top quark discovery in 1995 by the CDF [1] and DØ [2] collaborations, an extensive program is being conducted at the Tevatron to study and characterize its properties. Due to its large mass, the top quark is believed to play a special role in physics beyond the Standard Model (SM). Precision measurements have the potential to reveal effects from new physics. Previous Run I measurements, performed in 100 pb^{-1} data samples, were limited by low statistics. With the Run II well underway, more than 2 fb^{-1} of delivered integrated luminosity and analyzed datasets already ten times larger than those of Run I, the field of top physics has entered a new and exciting era.

The SM top quark at the Tevatron, a $p\bar{p}$ collider with $\sqrt{s} = 1.96$ TeV, is mostly produced in pairs with a theoretical NLO cross section prediction of 6.7 ± 0.8 pb [3] for a top mass of 175 GeV/c^2. Since it decays to a W boson and a b quark basically 100% of the time, the final states are defined based on the decay channel of the W boson. Topologies in which both W's decay to a lepton-neutrino pair are classified as "dilepton", while "lepton+jets" events are those where only one W decays leptonically. Dilepton and lepton+jets represent 5% and 30% of the $t\bar{t}$ decays, respectively. The rest of the branching ratio corresponds to the case where either both W's decay hadronically (45%) or when one or both decay into a tau lepton (20%). Top quark properties and cross section measurements presented here are performed in the lepton+jets or dilepton datasets with integrated luminosities up to 1.1 fb^{-1}.

2 Production Cross Section Measurements

The top quark pair production cross section measurement is an important test of QCD predictions and is key to other properties studies as it provides a well understood sample of candidate top quark events. This measurement is performed with a variety of techniques and in different topologies, which not only serves as a cross check, but is interesting in the search of new physics, as this would impact each final state differently. A brief description of the most recent results performed at the Tevatron is presented next, followed by a summary of the status of this measurement at the DØ and CDF collaborations.

2.1 Dilepton Channel

Due to the branching fraction (5% for e/μ analyses), this sample is small. However, it is a clean sample with contamination predominantly composed by Drell-Yan production and multijet events where a jet is misidentified as a lepton. While many of the studies are performed on very clean data sets obtained by means of tight lepton requirements, some use looser criteria to reduce statistical uncertainties. An example of the latter, is one of the most recent cross section measurements performed by the CDF collaboration. Using a 1.07 fb^{-1} data sample, a cross section of $\sigma_{t\bar{t}} = 9.0 \pm 1.3(stat) \pm 0.5(syst) \pm 0.5(lumi)$ pb [4] is obtained by selecting events with two or more jets, significant missing transverse energy and two opposite-sign leptons, where one is identified as an isolated track.
DØ's most recent and precise measurement in this channel, utilizes an integrated luminosity of approximately 1 fb^{-1} and combines the cross section obtained in events with ee, $e\mu$ and $\mu\mu$ final states. It requires 2 oppositely charge leptons, 2 or more jets for the ee and $\mu\mu$ channels, one or more for $e\mu$ and a set of optimized cuts per final state to discriminate against background. The cross section in each individual channel is extracted by minimizing a negative log-likelihood function based on the Poisson probability to observed a certain number of events given the luminosity, branching fraction, efficiency and the number of background events. The combined result is obtained by minimizing the sum of the negative log-likelihood function for each individual final state and is found to be $\sigma_{t\bar{t}} = 6.8^{+1.2}_{-1.1}(stat)^{+0.9}_{-0.8}(syst) \pm 0.4(lumi)$ pb [5].

2.2 Lepton + Jets Channel

Although the lepton+jets sample benefits from its larger branching fraction, there is significant background contamination from W boson production in association with jets and non-W QCD events (instrumental background). Signal to background discrimination can be improved using techniques to identify b-jets, a process known as "b-tagging". The latest and most precise DØ measurement, performed on a data set of about 900 pb^{-1}, uses a neural network that combines the outputs of several b-tagging algorithms rendering an efficiency of 54% and a misidentification rate below 1%. The event selection requires an identified lepton, large missing transverse energy and three or more jets. This sample is divided into 8 channels based on the lepton flavor (electron or muon), the jet multiplicity (three and four or more) and the number of tagged jets (one and two or more). The cross section is then calculated by performing a maximum likelihood fit to the observed number of events in the various channels. DØ finds a cross section of $\sigma_{t\bar{t}} = 8.3^{+0.6}_{-0.5}(stat)^{0.9}_{1.0}(syst) \pm 0.5(lumi)$ pb [6].

