Frascati Physics Series Vol. XLVI (2007), pp. 000-000
HADRON07: XII Int. Conf. on Hadron Spectroscopy – Frascati, October 8-13, 2007
Plenary/Parallel Session *pick one*

SEARCHES FOR NEW PHYSICS IN THE TOP QUARK SAMPLES AT THE CDF EXPERIMENT

Luca Scodellaro for the CDF Collaboration
Instituto de Fisica de Cantabria, Avda Los Castros s/n, 39005 Santander, Spain

Abstract

Twelve years after the discovery of the top quark at Fermilab's Tevatron, we are now finally beginning to shed light on this peculiarly massive quark. With 1-1.7 fb^{-1} of integrated luminosity collected by the CDF detector, we are able to probe our knowledge of the top quark physics, and to search for signals of physics beyond the Standard Model. In this paper, we present results of measurements of top quark properties, as well as tests for the production mechanism of the top quark. We also describe CDF latest searches for beyond Standard Model couplings of the top quark. Finally, we present the most recent searches for direct production of new particles in the collected data samples.

1 Introduction

The discovery of the top quark in 1995 [1, 2] completed the third generation of fundamental fermions in the quark sector of the Standard Model (SM). Its large mass, very close to the electroweak scale, results in a Yukawa coupling to the Higgs boson close to unity, suggesting a special role of the top quark in the electroweak symmetry breaking mechanism.

The CDF experiment studies proton-antiproton collisions produced at the Tevatron collider of Fermilab at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The particles produced in the interactions are reconstructed through the CDF detector [3]. At the energies reached by the Tevatron, the top quark is produced mainly in top-antitop pairs via strong interaction. The production cross section predicted by the Standard Model is 6.7 ± 0.8 pb for a top mass of 175 GeV/c^2. Due to its short lifetime, the top quark decays before hadronizing into a W boson and a bottom quark with a branching ratio of almost 100%. The observed final states can therefore be classified according to the successive W decays into leptons or quarks.

The analyzes presented in this paper are based on two distinct samples which amount to an integrated luminosity of about 1-1.7 fb^{-1} . The lepton plus jets sample is collected by requiring one electron or muon with transverse energy $E_T > 20$ GeV, at least four jets with $E_T > 20$ GeV, with at least one of them tagged as coming from a bottom quark hadronization, and missing transverse energy $\not{E}_T > 20$ GeV to account for the undetected neutrino from W decay. These requests are aimed to select events where one W boson decays into quarks and the other one decays into leptons. The dilepton sample is selected by requiring two leptons (electrons or muons) with transverse energy $E_T > 20$ GeV, two jets with $E_T > 15$ GeV and missing transverse energy $\not{E}_T > 25$ GeV. These requests are aimed to select events where both W bosons decay leptonically. The $t\bar{t}$ production cross section has been measured in both samples with different techniques [4, 5]. Good agreement with SM prediction is observed. Sample composition is well understood, allowing for detailed searches for new phenomena.

This paper is organized as follow. In sec.2, we present the results of the measurements of some properties of the top quark and we discuss their implication in the SM. Sec.3 is dedicated to the investigation of the production mechanism of the top quark, while sec.4 describes the searches for beyond SM couplings of the top quark. Finally, in sec.5 we present the results of direct searches for exotic particles production in the top samples.

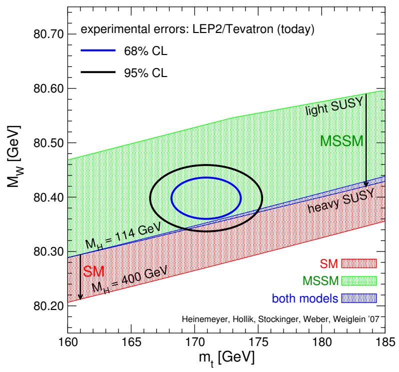

Figure 1: *SM and MSSM Higgs boson mass constraints in the m_t-M_W plane.*

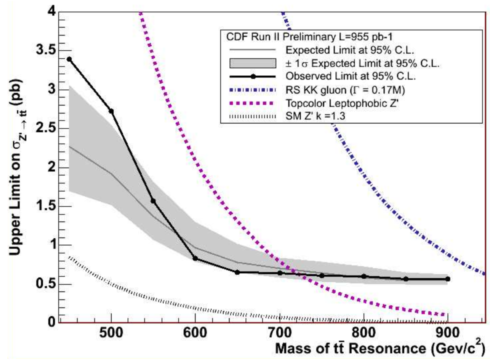

Figure 2: *Upper limits on the production cross section for $Z' \to t\bar{t}$ as a function of the Z' mass.*

