Properties of the Top Quark

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Measurements of the properties of the top quark carried out by the CDF and DØ experiments at the Tevatron are reviewed. The core of the published results available at the time of this talk comes from measurements carried out in the first run (Run I) of the Tevatron at $\sqrt{s}$ =1.8 TeV. New preliminary measurements using larger datasets provided by the upgraded Tevatron (Run II at $\sqrt{s}$ =1.96 TeV) are also reviewed.

1. INTRODUCTION

Production of top quark pairs was first observed by the CDF and DØ experiments in $p\bar{p}$ collisions at $\sqrt{s}$ =1.8 TeV at the Tevatron [1]. The core of the published measurements on the properties of the top quark is still from the Run I at $\sqrt{s}$ =1.8 TeV and with datasets of $\sim$ 100 pb^{-1}. During the period 1996 till 2001 the Tevatron accelerator as well as the CDF and DØ experiments underwent major upgrades to increase the accelerator luminosity and center of mass energy (the Tevatron now operates at $\sqrt{s}$ =1.96 TeV with luminosities in the range $0.2 - 2 \cdot 10^{32}\text{cm}^2\text{s}^{-1}$) and to enhance the detector capabilities [2, 3]. At the time of this talk the only published result on the top quark from Run II concerns the top quark pair production cross sections [4]. Nevertheless many preliminary results from Run II have been shown at conferences and several publications are in preparation by both the CDF and DØ Collaborations. The results presented in this proceeding are therefore either published results from Run I or preliminary results from Run II.

The top quark is of particular interest because it is the fermion with the highest mass. In fact its mass is remarkably close to the electroweak scale and it has been speculated that the top quark could be related to the Electroweak Symmetry Breaking Mechanism. It is therefore important to measure the properties of the top quark, not only to characterize it but also to understand whether it is a simple part of the standard model or if it is the first sign of new physics beyond it. The Run II of the Tevatron is now providing much larger dataset and will allow for a series of presicion measurements of the properties of the top quark.

2. TOP QUARK PRODUCTION AT THE TEVATRON

In $p\bar{p}$ collisions at the center of mass energy of $\sqrt{s}$ =1.96 TeV the top quark is expected to be dominantly produced via the strong interaction (85% $q\bar{q}$ annihilation and 15% gluon fusion). The leading diagrams for top pair production are shown in Fig. 1. At the center of mass energy of Run I the $t\bar{t}$ production was even more dominated by the $q\bar{q}$ annihilation, with 90% of the cross section.

The top production cross section can be derived from first principles in QCD, from the mass of the top quark and parton distribution functions. Existing theoretical predictions for the top-antitop production cross section at $\sqrt{s}$ =2 TeV at NLO in QCD ranges from 6.7 to 7.5pb for a top quark mass of 175 GeV [5] with an expected uncertainty of $\sim$5%. This represents a $\sim$30% increase with respect to the cross section at $\sqrt{s}$=1.8 TeV. The precise measurement of the top-antitop production cross section is not only of interest as a test of QCD, but also to probe for new physics effects which can lead to deviations from the standard model prediction.

Within the standard model a single top quark can also be produced via the weak interaction. The leading diagrams for single top production are shown in Fig. 2. The standard model predicts a single top production cross section of $\sim$3pb [6] for a top quark mass of 175 GeV. This cross section is only about a factor two smaller than the top pair production but this production mode has not been observed yet. Single top production is more difficult to detect due to a much larger background from other standard model processes with a lepton and two jets in the final state.

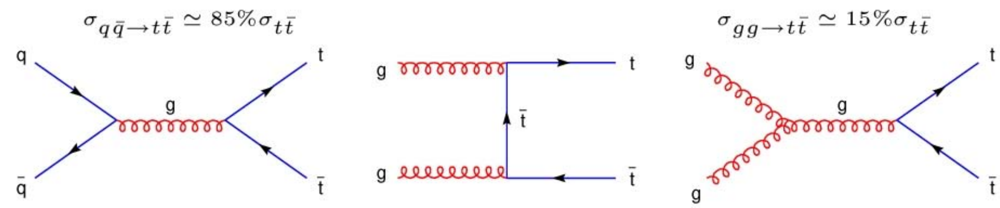

Figure 1: Leading diagrams for the production of a pair of top quarks at $\sqrt{s} = 1.96$ TeV.

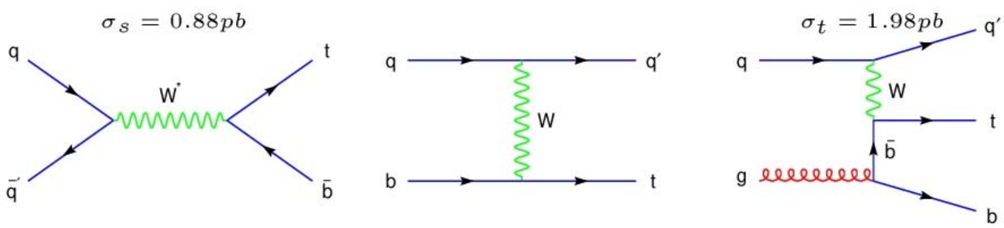

Figure 2: Leading diagrams for the production of a single top quark at $\sqrt{s} = 1.96$ TeV.

3. DECAYS OF THE TOP QUARK

Within the standard model the top quark is the Q=2/3, T_3=+1/2 member of a weak isospin doublet containing the bottom quark. The top quark decays therefore into a W boson and a down type quark. The coupling of the top quark to the different down type quarks is given by the CKM matrix. From existing experimental constraints on the CKM matrix [7] and assuming unitarity and 3 generations of quarks, the CKM matrix element $|V_{tb}|$ is constrained to be very close to unity. Therefore the top quark decays into Wb in nearly 100% of the cases while the CKM suppressed decays represent ∼0.1% for $t \to Ws$ and ∼0.01% for $t \to Wd$. The final states of a top-antitop ($t\bar{t}$) event are completely determined by the decay products of the two W-bosons from the two top decays and contains in addition two jets of hadronic particles arising from the hadronization of the two b-quarks (b-*jets*). The most common $t\bar{t}$ final state arises from the 2 W-bosons decaying hardronically, leading to a signature of 6 hadronic jets, at least 2 of which are b-jets. This final state is referred to as the "All jet" channel. One of the W-bosons can instead decay leptonically while the other decays hadronically, leading to a signature of one high p_T isolated lepton with missing transverse energy (from the leptonically decaying W) and 4 jets, at least two of which are b-jets. This channel is referred to as the "Lepton-plus-jets" channel. Finally both W-bosons can decay leptonically giving two high p_T isolated leptons, large missing transverse energy and two b-jets. These final states are referred to as the "Dilepton" channels. The various $t\bar{t}$ final states are summarized in Fig. 3.

4. PRODUCTION CROSS SECTION OF TOP QUARK PAIRS

A measurement of the top quark pair production cross section is interesting since it could be sensitive to physics beyond the standard model. First it represents a test of QCD, but deviations could also be observed if additional top quark pair production channels existed leading to higher than expected cross section. The top quark could also decay into exotic yet unobserved particles which in practice would lead to a lower than expected cross sections.