2.3 Summary

Figure 1 shows the summary[a] of the most recent top quark pair production cross section measurements from the Tevatron. Both the DØ and CDF collaborations perform the measurement in different topologies with various techniques. Results are in agreement with each other and with the theoretical prediction. The most precise measurements are no longer statistically dominated and have uncertainties of $\sim 14\%$. Shown is also the CDF combination result (analyses with integrated luminosity up to 760 pb^{-1}) which has an uncertainty of 12% comparable with the uncertainty from the theoretical prediction.

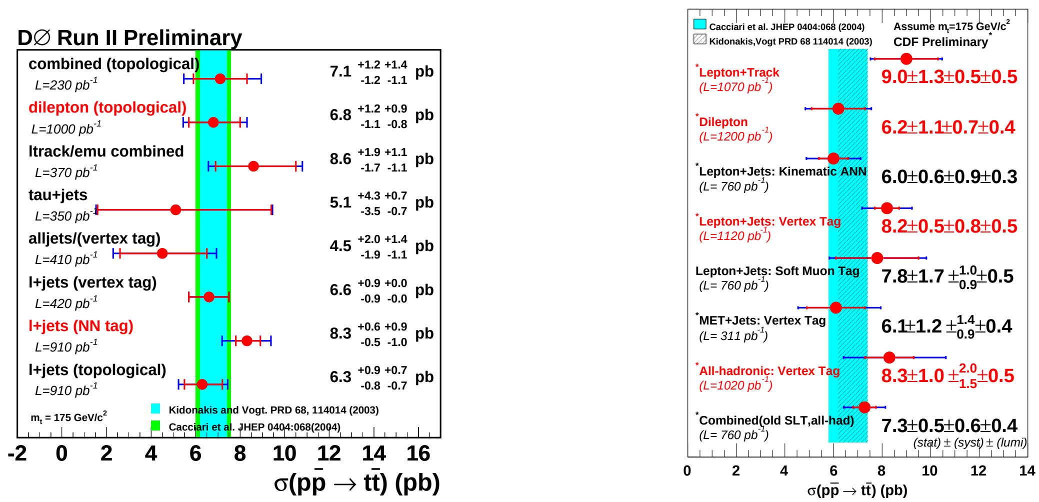

Figure 1: Summary of most recent top pair production cross section measurements from DØ (left) and CDF (right). The band represent the NLO theory calculation for a 175 GeV/c^2 top quark mass.

3 Top quark Properties

The goal of measuring the top quark properties is to find out whether the top quark behaves as the SM predicts or if new physics is present in the $t\bar{t}$ data sample.

3.1 Production Mechanism

The Standard Model predicts that, at the Tevatron, about 85% of the top pair events are produced through quark-antiquark annihilation while approximately 15% are produced through gluon fusion. CDF tests this prediction using the low p_T charged particle multiplicity as the discriminator between the two different production channels and performs the first measurement of the ratio $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$ using $1\,\text{fb}^{-1}$ of data. Figure 2 (left plot) shows the correlation between the average number of gluons (N_g) and the average number of low p_T charged particles (N_{trk}) in different samples. While N_{trk} is measured in high p_T inclusive lepton or inclusive jet data samples, N_g is obtained from simulation, where only gluons which are part of the hard scattering matrix element are used in the calculation. The higher the number of gluons in the sample, the larger the low p_T track multiplicity is. Using no-gluon and gluon-rich low p_T track multiplicity distributions, calibrated on data, CDF fits the signal sample of tagged W+4 (or more) jets events for the gluon rich fraction and obtains $f_g^{W+4jet} = 0.07 \pm 0.15(stat) \pm 0.07(syst)$. Figure 2 presents the two components (gluon rich and no-gluon) and fit result. Taking into

[a] CDF Dilepton and lepton+jets results in the 1.2 fb^{-1} dataset became available after the Conference.

account the relative acceptance between gg and $q\bar{q}$ events and the background contributions, a ratio of $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t}) = 0.01 \pm 0.16(stat) \pm 0.07(syst)$ is found [7], consistent with the SM expectation.

