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TOP-QUARK CROSS SECTION AND PROPERTIES AT THE TEVATRON

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At the Tevatron, the collider experiments CDF and DØ have data sets at their disposal that compromise several hundreds of reconstructed top-antitop-quark pairs and allow for precision measurements of the cross section and production and decay properties. Besides comparing the measurements to standard model predictions, these data sets open a window to physics beyond the standard model. Dedicated analyses look for new heavy gauge bosons, fourth generation quarks, and flavor-changing neutral currents.

1 Introduction

The top quark is by far the heaviest elementary particle observed by particle physics experiments and features a mass of $m_t = 173.1 \pm 1.3$ GeV/c^2 [1]. The large mass the top quark gives rise to large radiative corrections, for example to the W propagator, which causes a strong correlation between m_W, m_t, and the Higgs boson mass m_H. To predict m_H a precise measurement of m_t is crucial. The large mass leads also to a very short lifetime of the top quark, $\tau_t \simeq 0.5 \cdot 10^{-24}$ s, such that top hadrons are not formed. The top quark thus offers the unique possibility to study a quasi-free quark and as a consequence polarization effects are accessible in the angular distributions of top-quark decay products. Since m_t is close to the energy scale at which the electroweak symmetry breaks down (vacuum expectation value of the Higgs field $v = 246$ GeV), it has been argued that the top quark may be part of a special dynamics causing the break down of the symmetry [2]. Finally, the top quark gives access to the highest energy scales and offers thereby the chance to find new, unexpected physics, for example heavy resonances that decay into $t\bar{t}$ pairs.

In the past years the Fermilab Tevatron, a synchrotron colliding protons and antiprotons at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV, was the only place to produce and observe top quarks under laboratory conditions. Physics data taking of Tevatron Run 2 started in 2002 and in the meanwhile the accelerator has delivered collisions corresponding to an integrated luminosity of 7.0 fb^{-1}. The two general-purpose detectors CDF and DØ have recorded collisions data corresponding to 5.7 fb^{-1} and 6.1 fb^{-1}, respectively.

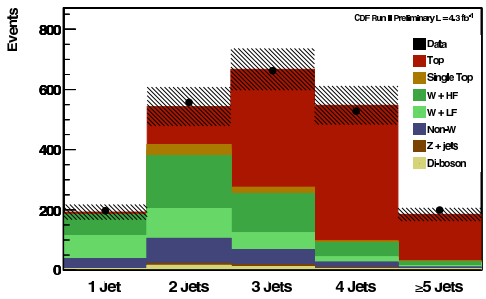
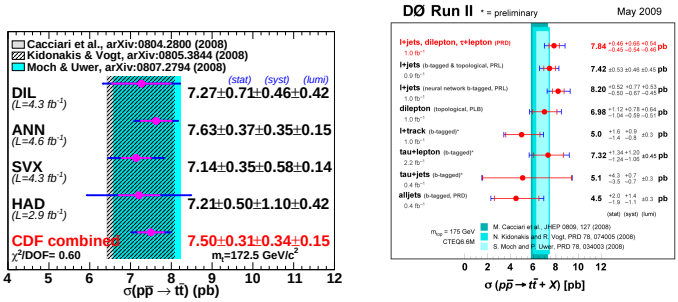


Figure 1: Jet multiplicity distribution for the $W+$ jets data set, where the W boson is reconstructed in its leptonic decay $W^{\pm} \to \ell^{\pm}\nu_e ll(\bar{\nu}_\ell)$. A cut on $H_T > 230\,\mathrm{GeV}$ was applied.



(a) (b)

Figure 2: Summary of the $t\bar{t}$ cross sections measured by (a)CDF and (b) DØ.

2 Top-Antitop Production

The main source of top quarks at the Tevatron is the pair production via the strong interaction. According to the standard model (SM) top quarks decay with a branching ratio of nearly 100% to a bottom quark and a W boson and the $t\bar{t}$ final states can be classified according to the decay modes of the W bosons. The most important (or golden) channel is the so-called *lepton+jets* channel where one W boson decays leptonically into a charged lepton plus a neutrino, while the second W boson decays into jets. The lepton+jets channel features a large branching ratio of about 30%, manageable backgrounds, and allows for the full reconstruction of the event kinematics. Other accessible channels are the *dilepton* channel, where both W bosons decay to leptons and the *all-hadronic* channel, where both W bosons decay hadronically.