The CDF and DØ experiments have presented preliminary measurements of the $t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV using various techniques and final states [8]. The CDF experiment has published a first measurement of the $t\bar{t}$ production cross section using dilepton final states. Two techniques were used, one is based on the explicit reconstruction of the two leptons using calorimeter for electrons and muon spectrometer for muons and makes use of event topology variables to improve the signal to background. The second approach or "lepton-plus-track" analysis

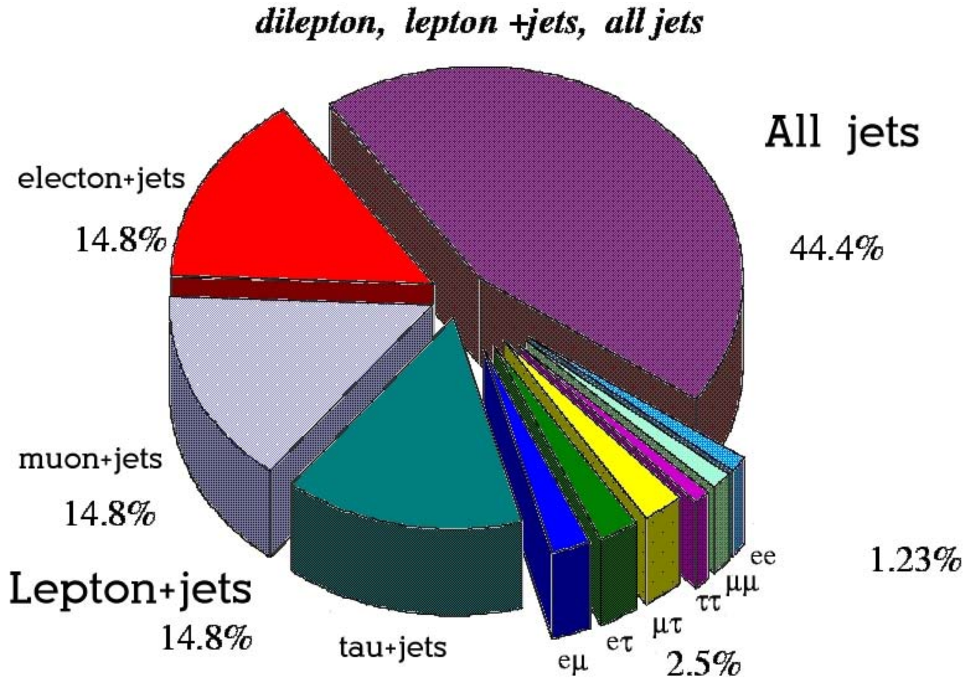

Figure 3: The top-antitop quark final states in the standard model. The definition of the "All jets", "Lepton-plus-jets" and "dilepton" are explained in the text.

requires only one explicitely reconstructed leptons (using the calorimeter or the muon system) while the other lepton is identified by a high p_T track in the tracking volume. The lepton-plus-track analysis is designed to have larger acceptance for tau leptons and thus gain in acceptance with respect to the explicit dilepton analysis. CDF combines both techniques on 191 pb^{-1} of data collected at Run II, which yields a cross section of $7.0^{+2.4}_{-2.1}(\text{stat})^{+1.6}_{-1.1}(\text{syst}) \pm 0.4(\text{lum})$ [pb]. The DØ collaboration has presented preliminary results of an explicit dilepton analysis also based on topological variables to improve the signal to background ratio (see summary in Fig. 4). Fig. 4 lists a number of preliminary results available to date. In general the analysis in the lepton-plus-jets final states provides the most accurate measurements thanks to large statistics compared to dilepton based analyses, and thanks to a better signal to background ratio compared to the All-jet analysis, which suffers from a large multijet background. In the Lepton-plus-jet channel the dominating background is the production of W-bosons in association with several jets. Two techniques are used to select top-antitop events and remove this background: topological variables sensitive to the presence of the decay of heavy objects such as top, these are topological analyses. A second class of analyses relies on the explicit identification of b-jets or *b-tagging* using lifetime tagging to suppress the backgrounds. This seems to be a promising approach for a precise measurement of the $t\bar{t}$ cross section and provides the best signal to background while keeping good signal efficiency. With datasets beyond 200 pb^{-1} and using b-tagging on the Lepton-plus-jets final states it is expected that the uncertainty on the cross section will be dominated by systematics. A summary of measurements of top production cross sections in various final states with the CDF and DØ experiments is shown in Fig. 4.

5. MEASUREMENT OF B($\mathrm{t} \rightarrow \mathrm{Wb}$)/ B($\mathrm{t} \rightarrow \mathrm{Wq}$)

The standard model predicts that the top quark decays in nearly 100% of the cases to a W boson and a b-quark. This prediction can be checked by measuring the ratio of branching fractions B$(t \rightarrow Wb)$/ B$(t \rightarrow Wq)$ in data. This measurement requires the experimental capability to distinguish between hadronic jets initiated by light quarks (s and d) and by b quarks i.e. b-jets. If the b-tagging efficiency is known then the fractions of $t\bar{t}$ events with 0, 1 or

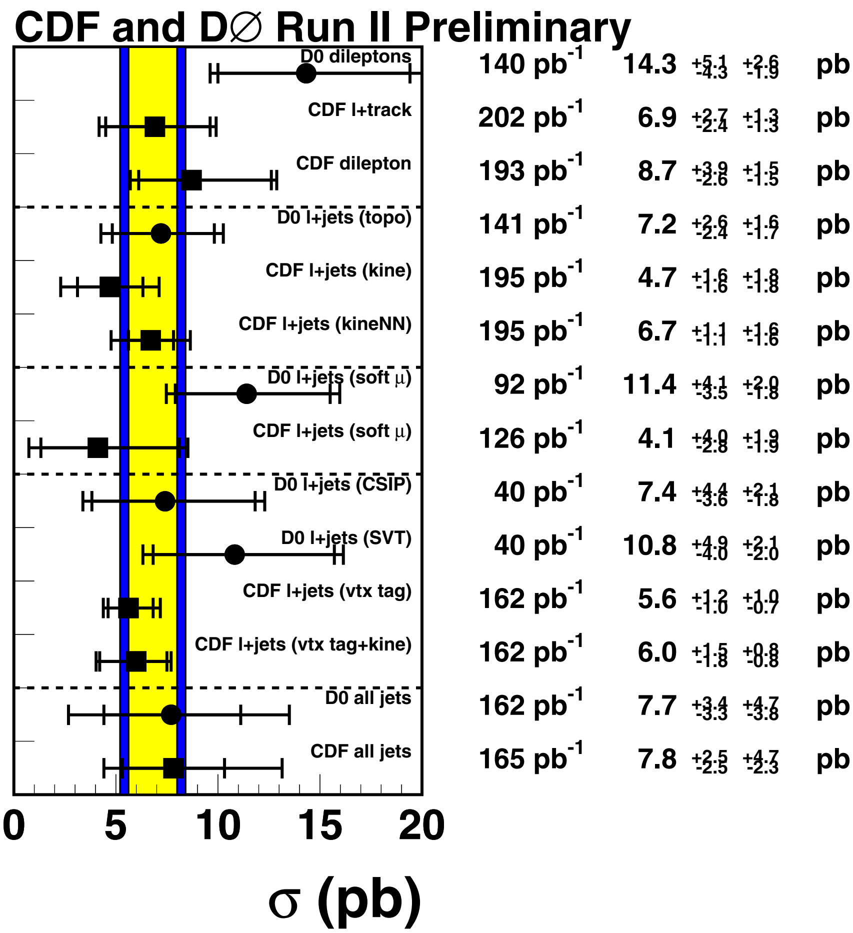

Figure 4: Summary of recent measurements of the $t\bar{t}$ production cross section at $\sqrt{s}$ =1.96 TeV with the CDF and DØ experiments in various final $t\bar{t}$ states.

