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MEASUREMENTS OF TOP PROPERTIES AT THE TEVATRON

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The large data samples of thousands of top events collected at the Tevatron experiments CDF and DØ allow for a variety of measurements to analyze the properties of the top quark. Guided by the question "Is the top quark observed at the Tevatron really the top quark of the standard model," we present Tevatron analyses studying the top production mechanism including resonant $t\bar{t}$ production, the $V-A$ structure of the $t \to Wb$ decay vertex, the charge of the top quark, and single-top production via flavor-changing neutral currents.

Keywords: Hadron Collider, Tevatron, Heavy Quark Production, Top Quark Properties

1 Introduction

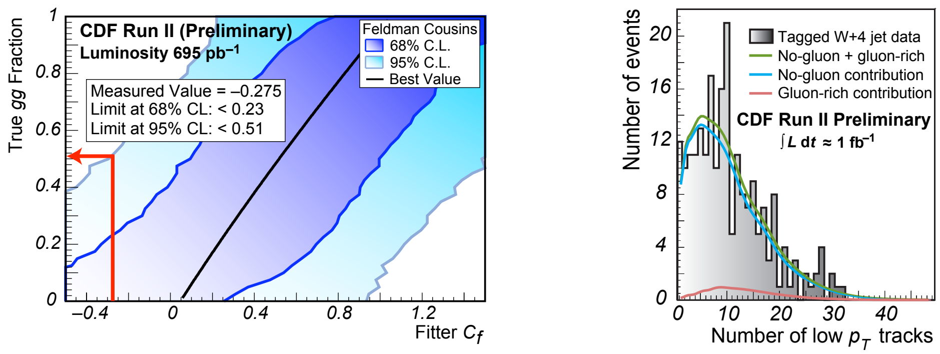
At the Tevatron collider at Fermi National Accelerator Laboratory, protons and antiprotons are collided at a center-of-mass energy of 1.96 TeV. The Tevatron provides the highest energies currently available at a hadron collider and is the only collider with sufficient energy to produce top quarks. The two multi-purpose experiments at the Tevatron, CDF II [1] and DØ [2], have studied production and decays of top quarks in great detail. The focus of this article will be on measurements of top properties at CDF and DØ (other than mass and cross section). The event selection for top properties measurements is built on the experience gained in the mass and cross section analyses in the "lepton+jets" channel ($t\bar{t} \to Wb\,Wb \to \ell\nu b\,qqb$) and the "dilepton" channel ($t\bar{t} \to Wb\,Wb \to \ell\nu b\,\ell\nu b$). Also the background composition, with W production in association with jets as the dominant source, and systematic uncertainties, mainly coming from determining the jet energy scale, are similar to those in the top mass and cross section analyses.

2 Top Pair Production

2.1 Fraction of $t\bar{t}$ Pairs Produced via Gluon-Gluon Fusion

In the standard model (SM), the production of $t\bar{t}$ pairs at the Tevatron is dominated by the process of $q\bar{q}$ annihilation. The contribution of the gg fusion channel to the $t\bar{t}$ production cross section amounts to $15 \pm 5\%$, where the large uncertainty is due to poor knowledge of the gluon parton distribution function inside the proton [3,4]. The CDF collaboration has developed two complementary methods to measure the fraction of $t\bar{t}$ pairs produced via gg fusion. With datasets of up to 1 fb^{-1} of integrated luminosity, both methods are dominated by statistical uncertainties and are therefore expected to improve with more data.

One method [5] utilizes an artificial neural network (NN) to distinguish the processes $q\bar{q} \to t\bar{t}$, $gg \to t\bar{t}$, and $q\bar{q}/gg \to W$+jets. The NN input comprises the velocity and angle of the top quark, and the angles of the three decay products in the off-diagonal spin basis. From the resulting NN discriminant, an upper limit on the gg fraction is derived via a Feldman-Cousins method that includes systematic uncertainties. As shown in Fig. 1a, the measurement yields a limit of $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t}) < 0.51$ at 95% C.L.



(a) (b)

Figure 1: Measurements of the gg fraction in $t\bar{t}$ production. (a) Feldman-Cousins band obtained for neural network discriminant method. (b) Distribution of low-p_T tracks fitted by gluon-rich and no-gluon templates in W+4-jet data.

The other method [6] is based on the observation that the number of tracks with small transverse momenta p_T in the range of 0.3–2.9 GeV/c is strongly correlated with the number of gluons in the event. The correlation is calibrated using gluon-rich and gluon-free control samples in the data, and then extrapolated to the top-rich sample of W+4 jets. Gluon-rich and no-gluon templates are fitted to the distribution of low-p_T tracks in the data, as depicted in Fig. 1b, to extract a gg fraction of $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t}) = 0.01 \pm 0.16(\text{stat.}) \pm 0.07(\text{syst.})$.

