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New physics searches using top quarks

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Summary. — This review summarizes recent searches for new physics at the Fermilab Tevatron Collider using final states involving top quarks and their analogues. The DØ and CDF Collaborations have used samples as large as $5\,\text{fb}^{-1}$ to search for charged Higgs bosons, massive resonances decaying to $t\bar{t}$ pairs, massive vector bosons decaying to $t\bar{b}$ final states, fourth-generation t' quarks and supersymmetric stop ($\tilde{t}$) quarks. These analyses have resulted in some of the most sensitive searches for new phenomena in the 1.96 TeV $\bar{p}p$ collisions.

PACS 13.85.-t – Hadron-induced high- and super-high-energy interactions (energy $> 10\,\text{GeV}$).
PACS 12.38.-t – Quantum chromodynamics.
PACS 14.65.-q – Quarks.

1. – Introduction

The discovery of the top quark by the CDF and DØ Collaborations in 1995 began a systematic study of the properties of this uniquely massive object [1, 2]. The first observation of the top quark was made with approximately $0.04\,\text{fb}^{-1}$ of data, but over the last 15 years, both the CDF and DØ Collaborations have collected data samples approximately 100 times larger. This has allowed studies that are reaching sensitivities that push the kinematic limits of the 1.96 TeV $\bar{p}p$ collisions.

I first will make some general comments regarding new physics searches using top quarks in sect. **2**. I will then review in the following four sections the latest results from the Tevatron Collider that use top quarks or their analogues to search for new phenomena. I will conclude in sect. **7** with some observations regarding future work.

2. – Strategies for identifying New Physics

There are two broad classes of signatures of new physics that involve top quarks. The first are those that modify the final state of top quarks. In the Standard Model (SM), the top quark is expected to decay almost 100% of the time into a W^+b final state. This

pattern would be significantly distorted if, for example, Supersymmetry (SUSY) exists and one of the expected charged Higgs bosons (H^+) has a mass, m_{H^+}, less than the top quark mass m_t. The detection of such processes requires detailed studies of the final states of top quark pair production, untangling the SM processes from those predicted from new physics.

The second class of new physics involves massive particles that preferentially have decays involving top quarks or top quark pairs. These involve final states with unique kinematic configurations, either because they result from the s-channel production of a resonance decaying to a top-quark pair, or because new particles are pair-produced and each decays into a top quark and other particles. This class of models yields final states that are complex and in some cases spectacular, given the very energetic particles produced.

Both of these signatures result in final states that are a mixture of charged leptons, neutrinos and jets. I will discuss the characteristics of these final states rather than give detailed selection criteria. I refer to the interested reader to the references for those details.

3. – Charged Higgs bosons in top quark decays

In SUSY models, the Higgs sector is predicted to be much more complex than the single Higgs boson of the SM, with at least five Higgs particles predicted in the Minimal SuperSymmetric Model (MSSM) [3]. The two charged Higgs bosons ($H^\pm$) would be expected to couple to top quarks and mediate their decay, provided that this is kinematically allowed and the branching fraction of $t \to H^+ b$ is sufficiently large. The latter is determined by $\tan\beta$, the ratio of vacuum expectation values for the two Higgs doublets in this model. Furthermore, the H^+ is expected to preferentially decay to $\tau\nu_\tau$ and $c\bar{s}$ final states, which change the mixture of top quark pair final states.

The DØ Collaboration has reported the results of a search for the H^+ [4] using a multi-channel approach where the branching fractions of 14 final states of lepton+jet and dilepton modes are measured in a data sample of $1.0\,\mathrm{fb}^{-1}$. The observed event rates are fit to a model that allows for a mixture of $t \to H^+ b$ and $t \to W^+ b$ decays as well as the corresponding rate of $H^+ \to \tau\nu_\tau$ and $H^+ \to c\bar{s}$ decays, where the $t\,\bar{t}$ cross section is allowed to be a free parameter. The data and the fits are summarized in fig. 1, where the observed numbers of candidates, background and signal predictions for the 14 final states are shown in 4 broader categories. These data are then interpreted in the context of specific models. For example, assuming that $BR(H^+ \to \tau\nu_\tau) = 1$, the collaboration excludes at 95% CL an H^+ with mass between 80 and $150\,\mathrm{GeV}/c^2$ with a branching fraction $t \to H^+ b$ greater than approximately 0.15.