2 tagged b-jets allow constrain the ratio $\mathrm{B}(t \to Wb)/\ \mathrm{B}(t \to Wq)$. The most accurate measurement of this ratio was performed by the CDF experiment using 109 pb^{-1} of data from the Run I of Tevatron and yields $\mathrm{B}(t \to Wb)/\ \mathrm{B}(t \to Wq) = 0.94^{+0.31}_{-0.24}(stat + syst)$ [9]. To maximize the statistical power this measurement combined both lepton-plus-jets and dilepton final states and used both a displaced vertex tagger and a soft muon tagger to identify b-jets. Assuming unitarity of the CKM matrix this measurement was translated into a measurement of the CKM matrix element $|V_{tb}| = 0.97^{+0.16}_{-0.12}$. A preliminary measurement from CDF using 108 pb^{-1} of Run II data gives $\mathrm{B}(t \to Wb)/\ \mathrm{B}(t \to Wq) = 0.54^{+0.49}_{-0.39}$. In this measurement the number of $t\bar{t}$ events in the untagged sample is determined with a neural network. This number is used as an additional constraint in the determination of $\mathrm{B}(t \to Wb)/\ \mathrm{B}(t \to Wq)$.

6. NON-W TOP QUARK DECAYS

Top pair production cross-section measurements always assume that the top quark decays with standard model branching fractions, i.e. a W boson is always present in the decay. The cross section is thus derived by assuming the branching ratios of Fig. 3. If this assumption is correct, the cross section measured in the dilepton ($\sigma_{\ell\ell}$) and in the lepton-plus-jet channels should be identical. In the standard model R_σ (defined as $\sigma_{\ell\ell}/\sigma_{\ell j}$) is thus constrained to unity. The parameter R_σ can be used to extract limits on non-standard branching fractions of top. In taking the

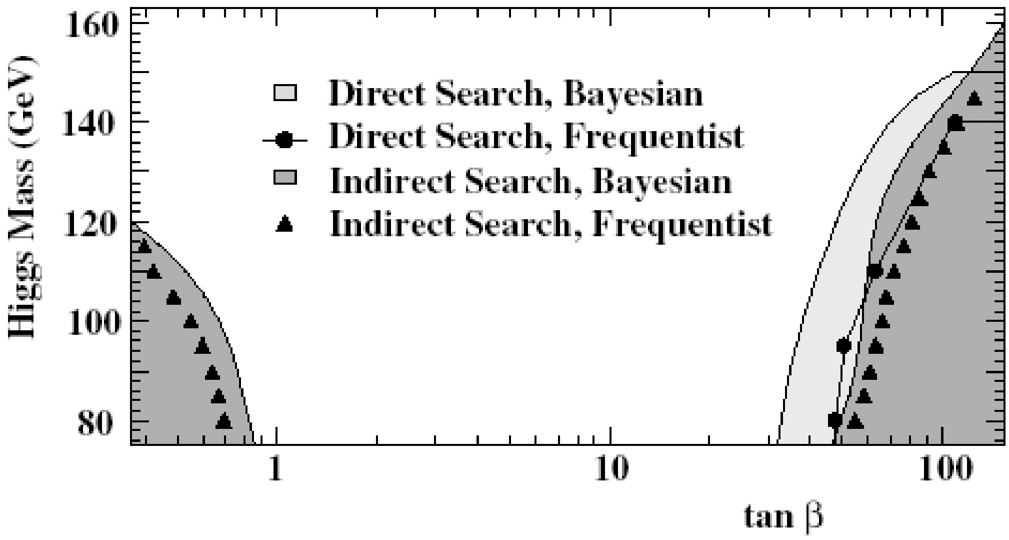

Figure 5: The region of exclusions at 95% C.L. in the ($\tan\beta$, $m_{H^\pm}$) plane for m_{top}= 175 GeV and $\sigma_{t\bar{t}}$=5.5 pb obtained with the data collected by the DØ experiment in Run I [13].

ratio of the cross sections in the dilepton to the lepton-plus-jet channels a number of correlated systematics can be made to cancel out. Such an analysis is performed by the CDF collaboration using 125 pb^{-1} of Run II data and yields a preliminary result of $R_\sigma = 1.45^{+0.83}_{-0.55}$, in agreement with the standard model.

7. FINAL STATES WITH TAU LEPTONS

Many extensions of the standard model include a Higgs sector with two Higgs doublets, resulting in the existence of charged (H$^\pm$) as well as neutral (h, H^0, A) Higgs bosons. The simplest extensions are the Two-Higgs Doublet Models (2HDMs) [10] in which the extension consists only of the extra doublet. Another potential extension of the standard model is the Minimal Supersymmetric Standard Model (MSSM) which also includes a Higgs doublet [11]. If the charged Higgs boson is lighter than the top quark (i.e. $m_{H^\pm} < m_{top} - m_b$), the decay $t \to H^+ b$ will compete with the standard model decay $t \to W^+ b$. In a 2HDM and in the MSSM the branching ratio for $t \to H^+ b$ depends on the charged Higgs mass and $\tan\beta$, the ratio of the vacuum expectation values for the two Higgs doublets. For $\tan\beta \lesssim 1$ or $\tan\beta \gtrsim 70$ the process $t \to H^+ b$ becomes in fact the dominant top decay. For $\tan\beta > 1$ the decay $H^+ \to \tau\nu$ dominates. Thus a 2HDM could manifest itself by an excess of top-antitop events with a tau lepton in the final state.

7.1. Search for Charged Higgs in Top Decays

Both the CDF and the DØ experiments searched for charged Higgs in top decays using Run I data. Two strategies are possible. An indirect search can be performed by using cross section measurements in final states other than containing tau leptons. If for instance a fraction of the top quarks were decaying into a charged Higgs boson, in turn decaying into $\tau\nu$, the efficiency of the event selections of the standard cross section analysis would be much lower for this unexpected decay. This would lead in practice to a lower than expected cross section, due to the disappearance of a fraction of top quarks into unexpected final states. Such searches were carried out at CDF and DØ in Run I [12].