2.2 Resonant Production of $t\bar{t}$ Pairs

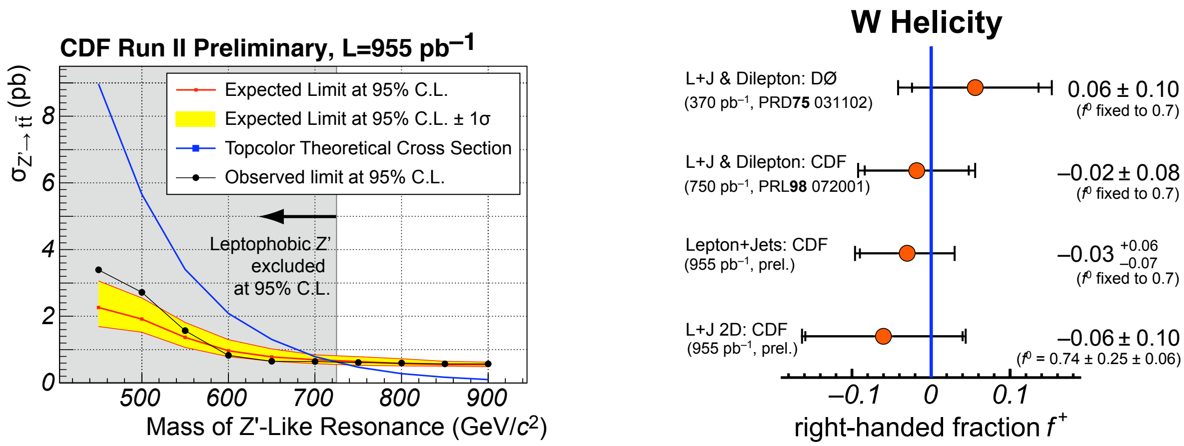
Several extensions of the SM predict $t\bar{t}$ production from the decay of heavy particles. In one particular model [7], the heavy particle is assumed to be a narrow Z' resonance that couples strongly only to third generation quarks and does not couple to leptons ("leptophobic Z'").

The CDF collaboration has studied the production of a Z'-like heavy $t\bar{t}$ resonance [8]. The $t\bar{t}$ invariant mass $M_{t\bar{t}}$ is reconstructed with the help of a kinematic fitter developed for top mass measurements. The $M_{t\bar{t}}$ distribution in the data is compared to the expectation for SM $t\bar{t}$ production and non-$t\bar{t}$ background. The background includes W+jets events, QCD multijet events, and diboson production (WW, WZ, ZZ), and was estimated with a method that combines input from Monte Carlo simulations and data control samples. The data are compatible with SM $t\bar{t}$ production, so that a limit on the Z' production cross section can be derived, see Fig. 2a. From the comparison with the cross section prediction for leptophobic Z', CDF obtains a limit of $M_{Z'} > 725\,\text{GeV}/c^2$ at 95% C.L.

3 Helicity of W Bosons from Top Decays

Due to its small lifetime of less than 10^{-24} s, the top quark decays before it hadronizes. As a consequence, the complete spin information is transferred to its daughter particles. In the SM, top quarks decay to a W boson and a b quark almost exclusively. The spin-1 W boson has three possible helicity states: longitudinal, left-handed, and right-handed. The $V-A$ structure of the tWb vertex in the SM does not allow for a right-handed state, so that any sizable admixture of right-handed W's would be a sign of new physics. The longitudinal fraction of the W helicity in the SM is determined by the Yukawa coupling of the top quark and amounts to $f^0 \approx 0.7$.

Both CDF and DØ have measured the right-handed helicity fraction f^+ of W bosons from top decays [9,10,11,12]. The analyses use different techniques to reconstruct the observable $\cos\theta^*$, the angle between the top boost direction and the charged lepton in the W rest frame, or the



(a) (b)

Figure 2: (a) Limit on the production cross section of leptophobic Z' bosons. The shaded area is excluded at 95% C.L. (b) Summary of W helicity measurements. Shown are fits to the right-handed helicity fraction f^+ in different analyses.

correlated quantity $M_{\ell b}$, the invariant mass of the charged lepton and the b jet. Due to the limited size of the data samples, most analyses [9,10,11] check the consistency of f^0 with the SM, assuming $f^+ = 0$, and fix the value to $f^0 = 0.7$ before f^+ is measured. With $1\,\mathrm{fb}^{-1}$ of data, a simultaneous fit to f^0 and f^+ becomes feasible [12]. As shown in Fig. 2b, all measurements are compatible with the SM prediction of $f^+ = 0$.