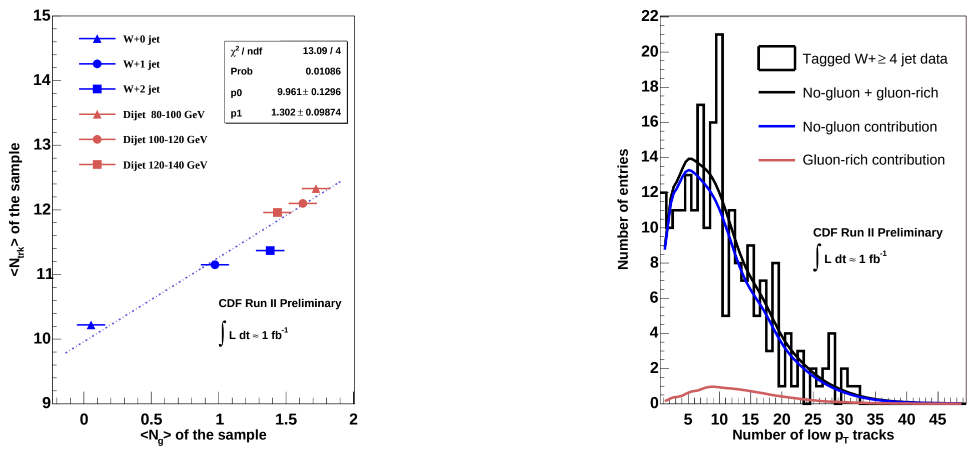

Figure 2: Left: Correlation between the average low p_T track multiplicity and the average number of gluons $< N_g >$ for different data samples. Right: Fit result for the tagged W+4 or more jet data sample. The two components of the fit (gluon rich and no-gluon) are also shown.

3.2 Anomalous Production

Non-SM top pair production mechanisms, like $t\bar{t}$ production via an intermediate resonance, are proposed by different theories. For example, the topcolor-assisted Technicolor [8] model predicts a heavy Z' boson which couples preferentially to the third generation of quarks and with cross sections expected to be visible at the Tevatron. These processes may manifest as narrow structures in the total pair mass, $M_{t\bar{t}}$, superposed on the SM expected spectrum.

Both the DØ and CDF collaborations have performed model independent searches for a narrow width heavy resonance in the lepton+jets channel by studying the $t\bar{t}$ invariant mass spectrum, reconstructed using a constrained kinematic fit. Results are found to be consistent with the SM expectation. Modeling the resonance as a Z^0-like boson, 95% CL upper limits are obtained for different resonances mass hypotheses. For a leptophobic Topcolor model with a resonance width of 1.2% of its mass and in a data sample of approximately 1 fb^{-1}, CDF excludes masses up to 725 GeV/c^2 [9]. For a data sample of 370 pb^{-1}, DØ excludes masses below 680 GeV/c^2 [10]. Figure 3 shows CDF $M_{t\bar{t}}$ spectrum and upper limits.

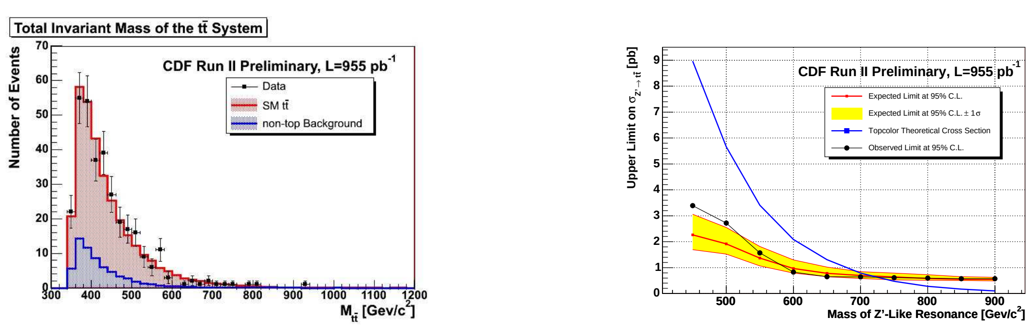

Figure 3: Left: Reconstructed invariant mass of the $t\bar{t}$ system. Right: Expected and experimental upper limits on the $Z' \to t\bar{t}$ production cross section together with leptophobic topcolor Z' cross section prediction.