2 Top Quark Properties

2.1 Top Quark Mass

The measurement of the top quark mass is a main goal for the Tevatron Run II. It requires to face several challenges such as a full final state reconstruction and a precise measurement of the energies of the jets and of the undetected neutrinos. A big effort has been put by the CDF collaboration to address these issues in the last years, finally leading to the best world measurement of the top mass, $m_t = 172.7 \pm 2.1$ GeV/c^2 [6]. Even without including this result, the most recent Tevatron combination reaches a precision of about 1% on the top mass, $m_t = 170.9 \pm 1.8$ GeV/c^2 [7]. Such a precise measurement of the top mass allows to constrain the mass of the Higgs boson through the radiative corrections to the mass of the W boson. Results are shown in fig.1 both for Standard Model and Minimal Supersymmetric Standard Model. Finally, the fit to electroweak parameter measurements tells us that the mass of the SM Higgs boson is lower than 144 GeV/c^2 at 95% CL.

2.2 Top Quark Charge

Fits to electroweak precision measurements seem to prefer a higher value for the top mass than measured. It has been suggested that the particle observed at CDF is not the top quark but a fourth generation quark with charge $Q = -4/3$.In order to test this hypothesis, the charge of the observed particle has been reconstructed by looking to its decay products $t \to Wb$. By requiring the W boson to decay leptonically, we can directly measure its charge through the charge of the electron or muon. Indirect information on the charge of the b quark can be extracted from the charged tracks inside its hadronic jet. The observed charge distribution has been tested versus both $Q = +2/3$ ans $Q = -4/3$ hypotheses. Data are consistent with SM top hypothesis and allows to exclude the exotic quark at 87% CL [8].

2.3 Top Quark Width

The lifetime of the top quark in the SM is extremely short, $\tau_t \sim 4 \times 10^{-25}$ s. We can test this prediction by measuring the width Γ_t of the top quark by means of a template fit to the observed top mass spectrum, which is sensitive to the top width. By comparing the fitted value of top width to results from simulated experiments, we set an upper limit on the top quark width $\Gamma_t < 12.7$ GeV, which results on a lower limit on its lifetime $\tau_t > 5.2 \times 10^{-26}$ s [9].

3 Top Production Mechanism

3.1 Fraction of $t\bar{t}$ Events from Gluon Fusion

Top quark pairs in $p\bar{p}$ collisions at the energy reached at the Tevatron are expected to be produced from quark annihilation (85%) and gluon fusion (15%).A measurement of the fraction of $t\bar{t}$ events from gluon fusion can provide a test of perturbative QCD and reveal new mechanisms of production and decay of the top quark.

The CDF experiment measured the fraction $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$ by using two different approaches. The first measurement relies on the fact that gluons tends to radiate gluons carrying a lower fraction of momentum of the initial parton with respect to quarks, leading to a higher number of tracks with low transverse momentum for $gg \to t\bar{t}$ events than for $q\bar{q} \to t\bar{t}$ production. The correlation between the average low p_T track multiplicity and the mean number of gluons is calibrated in control samples with different content of gluons, and used to build generic templates of low p_T track multiplicity for no-gluon and gluon-rich hypotheses. Fitting the track multiplicity observed in the top samples by these templates, CDF found $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t}) = 0.07 \pm 0.16$ [10].