The best sensitivity to charged Higgs is nevertheless obtained by directly searching for $t\bar{t}$ final states containing explicitly identified tau leptons. Such direct searches were carried out by CDF and DØ with the Run I datasets [13]. These analyses allowed to place new constrains on the allowed 2HDMs parameter space. Fig. 5 shows the limit put

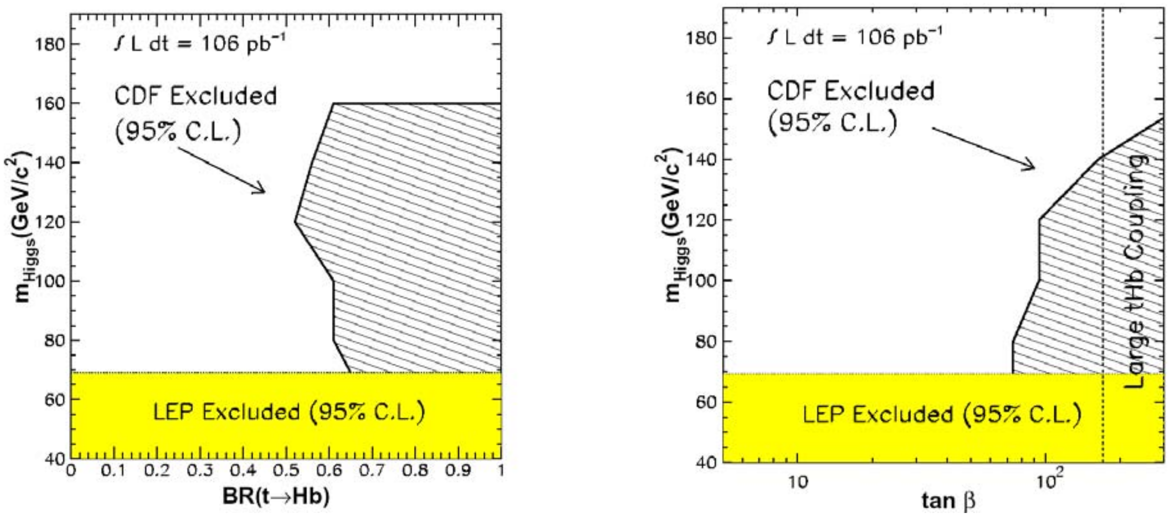

Figure 6: Left: The region excluded at 95% C.L. for charged Higgs production versus the branching ratio for the top decay into H^+b [13]. Right: Excluded regions (95% C.L.) at different values of $\tan\beta$ for charged Higgs production, at lowest order in the MSSM. The coupling $tbH^{\pm}$ may become non-pertubative at large values of $\tan\beta$, and the limit does not apply.

by the DØ experiment from direct and indirect searches using Run I data in the ($\tan\beta$, $m_{H^{\pm}}$) plane. The results from the CDF experiment are displayed in Fig. 6.

7.2. Measurement of B($\mathrm{t} \rightarrow \mathrm{b}\tau\nu$) / $\mathrm{B_{SM}}$($\mathrm{t} \rightarrow \mathrm{b}\tau\nu$)

Using Run II data the CDF experiment has looked for $t\bar{t}$ events where one W-bosons decays leptonically into an electron or a muon and a neutrino and the second W-boson decays into a τ and a neutrino. Only hadronic tau decays were considered since taus decaying into electrons and muons are difficult to differentiate from prompt leptons. The signature of this channel is defined by two b-jets, one high momentum isolated lepton (electron or muon), high missing transverse energy and a hadronic tau lepton. The observed rate is compared to the standard model prediction. The ratio between the observed rate and the standard model prediction $\mathrm{B(t \rightarrow b\tau\nu)/B_{SM}(t \rightarrow b\tau\nu)}$ is noted r_τ. The analysis of 193.5 pb^{-1} of data collected at Run II with the CDF experiment yields r_τ <5.0 at 95% C.L. A display of a candidate event is shown in Fig. 7.

8. RARE DECAYS

The standard model predicts very small rates (below 10^{-10}) for Flavor Changing Neutral Current (FCNC) decays of the top quark such as $t \rightarrow qZ$ and $t \rightarrow q\gamma$ [14] as shown in Fig. 8. Since these processes are so highly suppressed any observation would be clear evidence of new physics. Scenarios beyond the standard model such as supersymmetry, 2HDM or heavy fermions offer mechanisms through which this branching ratios could be raised.

The CDF experiment performed a search for such decays with 110 pb^{-1} of data collected during Run I. The analysis is performed by assuming that in a $t\bar{t}$ event one of the top quark decays via the standard process $t \rightarrow W^+b$, while the second top quark decays via FCNC interaction.

A signal from $t \rightarrow q\gamma$ is searched for in two different ways. The first approach is to consider events in which the W boson decays leptonically giving a final state characterized by large missing transverse energy, a high p_T isolated lepton from the W leptonic decay, a high energy photon and 2 b-jets. The main background for this process arises from $W + \gamma$ + 2 jet production. The background is estimated using the theoretical ratio between the rates of $W + \gamma$

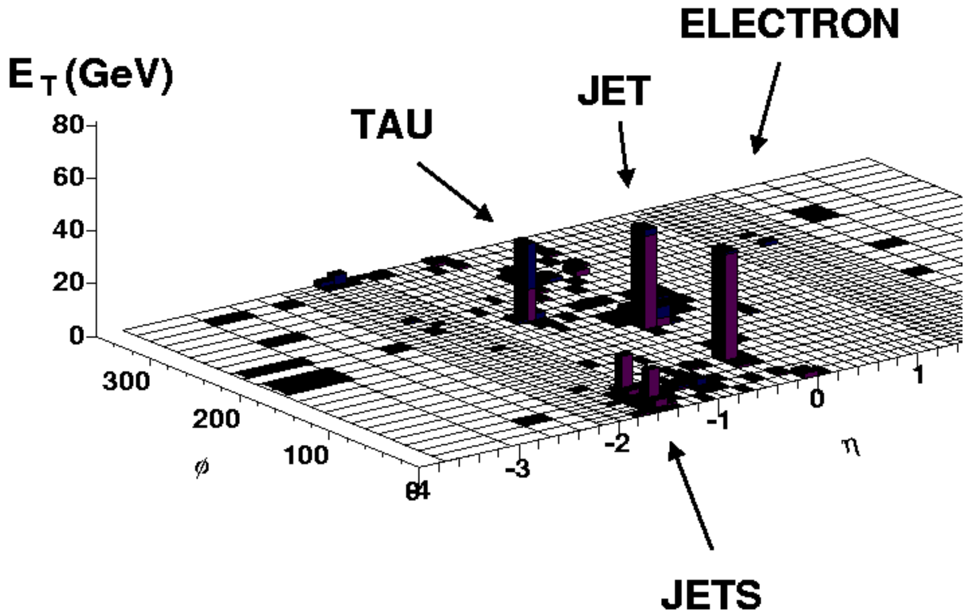

Figure 7: An event display of a $t\bar{t} \rightarrow \tau e$ event candidate. The event contains explicitly identified electron and tau leptons together with two jets. The x- and y- axis represent the $\eta \times \phi$ coordinates while the z- axis shows the energy of the reconstructed objects.

+ 2 jet and $W + \gamma$ events and is combined with the observed rate of $W + \gamma$ events in data. One event is observed in this channel, also consistent with $t\bar{t} \rightarrow W^+ b W^- \bar{b}\gamma$.

