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# Top quark properties and cross-section

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**Summary.** — The CDF and D0 experiments have performed measurements of production and decay properties of the top quark with an unprecedented precision. This talk gives an overview of top quark properties and cross-section measurements performed with top quark pair events in proton anti-proton collision at 1.96 TeV with a luminosity of up to 3.6 $\text{fb}^{-1}$.

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## 1. – Introduction

Since the top quark was discovered by CDF and D0 at the Tevatron in 1995 [1,2] the number of top events available for experimental studies has been increased by more than an order of magnitude. Tevatron now delivered a luminosity of more than 6 $\text{fb}^{-1}$ up to half of which has been analysed for top quark analyses in CDF and D0. These data are, amongst other studies, investigated to verify the production and decay properties of top quarks as expected by the Standard Model (SM).

In the SM top quark pair production at the Tevatron is expected to be dominated by quark anti-quark annihilation with a contribution of only 15% from the gluon fusion processes. The predicted cross-section depends on the top quark mass. The top quark decays to nearly 100% to a $W$-boson and a $b$-quark. The decay channels of top quark pairs are thus fully specified through the $W$-boson decay modes. Dileptonic decays including electrons and muons allow for the highest purity, but suffer from the low branching fraction of about 10%. The semileptonic decays are considered as the golden channel due to a sizable branching fraction combined with the possibility to reach a reasonable signal to background ratio. The all-hadronic decay channel has the largest cross-section, but due to the absence of leptons it suffers from a huge background due to multijet production. Channels including $\tau$ leptons are kept separately due to the difficulties in their identification.

In the following first some new results on the top quark pair production cross-section are described. Then selected measurements of top quark decay properties and the possible presence of particles beyond the SM are discussed. The final section presents a possible admixture of particles beyond the SM in the samples usually considered a top quark events. The top quark mass which is the only free parameter in the top quark sector of the SM and the observation of single top quark production are discussed separately [3,4].

 

## 2. – Top pair production cross-section

The total cross-section of top pair production has been computed in perturbation theory using various approximations [5-9]. For a top quark (pole) mass of 175 GeV Moch and Uwer [8] find $\sigma_{t\bar{t}} = 6.90^{+0.46}_{-0.64}$ pb, based on the CTEQ6.6 [10] PDF. Experimentally it is important to measure this value in various decay channels. In addition some measurements are done requiring identified $b$-jets while others avoid $b$-jet identification and rely on topological selections. Most analysis use sideband data to evaluate the normalisation of the important background contributions. In the lepton plus jets channel the precision is already dominated by systematic uncertainties.

A sizable contribution of the systematic uncertainties of these measurements stems from the luminosity determination. To overcome this limitation CDF has measured the ratio of top quark pair production to the $Z$-boson production cross-sections [11, 12]. In 2.7 and 2.8 fb$^{-1}$ of data CDF finds $\sigma_{Z\to\ell\ell}/\sigma_{t\bar{t}} = 35.7 \pm 3.8$ and $\sigma_{Z\to\ell\ell}/\sigma_{t\bar{t}} = 36.5 \pm 2.9$ for the analysis using $b$ jet identification and the topological analysis, respectively. These results are converted to top pair production cross-sections using the theoretical prediction for $Z$-boson production. The theoretical uncertainty induced by this step is much smaller than the luminosity uncertainties and thus yield results with an uncertainty comparable to the theoretical uncertainty:

$$(1)\quad \sigma_{t\bar{t}} = 7.0 \pm 0.4_{(\mathrm{stat})} \pm 0.6_{(\mathrm{syst})} \pm 0.1_{(\mathrm{theory})}\,\mathrm{pb}, \qquad \text{using } b \text{ jet identification,}$$
$$\sigma_{t\bar{t}} = 6.9 \pm 0.4_{(\mathrm{stat})} \pm 0.4_{(\mathrm{syst})} \pm 0.14_{(\mathrm{theory})}\,\mathrm{pb}, \qquad \text{using topological selection.}$$

DØ has recently extended the list of cross-section results measuring the cross-section in a final state with one $\tau$-lepton plus another lepton [13,14]. Hadronic decay of $\tau$-leptons are identified with neural networks for three different decay modes: single charged pion, single charged pion associated with neutral pions and three charged pions associated with neutral pions. Events are selected requiring one $\tau$-lepton identified in one of the above hadronic decay modes, one isolated electron or muon, missing transverse energy and at least two jets, one of which is required to be identified as $b$-jet. Background from $W$+jets is normalised to data before selecting events with identified $b$-jets, multijet background is estimated from events with same sign leptons. The cross-section measured from opposite-sign leptons in 2.2 fb$^{-1}$ of DØ has a systematic uncertainty with important contributions from the background estimation and from limited statistics of the simulation:

$$(2)\qquad \sigma_{t\bar{t}} = 7.32^{+1.34}_{-1.24\,(\mathrm{stat})}{}^{+1.20}_{-1.06\,(\mathrm{syst})} \pm 0.45_{(\mathrm{lumi})}\,\mathrm{pb}.$$