3 Top-Antitop Cross Section

The basic method to define a data sample of $t\bar{t}$ candidate events uses the identification of b-quark jets by reconstructing a secondary vertex within the jet [3]. The analysis is a counting experiment in which the background rate is estimated using a combination of simulated events and data driven methods. The signal region is defined as the data set with a leptonic W candidate plus ≥ 3 jets. To further suppress background, a cut on the sum of all transverse energies $H_T > 230\,\mathrm{GeV}$ is applied. The jet multiplicity distribution for the W+jets data set observed by this analysis is shown in Figure 1. The uncertainty on the luminosity measurement is reduced by measuring the ratio of $t\bar{t}$-to-Z-boson cross sections and the resulting cross section is listed in Fig. 2(a). The single most precise measurement of the $t\bar{t}$ cross section at CDF is based on a neural network technique applied to the $W+ \geq 3$ jets data set. The cross section measurements by DØ are summarized in Fig. 2(b) [4] and are interpreted by a global fit to set limits on a charged Higgs boson that decays either in the mode $H^+ \to c\bar{s}$ or $H^+ \to \tau^+\nu_t au$. The limits are placed on the

plane of m_{H^+} vs. $\tan\beta$ and exclude the region of $\tan\beta < 2$ and $m_{H^+} < 155\,\mathrm{GeV}/c^2$ for the leptophobic mode as well as $\tan\beta > 20$ and $m_{H^+} < 155\,\mathrm{GeV}/c^2$ for the tauonic mode.

4 Production Properties

Production Mechanism Calculations in perturbative QCD predict that the dominating subprocess of the production of $t\bar{t}$ pairs is $q\bar{q}$ annihilation (85%), while gluon-gluon fusion contributes 15%. One analysis idea to measure the fraction of $t\bar{t}$ pairs originating from a gg initial state uses the proportionality of the mean number of low-p_{T} tracks in an event, $\bar{N}_{\mathrm{trk}}$, and the gluon content. The physical reason for this is that gg initial states produce more initial-state radiation than $q\bar{q}$ initial states. The linear relation between $\bar{N}_{\mathrm{trk}}$ and the average number of hard initial-state gluons is calibrated in W+jets and dijet data samples. Using simulated events, templates for the $\bar{N}_{\mathrm{trk}}$ distribution are calculated for $gg \to t\bar{t}$ and $q\bar{q} \to t\bar{t}$ events. These templates are fit to the distribution observed in collision data, resulting in a measurement of $\sigma(gg \to t\bar{t})/\sigma(q\bar{q} \to t\bar{t}) = 0.07 \pm 0.14\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.})$ [5]. An alternative method exploits the spin information in the top-decay products employing neural networks and sets an upper limit on the gg initiated fraction of $t\bar{t}$ events of 0.61 at the 95% confidence level (C.L.) [6].

Forward-Backward Asymmetry Due to interference effects at next-to-leading order (NLO) QCD predicts a foward-backward asymmetry

$$A_{\mathrm{FB}} = \frac{N_t(p) - N_{\bar{t}}(p)}{N_t(p) + N_{\bar{t}}(p)} = (5.0 \pm 1.5)\%$$

at the Tevatron [7], where $N_t(p)$ is the number of top quarks moving in proton direction and $N_{\bar{t}}(p)$ is the number of antitop quarks moving in proton direction. Top quarks are thus more likely to be produced in proton direction, while antitop quarks are more likely to be produced in antiproton direction. Using events of the lepton+jets topology CDF and DØ have investigated the charge asymmetry. In the CDF analysis the hadronic top quark is reconstructed and the asymmetry

$$A_{\mathrm{FB}}^{\mathrm{lab}} = \frac{N(-Q_\ell \cdot y_{\mathrm{had}} > 0) - N(-Q_\ell \cdot y_{\mathrm{had}} < 0)}{N(-Q_\ell \cdot y_{\mathrm{had}} > 0) + N(-Q_\ell \cdot y_{\mathrm{had}} < 0)} = 0.193 \pm 0.065(\mathrm{stat.}) \pm 0.024(\mathrm{sys.})$$

is measured [8]. The relatively large value compared to the SM expectation confirms earlier CDF measurements [10]. The CDF measurement quoted above is corrected for background contributions, acceptance bias, and migration effects due to the reconstruction. DØ also uses ΔY as an observable, applies a background correction and obtains $A = 0.12 \pm 0.08 \pm 0.01$ [9]. To compare this value with the CDF measurements or with the theory prediction it has to be corrected for acceptance and migration effects. A prescription for this is provided in reference [9]. Based on this measurement the DØcollaboration derives limits on a heavy Z' boson that decays to $t\bar{t}$ pairs.