The CDF Collaboration has recently reported the results of several searches for H^+ that are similar to those summarized above, but using different strategies in detail [5]. The first is a search for evidence of the decay $t \to H^+ b$ with $H^+ \to c\bar{s}$. The lepton+jets final state is defined to be those candidates having either 4 or 5 jets. Efforts are made to identify the most likely association of jets with initial state quark showers, placing stringent requirements on the kinematics of the events. From a sample of $2.2\,\mathrm{fb}^{-1}$, the collaboration finds exactly 200 candidate events. The dijet mass distribution is used to set limits on the proportion of $H^+ \to c\bar{s}$ decays at 95% CL to be $< 30\%$ at $m_{H^+} = 90\,\mathrm{GeV}/c^2$ dropping to $< 10\%$ at $m_{H^+} = 160\,\mathrm{GeV}/c^2$.

The CDF Collaboration has performed a new search for an H^+ boson in the context of non-MSSM models, where now the H^+ prefers to decay to a W^+ boson and the A, the

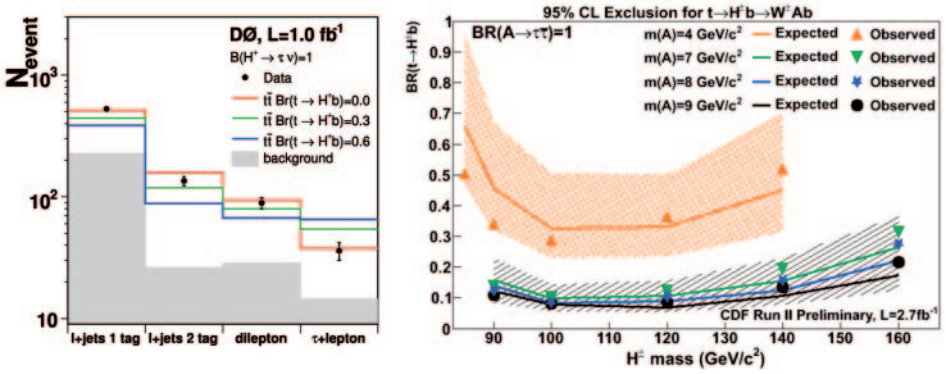

Fig. 1. – Selected results of charge Higgs searches. The left plot shows the number of predicted and observed DØ charged Higgs candidates in the different channels, showing the sensitivity to different signal levels. The right plot presents the 95% CL limits on the branching fraction of the top quark to a NMSSM H^+ as a function of H^+ mass. Both expected and observed limits are shown for different masses of the neutral Higgs boson A.

charge-parity odd, neutral Higgs boson, with the A then decaying to τ-lepton pairs [6]. This results in a leptons+jets final state with the additional requirement of a τ pair signature of isolated charged tracks. The search requires the use of a novel, data-driven background estimate to the charged track signature. Using $2.2\,\mathrm{fb}^{-1}$, the analysis sets limits on the branching fraction for $t \to H^+ b$ *vs.* the H^+ mass shown in the right plot of fig. 1. In the context of the specific model used here, the results place limits $< 10\%$ at 95% CL over a charged Higgs mass range from 90 to $160\,\mathrm{GeV}/c^2$. However, they are applicable to other variations of Higgs masses, as shown in the figure.

4. – Resonances decaying into top quark pairs

There are numerous theoretical models that predict massive particles that preferentially decay to top-quark pairs [7]. This motivates the search for resonances that decay to high-mass top quark pairs. Standard Model top quark production falls off quite rapidly at higher top quark p_T [8, 9] so that such a search is not background-limited but rather limited by the total sensitivity of the data sample.