The second measurement exploits the correlation in the spins of top and antitop, which tends to have the same sign in gluon fusion production and opposite sign in $q\bar{q}$ annihilation events. A neural network is used to discriminate different production processes. Information on the spin correlation is introduced by feeding the network with six angles between the products of the top decays. Data distribution is fitted to the neural network output shapes for simulated $t\bar{t}^{gg}$ and $t\bar{t}^{q\bar{q}}$ events, allowing to set an upper limit on the fraction of $t\bar{t}$ events from gluon fusion of $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t}) < 0.33$ at 68% CL [11].

3.2 Forward-Backward Asymmetry

A forward-backward asymmetry in $t\bar{t}$ production can arise from interference in the production diagrams. In the SM, it is computed to be within 4-6% at NLO. The CDF collaboration measured the related charge asymmetry, which is defined as the difference between the top and antitop rapidities and can be measured in the lepton plus jets sample as the rapidity difference between the leptonically and the hadronically decaying tops multiplied by the charge of the electron or muon from W boson decay. The measured asymmetry is $A_{\Delta Y * Q} = 28 \pm 13(\text{stat}) \pm 5(\text{syst})\%$ [12], in agreement with SM NLO prediction.

4 Non-Standard Model Top Couplings

4.1 Right-Handed Weak Coupling

The SM only admits a V-A weak coupling of the top quark to the W boson. This prediction can be tested by measuring the W boson helicity in top decays: in the limit $m_b \to 0$, the b quark has left-handed polarization, forcing the W boson to assume longitudinal (70%) or left-handed (30%) polarization, while the right-handed polarization results to be forbidden.

The helicity of the W boson in top decays is measured in the lepton plus jets sample through the angle θ^* between the charged lepton and the reconstructed top quark in the rest frame of the leptonically decaying W boson. The generic form of the differential cross section can be written as

$$\frac{d\sigma}{d\,\cos\theta^*} \sim f^- \frac{3}{8}(1 - \cos\theta^*)^2 + f^0 \frac{3}{4}(1 - \cos^2\theta^*) + f^+ \frac{3}{8}(1 + \cos\theta^*)^2, \quad (1)$$

where f^0, f^- and f^+ are the fraction of longitudinal, left-handed and right-handed polarized W bosons respectively. Two different fits of the observed $rmcos\theta^*$ distribution have been performed: a binned fit to the theoretical shapes corrected for efficiency and resolution effects, and an unbinned one to templates derived by Monte Carlo simulations. The two approaches give consistent results, and the measured fractions of differently polarized W bosons are in agreement with SM prediction. In particular, when assuming $f^0 = 0.7$ as in the SM, upper limits on the fraction of right-handed polarized W bosons are set at $f^+ < 0.12$ and $f^+ < 0.07$ at 95% CL for the two fitting techniques respectively [13, 14]. Yet another measurement has been realized by looking at the invariant mass of the charged lepton-bottom quark system in leptonically decaying top quarks: $M_{lb} \approx \frac{1}{2}(m_t^2 - M_W^2)\cos\theta^*$. An upper limit of $f^+ < 0.09$ at 95% CL has been derived by this approach [15].

4.2 Flavor Changing Neutral Current

The flavor changing neutral current decay $t \to Zq$ is highly suppressed in the SM, but a number of exotic models allow for a branching ratio up to few percent. CDF has recently performed a search for the process $t\bar{t} \to ZqWb$, where the successive decays $Z \to l^+l^-$ and $W \to q'\bar{q}$ provide a clean signature and a larger branching fraction of events respectively. A kinematic fit was used to reconstruct the events, and the fit χ^2 was used to discriminate background and signal events. No excess over SM expectation has been observed, and an upper limit of $BR(t \to Zq) < 10.6\%$ at 95% CL has been set [16], improving the previous world best limit $BR(t \to Zq) < 13.7\%$ set at LEP.

5 Searches for New Particles

5.1 $t\bar{t}$ Resonances

Top pair resonant production has been searched for in the $t\bar{t}$ invariant mass spectrum. A narrow Z′ resonance ($\Gamma_{Z'} \sim 1.2\% M_{Z'}$) with no interference with the s-channel of top pair production has been used as signal model. No excess over SM prediction has been observed, and upper limits on the production cross section as a function of Z′ mass (see fig.2) have been set at 95% CL [17].