Top-Antitop Resonances The $t\bar{t}$ candidate samples offer the another possibility to search for a narrow-width resonance X^0 decaying into $t\bar{t}$ pairs by investigating the $t\bar{t}$ invariant mass. In an analysis using data corresponding to 3.6 fb^{-1} the DØ collaboration found no evidence for such a resonance and places upper limits on $\sigma_X \cdot \mathrm{BR}(X^0 \to t\bar{t})$ range from 1.0 pb at $M_X = 350\,\mathrm{GeV}/c^2$ to 0.16 pb at $M_X = 1000\,\mathrm{GeV}/c^2$. If interpreted in the frame of a topcolor-assisted technicolor model these limits can be used to derive mass limits on a narrow lepto-phobic Z': $M(Z') > 820$ GeV/c^2 at the 95% C.L., assuming $\Gamma(Z') = 0.012\,M(Z')$ [11]. A similar analysis in the all-hadronic channel at CDF yields slightly lower mass limits [12]. Another CDF analysis searches for a fourth generation up-type quark t' and sets a lower limit of $m_{t'} > 311$ GeV/c^2 at the the 95% C.L. [13].

5 Decay Properties

According to the SM the top quark decays with a branching ratio of nearly 100% to W^+ boson and a bottom quark via the weak interaction. The charged-current weak interaction has a pure V-A structure and thereby strongly suppresses the production of right-handed W^+ bosons in top-quark decays. Only left-handed and longitudinally polarized W bosons are allowed, the production of the later being enhanced due to the large Yukawa coupling of the top quark to the Higgs boson. The fraction of longitudinally polarized W-bosons is predicted to be $f_0 = 0.70$, the left-handed fraction $f_- = 0.30$.

W Helicity CDF and DØ have measured the W-helicity fractions in fully reconstructed $t\bar{t}$ lepton+jets events. A suitable sensitive variable to determine the W-helicity fractions is the angle θ^* between the charged lepton and the negative direction of the top quark in the W rest frame. Performing a two-dimensional and thereby model-independent fit DØ obtains $f_0 = 0.43 \pm 0.17 \pm 0.10$ and $f_+ = 0.12 \pm 0.09 \pm 0.05$ [14]. Combining two similar analyses CDF finds $f_0 = 0.66 \pm 0.16 \pm 0.05$ and $f_+ = -0.03 \pm 0.06 \pm 0.03$ [15].

Branching Ratio The DØ collaboration has recently also measured the ratio of branching ratios $\mathcal{R} = \mathrm{BR}(t \to Wb)/\mathrm{BR}(t \to Wq)$, an analysis which tests the hypothesis whether there is any room for an additional top decay channel $t \to W + q_x$ into a yet undiscovered quark q_x. In the analysis, $\mathcal{R}$ and the $t\bar{t}$ cross section are simultaneously measured [16]. The W+jets data set is split in various disjoint subsets according to the number of jets (0, 1, or ≥ 2), the charged lepton type (electron or muon), and most importantly the number of b-tagged jets. The fit results are: $\mathcal{R} = 0.97^{+0.09}_{-0.08}$ and $\sigma(t\bar{t}) = 8.18^{+0.90}_{-0.84} \pm 0.50$ (lumi) pb, where the statistical and systematic uncertainties have been combined. The lower limit on $\mathcal{R}$ is obtained to be $\mathcal{R} > 0.79$ at the 95% C.L.

6 Conclusions

The large data sets available in Run II of the Tevatron have propelled top-quark physics in a new era in which precise investigations of top-quark properties are possible. The top-Antitop cross section has been measured with a relative precision of 6.4%. Many interesting analyses have searched for physics beyond the SM, for example for resonances decaying into $t\bar{t}$ pairs. The measurements of top quark decay show impressive progress, most importantly the measurement of the W-helicity fractions in top decay.

Acknowledgments

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