3.3 Examining the tWb vertex: W helicity

In the SM, top quark decays into a W boson and a b quark with a branching ratio close to 100%. The V-A coupling of the tWb vertex only allows the W boson to have longitudinal or left-handed polarizations while the right-handed polarization is suppressed. The fraction of decays to longitudinal and left-handed W bosons is expected to be $F_0^{SM} \sim 0.7$[11] and $F_- \sim 0.3$, respectively. Thus, measuring the W helicity provides a direct test of the V-A nature of the tWb coupling and a probe of new physics beyond the SM.
Through the study of sensitive observables, like lepton transverse momentum, invariant mass of the lepton and b-jet or $cos\theta^*$ (angle between the lepton momentum in the W boson rest frame and the W momentum in the top quark rest frame), DØ and CDF collaborations have measured F_0 and the right-handed F_+ fractions in both the lepton+jets and dilepton channels. One of the most recent measurements done by CDF on 955 pb^{-1} of data, uses lepton+jets final state events and $cos\theta^*$ as the discriminant variable. To build the $cos\theta^*$ distribution in data, the kinematics of the $t\bar{t}$ candidates is fully reconstructed. Performing a binned likelihood fit, with a fixed $F_+ = 0$ value, the longitudinal fraction is determined to be $F_0 = 0.59 \pm 0.12(stat)^{+0.07}_{-0.06}(syst)$. When fixing F_0 to its SM value of 0.7, a fraction $F_+ = -0.03 \pm 0.06(stat)^{+0.04}_{-0.03}(syst)$ is obtained. An upper limit of $F_+ < 0.1$ is set at the 95% CL[12]. All DØ and CDF results[13] for the W boson helicity are in agreement with the SM prediction within large statistical uncertainties.

3.4 Top Quark Charge

One of the fundamental quantities that characterize the top quark is its electric charge. Due to the ambiguity in the assignment of the b quark and W boson to which the top decays, it is possible to reconstruct an object of charge -4/3, instead of the 2/3 top quark charge that the SM predicts. In fact, such an hypothesis has been proposed[14], in which this new particle would correspond to an exotic quark, part of a fourth generation of quarks and leptons. Thus, determining whether the top quark ($\bar{t}$) decays into a W^+ and a b quark ($W^-\bar{b}$) would indirectly indicate that the top charge is indeed 2/3. Both CDF and DØ[15] have performed such a measurement. Presented here is the CDF result using a data sample of 955 pb^{-1} in the dilepton channel and 695pb^{-1} in the lepton+jets one. Double tagged lepton+jets events are reconstructed by means of a kinematic fitter while a discriminant based on the invariant mass of the lepton and the b-jet is used in single tagged dilepton ones. While the charge of the W boson is defined by the charge of the lepton, the flavor of the b-jets is assigned using a Jet Charge Algorithm. This algorithm, which sums up the charge of the tracks assigned to the jet, each weighted by its momentum along the jet axis, is calibrated in $b\bar{b}$ data events.
Each W-jet pair is labeled as being standard model like (SM-like) or exotic quark model like (XM-like) based on the product of their charges, negative for the SM and positive in the XM case. In order to obtain a confidence limit on either hypothesis, a profile likelihood method[16] is used to build a likelihood curve as a function of the fraction of SM-like events. Defining an a-priori probability of 1% (α) to incorrectly reject the SM when this model is true, the sensitivity, defined as the probability of rejecting the SM in the case that the XM model is true, is found to be 81%.
CDF observes 62 SM-like pairs and 48 XM-like ones, which corresponds to a p-value of 0.35 under the SM hypothesis. Since this p-value is larger than the α value, the result is found to be consistent with the SM and the XM hypothesis is excluded at 81% C.L.[17]. Figure 4 shows the distribution of the product of the W charge and the jet charge for the 110 observed pairs.

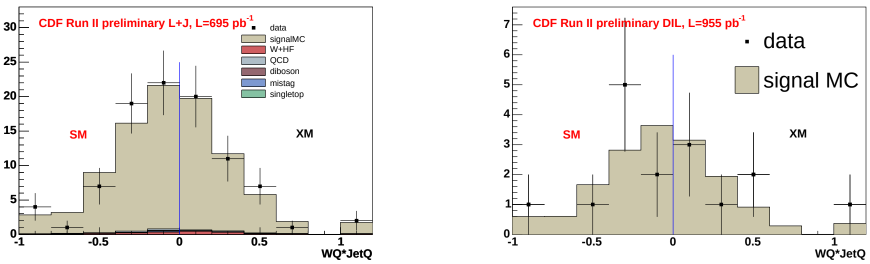

Figure 4: Product of the W charge and the associated jet charge for Data and MC Lepton+Jets pairs (left) and Dilepton ones (right). Negative values correspond to SM-like pairs (W^+b or $W^-\bar{b}$).

4 Conclusion

I have presented the latest top quark properties and pair production cross section measurements from the Tevatron in Run II with an integrated luminosity of up to 1.1fb^{-1}. Cross section results, which have reached a level of precision comparable with the theoretical one, are consistent with the NLO QCD predictions and in agreement with each other. Several properties measurements have been reported. So far no evidence of new physics has been found. With the Tevatron and the CDF and DØ experiments performing very well, an exciting landscape in top physics is foreseen for the coming years.

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