Figure 1 shows a summary of the cross-section measurements performed by CDF and DØ. The two recent results discussed above agree well with the other channels and all channels agree with the theoretical cross-section predicted within the SM.

**2**·1. *Limits on charged Higgs.* – The presence on beyond the SM particles may alter the branching fractions of the various top quark pair decay channels. This would alter the deduced cross-section depending on the decay channel. DØ used the cross-sections measured in the semileptonic, the dileptonic and the tau+electron/muon channel to search of a possible contributions of charged Higgs bosons in top quark decays [15, 16]. DØ considered all correlations between the various systematic uncertainties of these measurements and sets limits on $\sigma_{t\bar{t}}\mathcal{B}(t \to H^+)$ for a leptophobic and a tauonic scenario

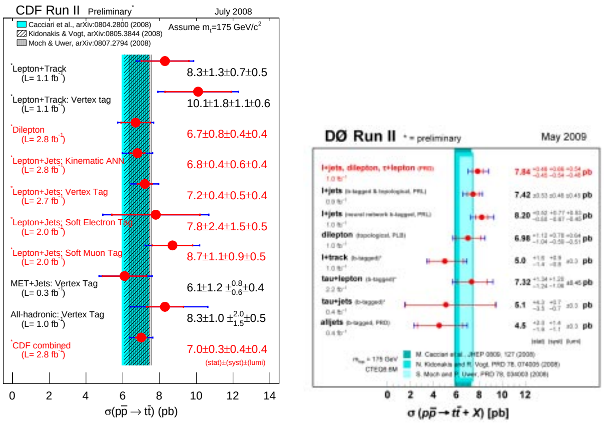


Fig. 1. – Summary of top quark cross-section results for various analysis channels.

for the charged-Higgs decay. These limits can be transfered to exclusion areas in the plane of $\tan\beta$ *vs.* charged-Higgs mass, as seen in fig. 2 (left).

CDF has searched for charged Higgs bosons in the top quark decay using kinematic differences of the two event types in lepton plus jets events. Comparing templates of the dijet invariant mass distribution yields an improved sensitivity at high-charged-Higgs masses, but is less sensitive for charged-Higgs masses near the $W$-boson mass. The obtained limits are shown in fig. 2 (right).

## 3. – Top quark decay properties

**3·1.** *$W$ helicity.* – The spin structure of the top quark decay is accessible by measuring the $W$-boson helicity. The SM expects about 70% longitudinally and 30% left-handed polarised $W$-bosons. Longitudinal polarised $W$ bosons preferably emit the charged leptons orthogonal to the $b$-quark. Left-handed $W$ bosons prefer the charged lepton to be emitted along the direction of the $b$-quark, while right-handed $W$-bosons prefer the charged boson to be opposite to the direction of the $b$-quark. Both Tevatron experiments mea-

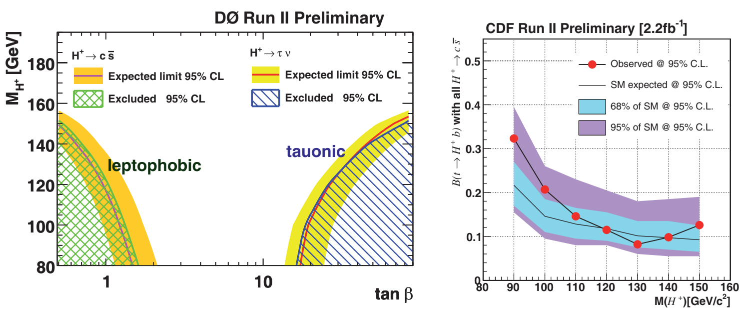


Fig. 2. – (Colour online) Left: exclusion limits derived in leading order for the $\tan\beta$ *vs.* $M_{H\pm}$ plane in the Minimal Supersymmetric SM [15]. Right: CDF observed limits on $\mathcal{B}(t \to H^+ b)$ from $2.2\,\mathrm{fb}^{-1}$ data (red dots) compared with the expected limit in the standard model (black line) [17].