The second approach to the $t \rightarrow q\gamma$ channel is to look for events in which the W boson decays hadronically. Here the signature is 4 jets and a high momentum photon. To improve background rejection at least on b-tagged jet is required, the photon must have at least 50 GeV and the event must contain at least one jet-photon combination whose invariant mass is consistent with the mass of the top quark. The background is determined by counting the number of events with the same selections but without the b-tagging requirement and by applying a probability to tag a light jet. The estimated background is about 0.5 events and no event passes these selections.

The $t \rightarrow qZ$ process is searched for in events where the standard model decaying top quark proceeds to a hadronically decaying W. Both ee and $\mu\mu$ final states of the Z boson are considered. The signature is thus 2 high p_T isolated leptons with identical flavor, opposite charges and with an invariant mass consistent with the mass of the Z and 4 jets. The main backgrounds are Z production in association with jets, standard $t\bar{t}$ with dilepton final states and diboson production. The total background is expected to be 1.2 events. One event is observed in data with kinematics consistent with Z plus jet production.

In this analysis CDF could place the following limits on these processes: B$(t \rightarrow q\gamma) < 3.5\%$ and B$(t \rightarrow qZ) < 33\%$ at 95% C.L [15]. It should be noted that LEP experiments were able to place a better limit on B$(t \rightarrow qZ)$ [16].

9. W-HELICITY IN TOP DECAYS

An important consequence of a heavy top quark is that, to good approximation, it decays as a free quark. Its expected lifetime is approximately 0.5×10^{-24} s. This implies that it decays about an order of magnitude faster than the time needed to hadronize. Consequently, the spin information carried by top quarks is expected to be passed directly on to their decay products, so that top quark decays provide a probe for the underlying dynamics, with

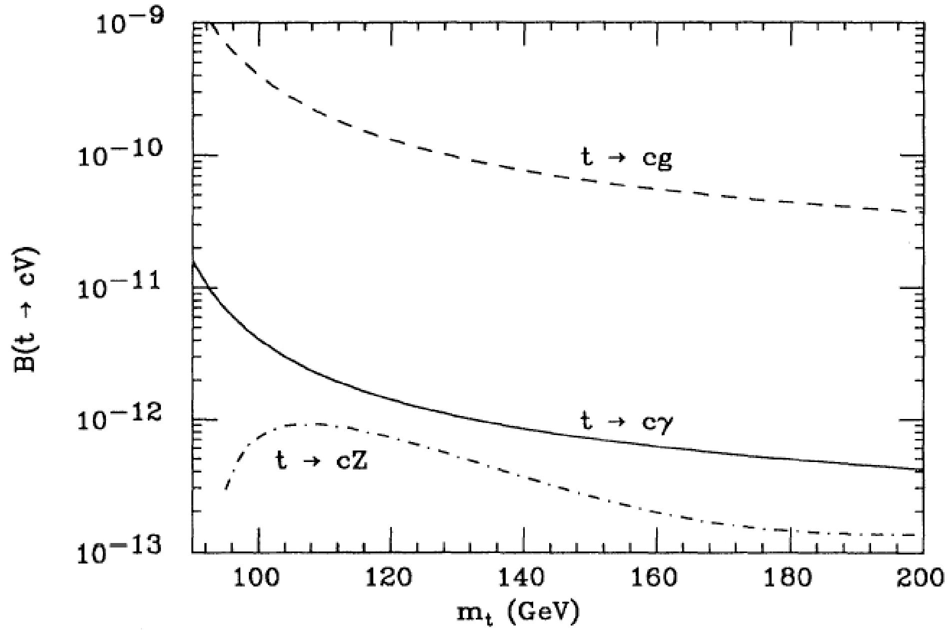

Figure 8: The branching ratio of the process $t \rightarrow cV$ as function of the top mass m_t, where $V = g$, γ or Z. Extracted from [14].

minimal impact from gluon radiation and binding effects of QCD. The standard top quark decays through a V-A charged-current weak interaction. The emitted b-quark can be considered as essentially massless compared to the top quark. To conserve angular momentum, the spin of the b-quark, with its dominantly negative helicity can therefore either point opposite or along the spin of the top quark (see Fig. 9 a and b). In the first case the spin of the b-quark points opposite to the top quark spin (Fig. 9 a) and the W boson must have negative helicity (i.e. its spin points opposite to the W momentum). If the spin of the b-quark points along the spin of the top quark (Fig. 9 b) the spin projection of the vector W boson must vanish (the W must be longitudinally polarized, or has zero helicity). Hence for massless b-quarks, a top quark can only decay to a left-handed (W_-) or a longitudinally polarized (W_0) W boson. In the approximation that the mass of the b-quark is zero, the fraction of longitudinally polarized W bosons (F_0) is determined by

$$F_0 = \frac{m_{top}^2}{m_{top}^2 + 2M_W^2} = 0.70 \pm 0.01 \tag{1}$$

where M_W^2 is the mass of the W boson. Three techniques used to measure the fraction of longitudinally (F_0) and left-handed (F_-) polarized W bosons are briefly reviewed below.

9.1. W-Helicity and Angular Distributions

Both the CDF and DØ collaborations have shown preliminary measurements of the W helicity in top decays using this technique with the data collected in Run II. Both analyses consider only the lepton-plus-jets final states of $t\bar{t}$ events. The angle θ^* between the charged-lepton in the W rest frame and the W momentum in the top rest frame is sensitive to the helicity of the W boson. Fig. 11 shows the $\cos\theta^*$ distributions for the three helicity states. Templates of $\cos\theta^*$ for the background, for left-handed, right-handed and longitudinally polarized W bosons can be fitted to the distribution of $\cos\theta^*$ observed in data. Both CDF and DØ extract the signal templates from Monte Carlo using full detector simulation and for the three potential helicity states. The background in the lepton-plus-jets channel is dominated by W plus jets and has also a small component of multijet QCD production. The CDF analysis models