Both the CDF and DØ Collaborations have reported results of increasingly sensitive searches. The DØ analysis [10] selects candidate top quark pairs by requiring a high transverse momentum muon or electron, significant $\not\!\!E_T$ and at least three jets with one of these jets tagged as a b-quark candidate. They find 2345 candidate events in a $3.6\,\mathrm{fb}^{-1}$ sample, and estimate the backgrounds to $t\bar{t}$ to be less than 50%, with the single largest source coming from $W+$ jet production. They fit the mass distribution, shown in the left panel of fig. 2, to the distributions from SM $t\bar{t}$ production and a potential resonance of mass $m_{Z'}$ and width $\Gamma = 0.012 m_{Z'}$. Although this model is motivated by TopColor theories [11], it can be considered an example of a more generic form of a narrow resonance decaying to $t\bar{t}$ to set cross section and mass limits. The DØ analysis sees no evidence for a resonance signal and the collaboration sets an upper limit on the production cross section of a narrow state $< 200\,\mathrm{fb}$ at 95% CL, which can then be translated into a lower limit on the Z' mass of $> 820\,\mathrm{GeV}/c^2$. The CDF Collaboration has updated a similar analysis employing $4.8\,\mathrm{fb}^{-1}$ of data using a matrix-element technique to reconstruct the $t\bar{t}$ final

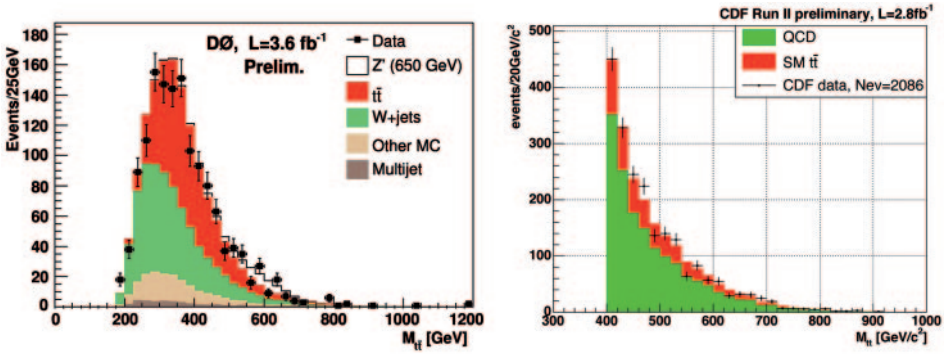

Fig. 2. – The $t\bar{t}$ invariant mass distributions for the DØ lepton+jets search (left) and the CDF all-hadronic search (right). Both experiments see very few candidates at high $t\bar{t}$ invariant mass, allowing them to set limits of $> 820\ \mathrm{GeV}/c^2$ and $> 805\ \mathrm{GeV}/c^2$ at 95% CL for the DØ and CDF analysis, respectively.

state. Upper limits at 95% CL of $< 70\,\mathrm{fb}$ are set on the Z' cross section, translating into a lower limit of $m_{Z'} > 900\,\mathrm{GeV}/c^2$.

The CDF Collaboration has also performed a Z' search using the $t\bar{t}$ all-hadronic channel requiring 6 or 7 jets in the final state with each jet having $p_T > 15\,\mathrm{GeV}/c$ and $|\eta| < 2.0$ [12]. In addition, at least one jet is required to be b-tagged. The resulting $t\bar{t}$ invariant mass distribution for the 2086 candidates with $m_{t\bar{t}} > 400\,\mathrm{GeV}/c^2$ is shown in fig. 2. Although background-limited, the higher $t\bar{t}$ detection efficiency results in a a cross section upper limit of $< 210\,\mathrm{fb}$ and a mass limit of $m_{Z'} > 805\,\mathrm{GeV}/c^2$ at 95% CL, assuming that the Z' resonance couples solely to quark-antiquark pairs (a so-called "leptophobic" Z').

5. – Massive vector bosons

Many models of extended gauge symmetries predict the existence of one or more massive charged bosons. These have motivated searches for massive particles decaying to $e^+\nu_e$ and $\mu^+\nu_\mu$ final states. However, the quark final states have been background-limited though important constraints have come from the study of dijet final states [13]. The CDF Collaboration performed the first search for a W' decaying to a $t\bar{b}$ final state using $0.1\,\mathrm{fb}^{-1}$ of Run I data and excluded a W' with mass below $536\,\mathrm{GeV}/c^2$ at 95% CL [14], showing that the $t\bar{b}$ final state provides an effective tool to search for such particles in quark final states.