4 Top Charge

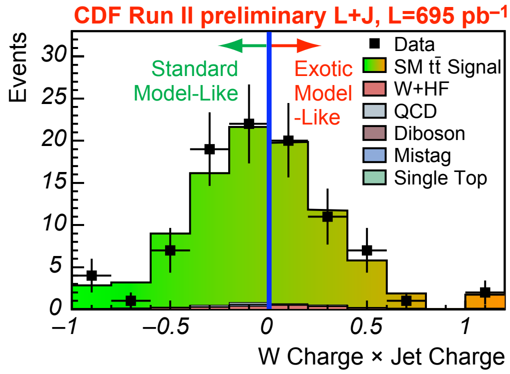
In the SM, the top quark and the bottom quark form a left-handed isospin doublet with charges $(2/3\,e, -1/3\,e)_L$, where e is the elementary charge. Fits to electroweak precision data can be improved using a theoretical model with a top mass of $270\,\mathrm{GeV}/c^2$ and an exotic right-handed quark doublet with charges $(-1/3\,e, -4/3\,e)_R$ that mixes with right-handed b quarks [13]. In this model, the exotic replacement for the top quark has a charge of $-4/3\,e$.

The CDF collaboration has performed a measurement to test if the top charge is $2/3\,e$ or $-4/3\,e$ [14]. The measurement consists of three steps. The W charge is obtained via the charge of the lepton in the decay $W \to \ell\nu$. To reconstruct the top from the decay $t \to Wb$, the W is paired with a b jet, using a kinematic fitter (lepton+jets channel) or a cut on $M_{\ell b}$ (dilepton channel). Finally, the observable "jet charge," a weighted sum of the charge of all tracks that form a jet, is employed to measure the flavor of the b jet. The product of W charge and jet charge is used to distinguish the exotic model from the SM, see Fig. 3a.

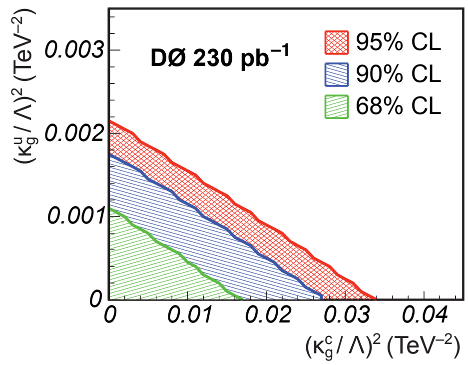
CDF has tested the consistency of the data with the SM and the exotic model with a hypothesis test, with the null hypothesis that the SM is correct. If the exotic model were correct, 81% of all measurements would return p-values below 0.01 (probability to incorrectly reject the SM, chosen *a priori*). The measured p-value of 0.35 shows that the data are consistent with the SM, and the exotic model is excluded at 81% C.L.

5 Single-Top Production via Flavor-Changing Neutral Currents

Flavor-changing neutral currents (FCNC) in the top quark sector are heavily suppressed in the SM. For example, the branching fraction $\mathcal{B}(t \to gc)$ is approximately 5×10^{-12}, far below the reach of present and future hadron collider experiments [15]. Any FCNC signal at the Tevatron would be a sign of physics beyond the SM.



(a)



(b)

Figure 3: (a) Top charge measurement via jet charge. The data are compared to the predictions of the SM for $t\bar{t}$ signal and background. (b) Exclusion contours for the couplings $(\kappa/\Lambda)^2$ of the flavor-changing neutral current vertices tgu and tgc.

The DØ collaboration has searched for FCNC in the production of single top quarks [16]. In the presence of the processes $ug \to t$ and $cg \to t$, the single top production rate is enhanced. DØ has deployed a NN to discriminate the kinematics of the FCNC signal from $t\bar{t}$, W+jets, and QCD multijet backgrounds. The data agrees very well with the SM prediction, so that an upper limit on the FCNC couplings tgu and tgc could be derived. Fig. 3b shows the upper limit as a function of the strengths $(\kappa/\Lambda)^2$ of the tgu and tgc coupling, where κ is the coupling parameter in the Lagrangian, and Λ is a generic new physics scale. The DØ measurement improves upon previous measurements, prominently by the HERA experiments, by a factor of 3–11.

Acknowledgments

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