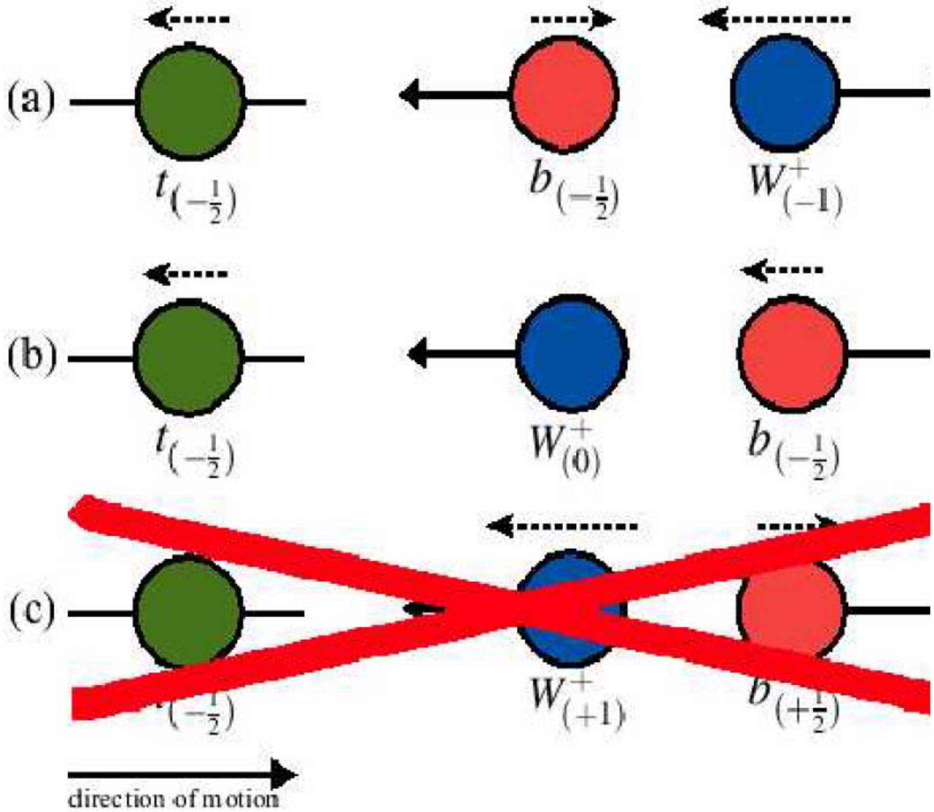

Figure 9: Helicity configurations in the $t \to Wb$ decay.

entirely the background using $Wb\bar{b}$ Monte Carlo while DØ uses a combination of W plus jet Monte Carlo and data to model the multijet QCD template.

The CDF result [17] with 162 pb^{-1} gives $F_0 = 0.89^{+0.30}_{-0.34}$(stat)±0.17(syst), consistent with the standard model expectation. The DØ result [18] obtained with 163 pb^{-1} concerns instead the fraction of right-handed W bosons and yields $F_+ < 0.207$ at 90% C.L. using a Bayesian analysis.

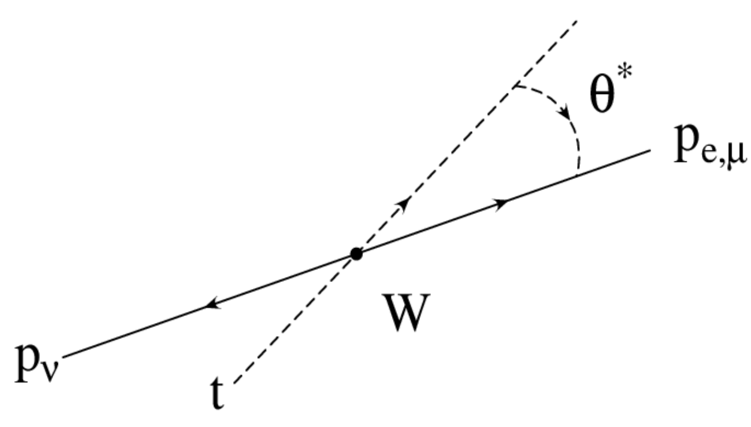

Figure 10: The W rest frame. θ^* is the angle between the charged-lepton momentum in the W rest frame and the W momentum in the top rest frame.

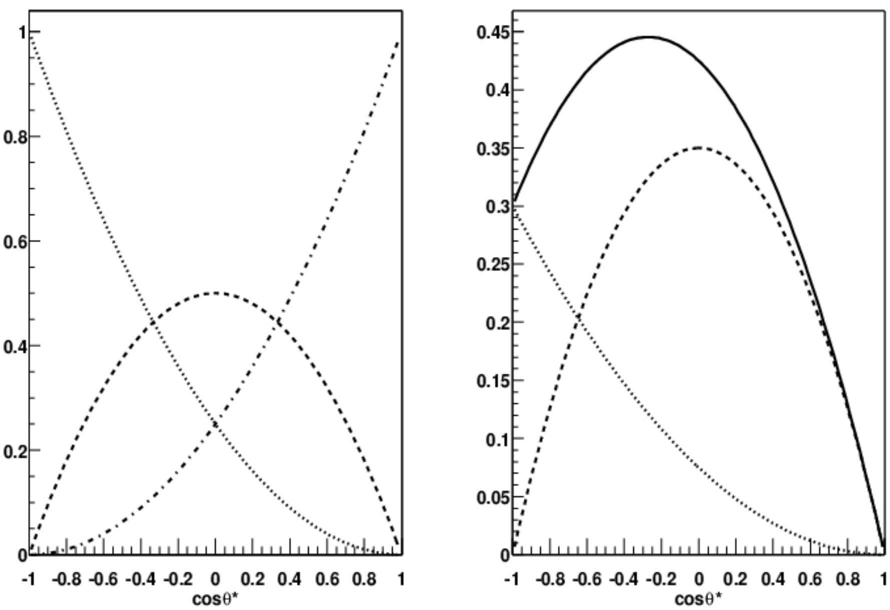

Figure 11: Left: The $\cos\theta^*$ distribution for left-handed W bosons (dotted line), longitudinal Ws (dashed line), and right-handed Ws (dash-dotted line). Right: The solid line indicates the standard model $\cos\theta^*$ distribution which is a combination of 70% longitudinal (dashed) and 30% left-handed (dotted) helicity Ws.

9.2. Lepton $\mathbf{p_T}$ Spectra and W-Helicity

The momentum of the lepton coming from the W decay is also sensitive to the helicity of the W boson. For left-handed W bosons the lepton is preferentially emitted antiparallel to the W boost, for right-handed W the lepton is preferentially emitted parallel to the W boost while for a longitudinally polarized W the lepton is preferentially emitted perpendicular to the W boost. This results in a harder lepton p_T spectrum in the case of a right-handed W boson than in the case of a longitudinal or a left-handed W boson. This feature has been used by the CDF experiment in both Run I and II to measure the W helicity in top decays.

The Run II preliminary measurement [19] uses both lepton-plus-jets and dilepton $t\bar{t}$ final states. Templates of the p_T of the lepton for the 3 helicity states are derived using Monte Carlo simulations and detailed detector simulations to reproduce detector effects. All background templates are similarly obtained from Monte Carlo, except for the QCD background in the lepton-plus-jets final state and the fake lepton backgrounds in the dilepton final state.

The templates for $t\bar{t}$ with the various helicity states for the W together with the template for the background are fitted to the lepton p_T spectrum observed in the data candidate sample. This allows to extract the fraction of each helicity state. With 200 pb^{-1} of data collected in Run II the CDF experiment has made a preliminary measurement of the fraction of longitudinally polarized W bosons. Fig. 12 shows the p_T distribution observed in the data together with a fit containing a left-handed and a longitudinal W component and the background component. The result of the fit gives $F_0 = 0.88^{+0.12}_{-0.47}$(stat+syst) in the lepton-plus-jet channel only, $F_0 < 0.52$ at 95% C.L. in the dilepton channel and $F_0 = 0.27^{+0.35}_{-0.21}$(stat+syst) for the combined analysis. The same analysis was carried out in Run I data at CDF with 106 pb^{-1} yielding a result consistent with standard model expectation [20].