The DØ Collaboration has reported a search for a massive resonance decaying to a $t\bar{b}$ final state using $0.9\,\mathrm{fb}^{-1}$ of data [15]. The analysis required a charged lepton, missing transverse energy and 2 or 3 jets, with at least one of the jets being tagged as a b-quark candidate. The sample was sub-divided into 8 channels to maximize the different signal-to-background ratios expected in each channel. Taken together, they selected 182 events and estimated that $\sim 1/3$ came from Standard Model $t\bar{t}$ production and $\sim 2/3$ from other background sources. The $t\bar{b}$ invariant mass is shown in fig. 3 (left), illustrating that the data has no evidence of resonant structure. A 95% CL lower limit on a W' mass $> 731\,\mathrm{GeV}/c^2$ is set.

The CDF Collaboration has performed a similar search in the same final states, but employing a $1.9\,\mathrm{fb}^{-1}$ sample and subdividing the final states in somewhat different

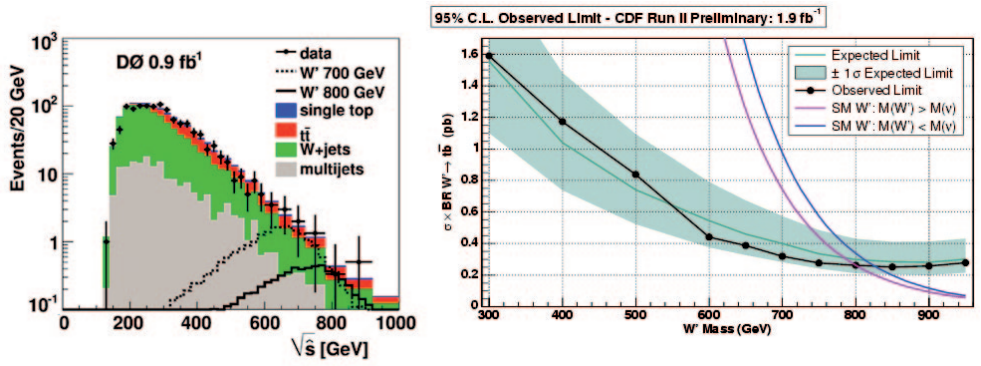

Fig. 3. – The $t\bar{b}$ invariant mass distributions for the DØ lepton+jets search (left) for the process $W' \to t\bar{b}$ and the 95% CL upper limits on the W' cross section times branching ratio set by the CDF analysis for the same final state. The DØ and CDF experiments set limits of 731 GeV/c^2 and 800 GeV/c^2 at 95% CL, respectively.

subsamples [16]. They also see no evidence of a signal above the expected background and use these data to set 95% CL limits on the W' cross section of < 250 fb, which translate to a W mass limit of $> 800\,\mathrm{GeV}/c^2$ using SM couplings for the W'. They note that this limit rises to $825\,\mathrm{GeV}/c^2$ if one assumes that right-handed neutrinos are more massive than the W'.

6. – Fourth-generation quarks and supersymmetric top production

It is a natural extension to extend these searches involving top quarks to other final states with similar kinematics. I will report here on two recent examples: the search for a fourth-generation quark that decays, like a top quark, into a W^+q final state (t'), and a search for supersymmetric top quarks (*i.e.* a stop quark or $\tilde{t}$).

A search for a t' was performed by the CDF Collaboration assuming that the t' was pair-produced and decayed to a W^+q final state [17]. This produces exactly the same topologies as $t\,\bar{t}$ production, but now with a parent quark mass higher than the top quark mass. Figure 4 shows the reconstructed W^+q mass distribution for a sample of lepton+$\geq$ 4 jet candidates, where the best combination that kinematically can be constrained to a t' pair production hypothesis has been chosen. There is no b-quark tagging in this analysis, so the backgrounds from $t\,\bar{t}$, QCD production of multijet states and $W+$ jet production are large. There are 3648 candidates in a $4.6\,\mathrm{fb}^{-1}$ sample, where one expects 3664 ± 1570 background events (the large uncertainty comes from the uncertainties in the QCD background). A multidimensional kinematic fit is performed to provide greater separation between a potential signal and background, but no evidence for a signal is uncovered. The analysis sets an upper limit on the t' pair production cross section of approximately 100 fb, which excludes at 95% CL a t' with mass less than $335\,\mathrm{GeV}/c^2$.