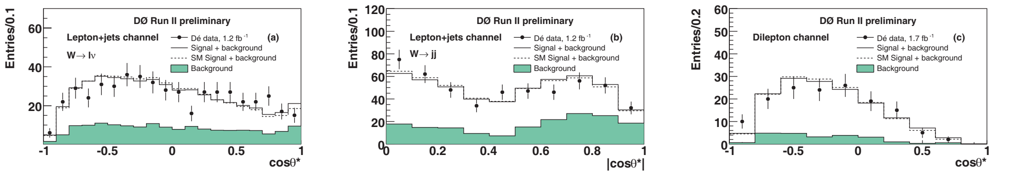


Fig. 3. – $W$ decay angle distributions as measured in 1.2–1.7 fb$^{-1}$ of DØ Run-IIb data. The left and middle show the leptonic decay and the hadronic in the lepton+jet events, respectively. The right plot shows the distribution obtained from dilepton events. The shaded area represents the background contribution [19].

sure cosine of the angle between the $b$-quark and the charged lepton in the $W$-boson rest-frame. CDF measures $\cos\theta^*$ from the lepton plus jet events [18] in 1.9 fb$^{-1}$. DØ uses lepton plus jets and dilepton events using 2.2–2.7 fb$^{-1}$ [19], see fig. 3. The expectations for the left-handed, the right-handed and the longitudinal fractions are compared to the observed data to simultaneously fit the left-handed and the longitudinal fractions:

$$\begin{aligned} \text{D0:}\quad & f_0 = 0.49 \pm 0.14 \quad \text{and} \quad f_+ = +0.11 \pm 0.08, \\ \text{CDF:}\quad & f_0 = 0.66 \pm 0.16 \quad \text{and} \quad f_+ = -0.03 \pm 0.07. \end{aligned} \tag{3}$$

The $W$ helicity measurement is sensitive to anomalous couplings in the $Wtb$ vertex. In general this vertex can contain vector and tensor couplings in left- and right-handed variations. DØ has combined the above measurement of the $W$ helicity with a search for anomalous coupling in single top quark events [20, 21]. The single top quark analysis uses boosted decision trees trained with various anomalous coupling scenarios. The single top quark and the top quark pair events are simultaneously compared to templates that describe the SM coupling and one anomalous coupling at a time. All three scenarios show good agreement with a pure SM coupling as shown in fig. 4.

## 4. – New physics in top quark like signatures

In the SM top quark pair production does not show any resonances. However, unknown heavy resonances decaying to top pairs may add a resonant part to the SM production mechanism. Resonant production is possible for massive $Z$-like bosons in extended gauge theories [22], Kaluza-Klein states of the gluon or $Z$-boson [23, 24], ax-

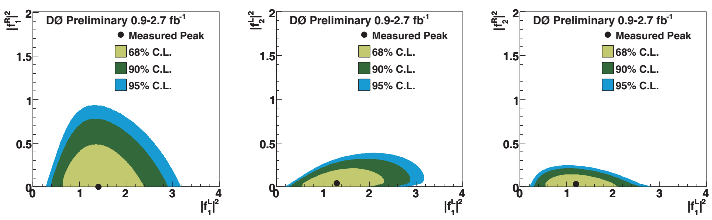


Fig. 4. – Allowed 68%, 90% and 95% CL regions for SM $Wtb$ coupling, $f_1^L$ with anomalous right-handed vector coupling, $f_1^R$ (left) and with anomalous left- and right-handed tensor couplings, $f_1^{L/R}$ (middle and right) [20, 21].

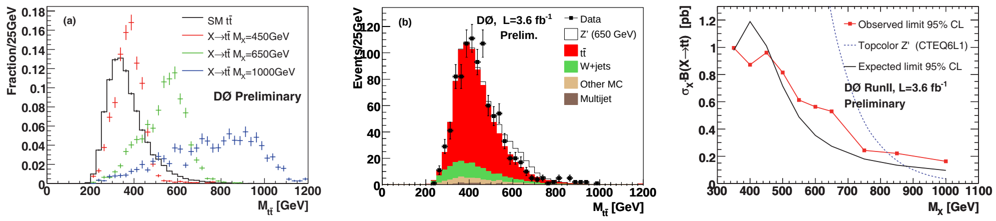


Fig. 5. – Left: shape of SM top pair production (black line) compared to resonant production through a narrow resonance at three different resonance masses. Middle: expected and observed $t\bar{t}$ invariant-mass distribution for the $\ell + 4$ or more jets channels, with at least one identified $b$-jet. Superimposed as white area is the expected signal for a Topcolor-assisted Technicolor $Z'$-boson with $M_{Z'} = 650\,\text{GeV}$. Right: limits on $\sigma_X \mathcal{B}(X \to t\bar{t})$ obtained in $3.6\,\text{fb}^{-1}$ [28-30].

igluons [25], Topcolor [26,27], and other theories beyond the SM. Independent of the exact model, such resonant production could be visible in the reconstructed $t\bar{t}$ invariant mass.