9.3. W-Helicity using the Matrix Element Method

The helicity state of the W bosons in a $t\bar{t}$ event affects angular distributions and lepton momenta. To exploit all available information the DØ experiment has carried out an analysis of 125 pb^{-1} of Run I data using the matrix

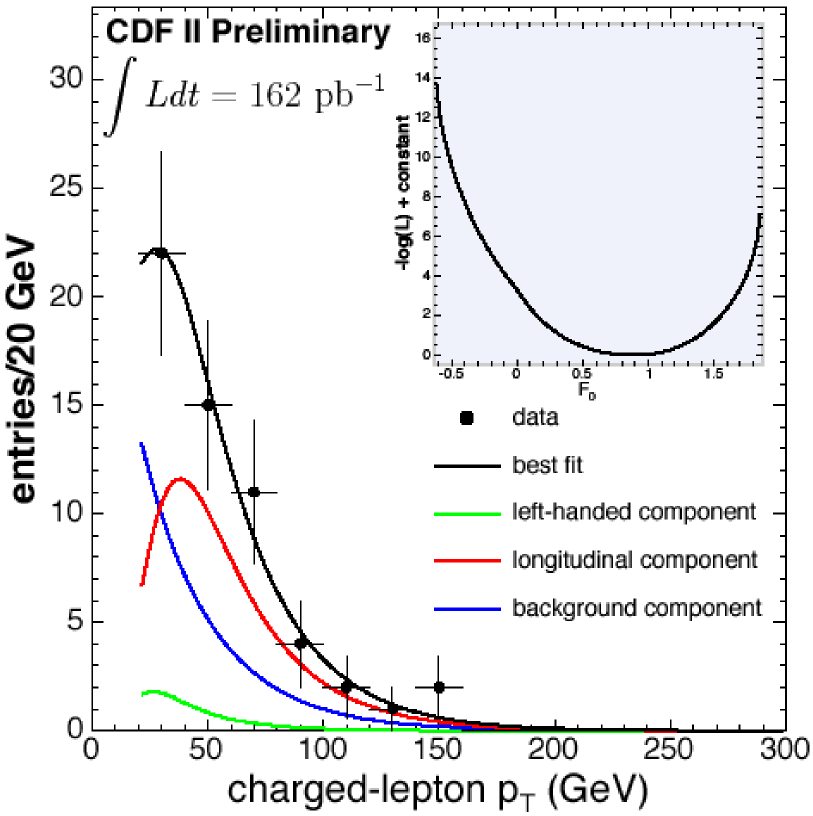

Figure 12: The distribution of charged-lepton p_T for the lepton-plus-jets and dilepton samples combined, overlaid with the maximum likelihood fit of the signal and background components. Inset is the projection of $-\log \mathcal{L}$ as function of F_0.

element method [21]. This method is based on the direct calculation of a probability that each event corresponds to a $t\bar{t}$ final state, as a function of the helicity of the W boson. The calculation of this probability is based on the LO matrix element of the transition from 2 partons to a $t\bar{t}$ final state. The matrix element is a function of the fraction F_0 of longitudinally polarized W bosons. The probability density for $t\bar{t}$ production and decay into the lepton-plus-jets final state, for a given value of F_0, is defined as:

$$P_{t\bar{t}}(F_0) = \frac{1}{12\sigma_{t\bar{t}}} \int \mathrm{d}\rho_1 \mathrm{dm}_1^2 \mathrm{dM}_1^2 \mathrm{dm}_2^2 \mathrm{dM}_2^2 \times \sum_{\mathrm{perm},\nu} |\mathcal{M}_{\mathrm{t\bar{t}}}(\mathrm{F_0})|^2 \frac{\mathrm{f(q_1)f(q_2)}}{|\mathrm{q_1}||\mathrm{q_2}|} \Phi_6 \mathrm{W_{jets}(E_p, E_j)} \tag{2}$$

where $\mathcal{M}_{t\bar{t}}$ is the leading-order matrix element, $f(q_1)$ and $f(q_2)$ are parton distribution functions for the incident quarks, Φ_6 is the phase space factor for the 6-object final state and the sum is over all twelve permutations of jets. The integration variables are the two top quark invariant masses ($m_{1,2}$), the W boson invariant masses ($M_{1,2}$), and the energy of one of the quarks from W decay (ρ_1). The function $W_{jets}(E_p, E_j)$ parametrises the mapping between parton-level energies E_p and jet energies measured in the detector E_j. In the electron-plus-jets channel the momenta of the electrons is assumed to correspond to the momenta of the produced electrons, while in the muon-plus-jets channel the function W is expanded to include the muon momentum resolution. Since most of the background is made up by W plus jet production the VECBOS matrix element for W+jets is used to build the probability density of the background. Figure 13 shows the resulting likelihood as function of the top mass and the fraction F_0 of longitudinally polarized W. This leads to F_0 =0.56±0.31(stat+syst), in agreement with the standard model. The same technique was used by the DØ experiment to determine the top mass with the data collected in Run I [22].

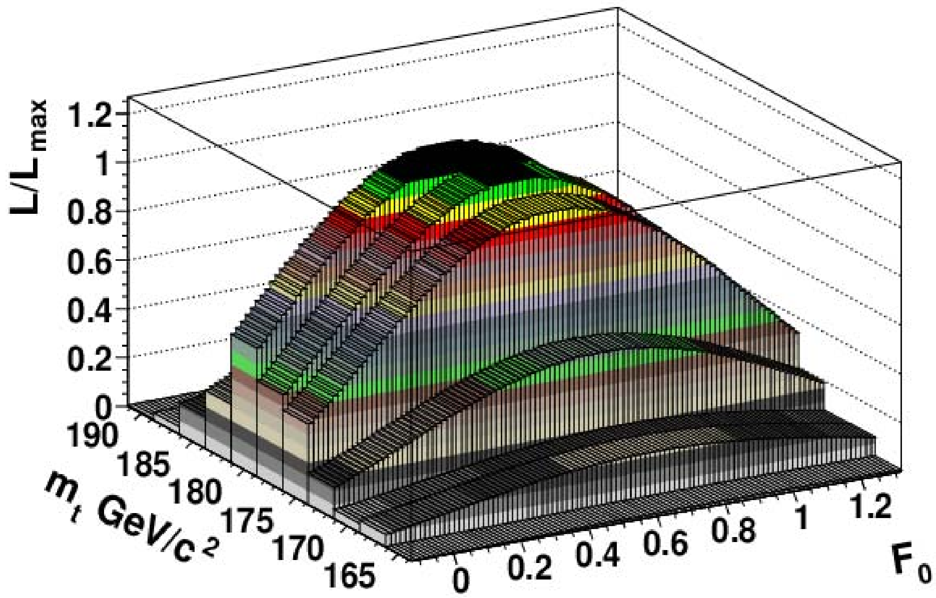

Figure 13: Likelihood distribution for the data and normalized to its maximum value as a function of the top mass and the fraction of longitudinally polarized Ws, F_0.