A stop search, also performed by the CDF Collaboration [18], uses a specific model for stop quark decay in order to be able to set specific limits. In particular, they assume that the stop decays to a chargino, χ_1^2 and a b quark, with the chargino then decaying in a number of possible ways to the lightest supersymmetric particle that is assumed to be the neutralino, χ_1^0, and one or more leptons. There is a sizeable branching fraction to

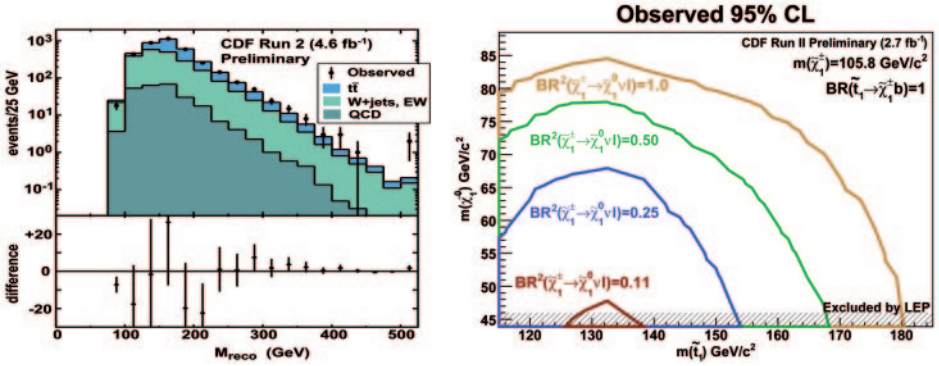

Fig. 4. – The observed W^+q invariant mass distribution in the CDF t' search (left). Overlaid are the predictions for the various backgrounds, and the inset below shows the difference between the observed and predicted distributions, bin-by-bin. The plot on the right shows the chargino mass *vs.* stop mass limit contours for different assumptions on the branching fraction of the chargino to the neutralino, assuming a chargino mass of 105.8 GeV/c^2 and that the stop decays 100% into a chargino and b quark.

dilepton final states, so that the search is performed by selecting two charged leptons (e or μ), two or more jets and significant $\not\!\!E_T$. The samples with and without b-tagged jets are analyzed separately to improve the overall sensitivity of the search.

The results of the search are summarized in the right plot in fig. 4 where one sees that 95% CL limits can be set in the $m_{\chi_1^0}$-$m_{\tilde{t}}$ plane that extend to χ_1^0 masses of over 80 GeV/c^2 and $\tilde{t}$ masses of up to 180 GeV/c^2. Although these limits are based on a specific model, they illustrate that a large range of mass combinations of the $\tilde{t}$ and χ_1^0 can be excluded.

7. – Conclusions

I hope that this short review provides the reader with a sense of the power of using the top quark and its analogues for searching for new physics. Limits have been placed on the masses and branching fractions of charged Higgs bosons. Lower limits have been set on the masses of narrow resonances decaying to $t\,\bar{t}$ of 900 GeV/c^2 and on the masses of vector bosons decaying to $t\bar{b}$ of 800 GeV/c^2. A search for a fourth-generation quark with properties similar to the top quark has resulted in lower limits on its mass of 335 GeV/c^2 and a search for a supersymmetric partner to the top quark has resulted in lower limits on the $\tilde{t}$ and χ_1^0 masses of up to > 180 GeV/c^2 and > 45 GeV/c^2, respectively.

Because of limitations of space, I have not been able to discuss many other topics involving top quarks that probe new physics, such as the spin structure of top quark production and decay, the search for top quark rare decays such as $t \to Zq$ and the use of top quark production to search for other phenomena, such as associated production of $t\,\bar{t}$ with the SM Higgs boson. Proper justice to this topic could only be done with a more extended discourse and presentation.

The relatively modest samples of top quarks detected at the Fermilab Tevatron will soon be supplanted by the copious top quark production at the Large Hadron Collider, where we expect the rate of top quark production to be approximately 20 times larger in 7 TeV pp collisions. Although the Tevatron experiments have an immediate opportunity to extend these searches, with almost twice as much data already collected than reported

here, it is likely the purview of the LHC to discover the new physics that couples to top quarks.

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