**4·1.** *Top quark pair invariant-mass distribution.* – DØ investigated the invariant-mass distribution of top pairs in up to $3.6\,\text{fb}^{-1}$ of $\ell$+jets events [28-30]. Signal simulation is created for various resonance masses between 350 and 1000 GeV. The width of the resonances was chosen to be 1.2% of their mass, which is much smaller than the detector resolution. The top pair invariant mass, $M_{t\bar{t}}$, is reconstructed directly from the reconstructed physics objects. A constraint kinematic fit is not applied. Instead the momentum of the neutrino is reconstructed from the transverse missing energy, $\not{E}_T$, which is identified with the transverse momentum of the neutrino and by solving $M_W^2 = (p_\ell + p_\nu)^2$ for the $z$-component of the neutrino momentum. $p_\ell$ and $p_\nu$ are the four-momenta of the lepton and the neutrino, respectively. Figure 5 shows the expected shapes of SM and resonant production (left) and the expected and observed invariant mass distribution for the $\ell + 4$ or more jet channel. As the data agrees with the SM expectations, limits on the possible contribution of resonant production $\sigma_X \mathcal{B}(X \to t\bar{t})$ are set. The benchmark model of Topcolor assisted Technicolor can be excluded for $Z'$ masses of $M_{Z'} < 820\,\text{GeV}$.

Recent CDF results unfold the distribution invariant top quark pair mass and measure the differential cross-section in semileptonic events [31]. The invariant mass of the top pairs is reconstructed from the four-momenta of the four leading jets in $p_T$, the four-momentum of the lepton and the missing transverse energy. The $z$-component of the neutrino is not reconstructed but used as if it was zero [32]. To obtain the differential cross-section from the background-subtracted distribution of observed $M_{t\bar{t}}$ values, acceptance effects and smearing effects from the reconstruction need to be corrected for. The required acceptance correction is computed from signal simulation with Pythia. Correction factors to correct for differences between data and Monte Carlo observed in control samples are applied for the lepton identification and $b$-jet identification rates. The distortions of the reconstructed distribution are unfolded using the singular value decomposition of the response matrix that is obtained from simulations. The differential cross-section obtained in $2.7\,\text{fb}^{-1}$ of data using the semileptonic decay mode is shown in fig. 6 [31]. The consistency with the Standard Model expectation is computed using Anderson-Darling statistics [33]. The observed $p$-value is 0.28, showing good agreement with the Standard Model. Finding no evidence for physics beyond the Standard Model limits on gravitons in a Randall-Sundrum model [35] decaying to top quarks are set using the $\text{CL}_s$ method. The first resonance is assumed to have a mass of 600 GeV. The

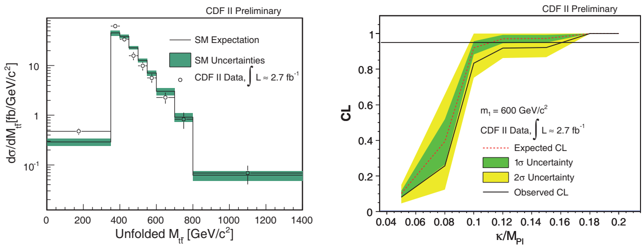


Fig. 6. – Left: differential top pair production cross-section measured by CDF in 2.7 fb$^{-1}$ of data using the semileptonic decay mode. Indicated are the total uncertainties for each bin, excluding the overall luminosity uncertainty of 6%. Right: expected and observed limit on $\kappa/M_{\rm Pl}$ in a RS model [31, 34].

Anderson-Darling statistics is used as test statistics in the CL$_s$ method. For the ratio of the warping parameter over the Planck mass CDF finds $\kappa/M_{\rm Pl} < 0.16$ at 95% CL, see fig. 6 (right).