10. SPIN CORRELATIONS

As mentioned above the top quark decays before it is able to hadronize. For this reason any polarization information should be fully transmitted to the decay products of the top quark. The top quarks produced at the Tevatron are unpolarized but the top-antitop pair have correlated spins [23]. The observation of spin correlations in the decay products of the $t\bar{t}$ system are interesting for several reasons. First it provides a probe of a quark that is almost free of confinement effects and the observation of the correlation would be evidence that the top quark decays as a free quark. The observation of spin correlations would also provide a lower limit on the width of the top quark and on $|V_{tb}|$. Finally the spin correlation could be used to probe for non standard interactions in the weak decay of the top quark.

The DØ collaboration has looked for such correlations in the data collected in Run I. An optimal spin quantization basis called the "off diagonal" basis is introduced. In this basis the contributions from opposite spin projections for top quark pairs arising from $q\bar{q}$ annihilations are suppressed and only like-spin configurations survive. The top quarks produced from $q\bar{q}$ will thus have their spin fully aligned along this basis. To experimentally look for the correlation the DØ experiment uses dilepton final states of $t\bar{t}$. If θ^+ is the angle between one of the charged leptons and the axis of quantization in the rest frame of its parent top quark, and similarly θ^- for the other charged lepton, the spin correlation can be expressed in the following way:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta^+)d(\cos\theta^-)} = \frac{1+\kappa\cos\theta^+\cos\theta^-}{4} \tag{3}$$

where the degree of correlation between the leptons from the two top quarks is characterized by the correlation coefficient κ. At the Tevatron the standard model predicts a correlation coefficient κ =0.88. The DØ experiment used 125 pb^{-1} of data collected in Run I to place a lower limit on κ. In this analysis 6 $t\bar{t}$ events in the dilepton final state were used, leading to κ >-0.25 at 68% C.L [24].

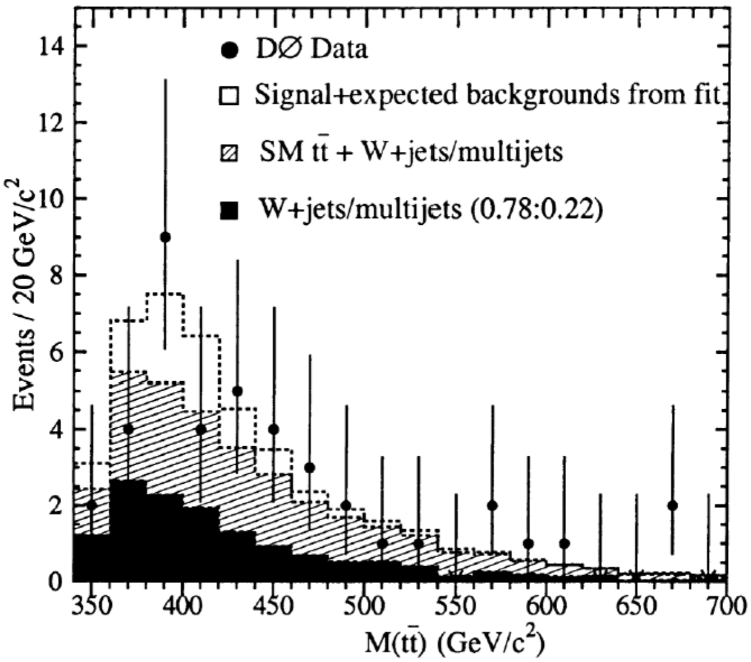

Figure 14: Invariant mass spectrum of the top-antitop pairs observed in data and the result of the fit to data with all standard model processes and the signal ($X \to t\bar{t}$) contribution, here for M_X =400 GeV.

11. SEARCH FOR TOP-ANTITOP RESONANCES

Narrow resonances decaying to $t\bar{t}$ are predicted by several theories beyond the standard model. Such a model could be for instance the top-color assisted technicolor model [25]. In practice such an extension of the standard model could lead to the presence of a heavy Z' boson decaying into $t\bar{t}$. The cross section for this process is potentially large for a range of mass and width of the heavy boson. The DØ experiment looked for such top antitop resonance using 130 pb^{-1} of the Run I data [26]. This analysis is performed by seeking an excess in the invariant mass spectrum (see Fig. 14) of the $t\bar{t}$ decay products and relies on $t\bar{t}$ final states with at least 4 jets, high missing transverse energy and a high p_T isolated lepton (e or μ).

DØ finds no significant excess with respect to the standard model and therefore uses this analysis to derive an upper limit on the cross section σ times branching fraction to $t\bar{t}$ (B) for the potential resonance. Fig. 15 shows the 95 % C.L. excluded region in the plane defined by the mass of the resonance M_X and the production cross section for such a resonance times its branching ratio into $t\bar{t}$ ($\sigma_X \times B$). Superimposed is shown the expected rate as a function of the mass of the particle X when X is a leptophobic top-color particle. With the assumption $\Gamma_X = 0.012 M_X$, a lower limit of 560 GeV at 95%C.L. on the mass of the top-color particle can be placed.

12. CONCLUSION

Many pioneering measurements of the properties of the top quark were carried out using the datasets from the Run I of Tevatron. Thanks to the Tevatron and the CDF and DØ Run II upgrades, much larger datasets are now available to make more precise measurements of the detailed top quark properties. A large number of preliminary results have already presented by the CDF and DØ collaborations. The field is today evolving very fast as new competitive results appear at each conference season. This opens a very interesting period for top physics especially since the top quark could well be related to physics beyond the standard model. Finally this talk did not cover all

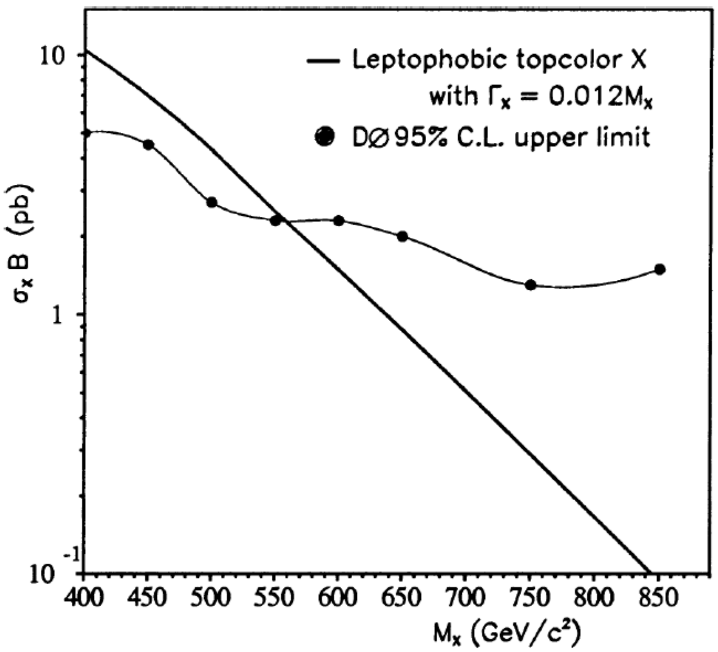

Figure 15: The 95% C.L. upper limit on $\sigma_X B$ as a function of the resonance mass M_X. The continuous non-dotted line shows the expectation for a top-color assisted techinicolor model.

properties of the top quark. Topics such as the top width or charge or searches for anomalous couplings were not covered, while measurement of the top mass was covered by another talk in the present proceedings [27].

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