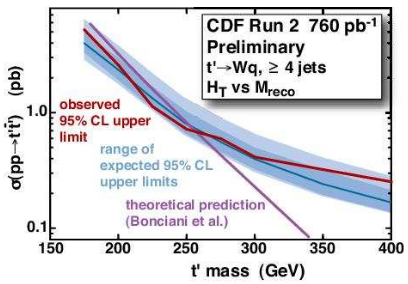

Figure 3: *Upper limits at 95% CL on the production rate for a massive t' quark as a function of the t' mass.*

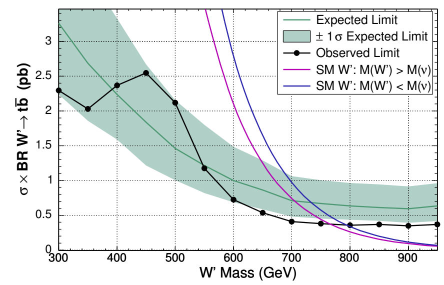

Figure 4: *Observed 95% CL upper limits on $\sigma(p\bar{p} \to W'X) \times BR(W' \to t\bar{b})$ as a function of W' mass.*

5.2 Search for Massive $t' \to Wb$

A fourth generation of heavy fermions with $M_Z < m_f < M_H$ is compatible with electroweak precision measurement. CDF searched for pair production of massive top-like quarks t′ decaying into a W boson and a quark by looking at two distinct experimental signature: the sum of the transverse energy of all the objects in the event final states, and the reconstructed mass of the candidate t′ quark. Fitting the data to two-dimensional templates for signal and background simulated events, a 95% CL lower limit on the t′ mass has been set at $m_{t'} > 256$ GeV/c^2 [18], as shown in fig.3.

5.3 Heavy W′ Production

A W-like heavy boson decaying into a top and a bottom quarks would mimic the signature of a single top production. CDF searched for a heavy W′ production $q\bar{q}' \to W' \to t\bar{b} \to Wb\bar{b}$ in a sample of events selected by requiring a high-p_T charged lepton, large missing transverse energy but only two jets. No evidence for a W′ boson has been observed in the reconstructed $M_{Wb\bar{b}}$ mass spectrum, and 95% CL upper limits on W′ production and its couplings to fermions have been set [19] (see fig.4).

6 Conclusions

The top quark samples collected by the CDF detector in 1-1.7 fb^{-1} of $p\bar{p}$ collision data at the Tevatron collider have been established and well understood.

Lot of precision measurements and first results in searches for new physics have been achieved. No deviation from SM predictions have been so far observed, but CDF begins to have sensitivity to unexpected top quark properties and new phenomena in its top quark samples.

References

1. F. Abe *et al* (CDF Collaboration), Phys. Rev. Lett. **74**, 2626 (1995).
2. S. Abachi *et al* (D0 Collaboration), Phys. Rev. Lett. **74**, 2632 (1995).
3. D. Acosta *et al* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
4. CDF Collaboration, CDF Public Note 8795, (2007).
5. CDF Collaboration, CDF Public Note 8802, (2007).
6. CDF Collaboration, CDF Public Note 9025, (2007).
7. CDF and D0 Collaboration, arXiv:hep-ex/0703034v1, (2007).
8. CDF Collaboration, CDF Public Note 8967, (2007).
9. CDF Collaboration, CDF Public Note 8953, (2007).
10. CDF Collaboration, CDF Public Note 8724, (2007).
11. CDF Collaboration, CDF Public Note 8811, (2007).
12. CDF Collaboration, CDF Public Note 8963, (2007).
13. CDF Collaboration, CDF Public Note 8938, (2007).
14. CDF Collaboration, CDF Public Note 8971, (2007).
15. A. Abulencia *et al* (CDF Collaboration), Phys. Rev. Lett. **98**, 072001 (2007).
16. CDF Collaboration, CDF Public Note 8888, (2007).
17. CDF Collaboration, CDF Public Note 8675, (2007).
18. CDF Collaboration, CDF Public Note 8495, (2007).
19. CDF Collaboration, CDF Public Note 8747, (2007).