4·2. *Stop quark admixture.* – Particles beyond the SM may hide in the samples usually considered to be top quarks. One such candidate is the top quarks supersymmetric partner, the stop quark. The stop decay modes to neutralino and top quark, $\tilde{\chi}_1^0 t$, or through chargino and $b$-quark, $\tilde{\chi}_1^{\pm} b$, both yield neutralino, $b$-quark and $W$-boson, $\tilde{\chi}_1^0 bW$. The neutralino is the lightest supersymmetric particle in many models and is stable if $R$-parity in conserved. Then it escapes the detector and the experimental signature of stop pair production differs from that of top pair production only by the additional contribution to the missing transverse energy from the neutralino. Production of $\tilde{t}_1\bar{\tilde{t}}_1$ is simulated for various combinations of stop and chargino masses, $m_{\tilde{t}_1}, m_{\tilde{\chi}_1^{\pm}}$.

DØ has performed a search for the top quarks supersymmetric partners in 0.9 fb$^{-1}$ of semileptonic events [36, 37]. For the sake of this analysis the stop mass was chosen to be less or equal to the top mass. The neutralino mass $m_{\tilde{\chi}_1^0} = 50\,\text{GeV}$ was chosen to be close to the experimental limit. Stop quark signal events are distinguished from SM top quark events using a likelihood discriminant obtained from simulation. The most sensitive observable in this likelihood is the top quark mass reconstructed assuming a SM top quark pair event. Limits are set on the cross-section of various masses of the stop and the chargino, see fig. 7 (left). The sensitivity is not sufficient to exclude MSSM parameter values.

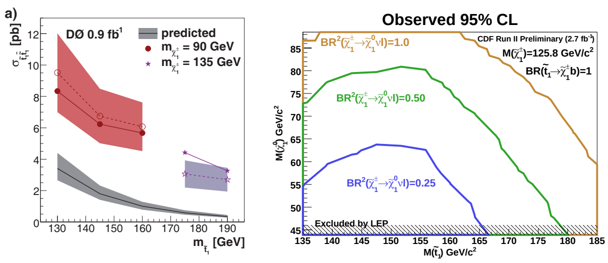


Fig. 7. – Left: limits on stop quark production in semileptonic events obtained in 1 fb$^{-1}$ by DØ for an example parameter set [37]. Right: exclusions in the stop mass *vs.* neutralino mass plane of the MSSM obtained with 2.7 fb$^{-1}$ of CDF data [38].

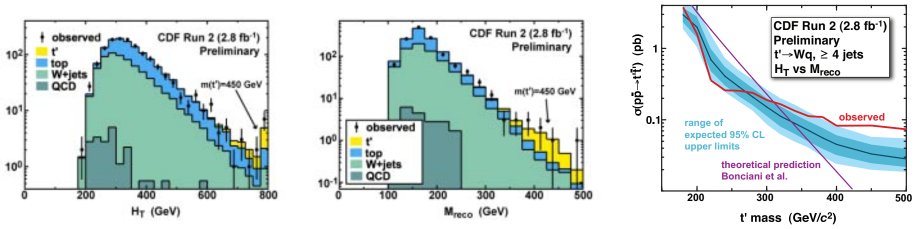


Fig. 8. – Expected and observed distribution of $H_T$ and $m_{t^{(\prime)}}$ (left and middle). Resulting limits on the allowed cross-section of a $t^{(\prime)}$ production (right) [38].

CDF has used the dilepton channel to search for stop quark admixture in $2.7\,\mathrm{fb}^{-1}$ [38]. To distinguish the stop quark events from the SM to quark events, the stop mass is reconstructed using neutrino weighting technique. It is possible to exclude some portion in the stop mass *vs.* neutralino mass plane of the MSSM parameter space as shown in fig. 7 (right).

**4˙3.** *Fourth-generation u-type quark, $t'$.* – Another particle that may hide in the top quark samples is a fourth-generation quark, $t'$. CDF has searched for such a contribution in up to $2.8\,\mathrm{fb}^{-1}$ [39, 38]. In semileptonic events $t'$ quarks are distinguished from SM $t$-quarks using the scalar sum of transverse momenta, $H_T$, and the $t^{(\prime)}$ mass reconstructed in a kinematic fit. The observed data are compared to the expectations for the SM and an additional contribution for a $t'$-quark assuming various $t'$-quark masses. The observed limits on possible cross-section for such a $t'$-quark production fall behind the expected ones for $m_{t'} > 300\,\mathrm{GeV}$. They allow to exclude $t'$ masses of less than 311 GeV, c.f. fig. 8.

## 5. – Conclusions

The increasing Tevatron luminosity allows to measure the top quark cross-section and properties with improved precision. This note only describes a small fraction of all measurements. The Tevatron experiments measure the full spectrum of top quark properties to check the production, the decay and inherent properties of the top quark against the SM expectation. So far no evidence for new physics has been found.

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