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Top Quark Highlights

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Highlights of top quark physics presented at the 2009 Europhysics Conference on High Energy Physics from 16-22 July 2009 in Krakow, Poland, are reviewed.

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1. Introduction

At hadron colliders, top quarks can be produced in pairs via the strong interaction or singly via the electroweak interaction [1]. Top quarks were first observed via pair production at the Fermilab Tevatron Collider in 1995 [2]. Since then, pair production has been used to make precise measurements of several top quark properties, including the top quark mass [3].

This review gives an overview of current measurements of top quark cross sections, top quark properties and searches for new physics in the top sector at the Tevatron proton-antiproton collider at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV at Fermilab with datasets corresponding to an integrated luminosity of up to 3.6 fb^{-1}. It also presents one result from the HERA $e^{\pm}p$ collider at a center-of-mass energy of $\sqrt{s} = 319$ GeV using a dataset of 474 pb^{-1}. Prospects for top quark analyses in proton-proton scattering at the Large Hadron Collider (LHC) are discussed as well.

2. Top Quark Physics at the Tevatron

The Tevatron is still the only place where top quarks can be produced and studied directly. At the Tevatron, top quarks are either produced in pairs via the strong interaction or singly via the electroweak interaction. In the framework of the Standard Model (SM), each top quark is expected to decay nearly 100% of the times into a W boson and a b quark [3]. W bosons can decay hadronically into $q\bar{q}'$ pairs or leptonically into $e\nu_e$, $\mu\nu_\mu$ and $\tau\nu_\tau$ with the τ in turn decaying into an electron, a muon, or hadrons, and associated neutrinos.

In $t\bar{t}$ production, if both W bosons decay hadronically the final state is called all-hadronic (or all-jets) channel. If one of the W bosons decays hadronically while the other one produces a direct electron or muon or a secondary electron or muon from τ decay, the final state is referred to as the ℓ+jets channel. If both W bosons decay leptonically, this leads to a dilepton ($\ell\ell$) final state containing a pair of electrons, a pair of muons, or an electron and a muon, or a hadronically decaying tau accompanied either by an electron or a muon (the $\tau\ell$ channel).

2.1 Top Production Cross Sections

Exploring the top cross section in different decay channels and using different assumptions is important because signs of new physics might appear differently in the various channels.

2.1.1 Top Quark Pair Production

The top quark pair production cross section $\sigma_{t\bar{t}}$ is known to high accuracy in the Standard Model (SM) [4, 5, 6]. The measurement of the top quark pair production cross section therefore provides an important test of such higher order QCD calculations including soft gluon resummations. Any deviation from the SM prediction of the measured $t\bar{t}$ cross section could either be a hint for new physics in top pair production or in top quark decays. For example, an exotic decay of the top quark, such as the decay into a charged Higgs boson and a b quark ($t \to H^+b$) would lead to deviations of the measured $\sigma_{t\bar{t}}$ in individual final states compared to the SM prediction.

There are two different techniques to enhance the top pair signal over the background. In one method topological variables are used, in the other method the identification of jets originated from b quarks (b-tagging) is utilized.

For the ℓ+jets channel, the CDF collaboration developed a neural network technique to maximize the discriminating power from kinematic and topological variables using 2.8 fb^{-1} of data [7]. A fit to a neural network output constructed of those variables was performed. The sensitivity of the neural network technique is comparable to that for the traditional CDF secondary vertex b-tag method [8], which suppresses the dominant background from W+jets at a cost of a 45% loss in signal efficiency.

The $t\bar{t}$ cross section measurement using the topological method is dominated by systematic uncertainties. The largest source is the uncertainty on the luminosity determination which is 5.8%. In order to significantly reduce this uncertainty, the correlation between the luminosity measurements in two different processes can be exploited. Here the ratio of the $t\bar{t}$ and Z cross sections is used where the luminosity uncertainty almost entirely cancels out. Multiplying this ratio by the best theoretical calculation of the Z cross section, a $t\bar{t}$ cross section can be obtained. In effect, the luminosity uncertainty is replaced by the significantly smaller theoretical and experimental uncertainties on the Z cross section. The measured $t\bar{t}$ cross section is $\sigma_{t\bar{t}} = 6.9 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{sys}) \pm 0.1(\mathrm{theory})$ pb for a top quark mass of 175 GeV. The total uncertainty is 8%.

In the all-hadronic channel with 2.9 fb^{-1} of data collected with a multijet trigger, for example, b-tagging is used for the measurement of the $t\bar{t}$ cross section [9]. Using a dedicated neural network based kinematic selection, events with one or at least 2 b-tags are studied using templates for the reconstructed top quark mass simultaneously with an in situ measurement of the Jet Energy Scale (JES). The measured $t\bar{t}$ production cross section amounts to $\sigma_{t\bar{t}} = 7.2 \pm 0.5(\mathrm{stat}) \pm 1.1(\mathrm{syst}) \pm 0.4(\mathrm{lumi})$ pb for a top mass of 172.5 GeV.

Figure 1 summarizes the measurements of the $t\bar{t}$ cross section in different decay channels performed by the CDF and DØ Collaborations. All measurements agree with each other and agree with the SM predictions.

2.1.2 Single Top Quark Production

Single top quark production serves as a probe of the Wtb interaction [10], and its production cross section provides a direct measurement of the magnitude of the quark mixing matrix element V_{tb} without assuming three quark generations [11]. However, measuring the yield of single top quarks is difficult because of the small production rate and large backgrounds. At the Tevatron single top quarks are produced by either a t-channel exchange of a virtual W boson which combines with a highly energetic b quark to produce a top quark, or by an s-channel exchange of a far off-shell W boson which decays to produce a top quark and a b antiquark.

In March 2009, the CDF and DØ Collaborations reported observation of the electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV based on 3.2 fb^{-1} (CDF) [12] and 2.3 fb^{-1} (DØ) [13] of data. Both collaborations used events containing an isolated electron or muon and missing transverse energy, together with jets where one or two of the jets were required to originate from the fragmentation of b quarks.

CDF and DØ each combine many variables using different multivariate analysis methods such as Boosted Decision Trees, Neural Networks, Bayesian Neural Networks, Matrix Elements and Likelihood functions to increase the separation power between signal and background. The discriminant outputs of each multivariate analysis are combined to one discriminant taking the corre-

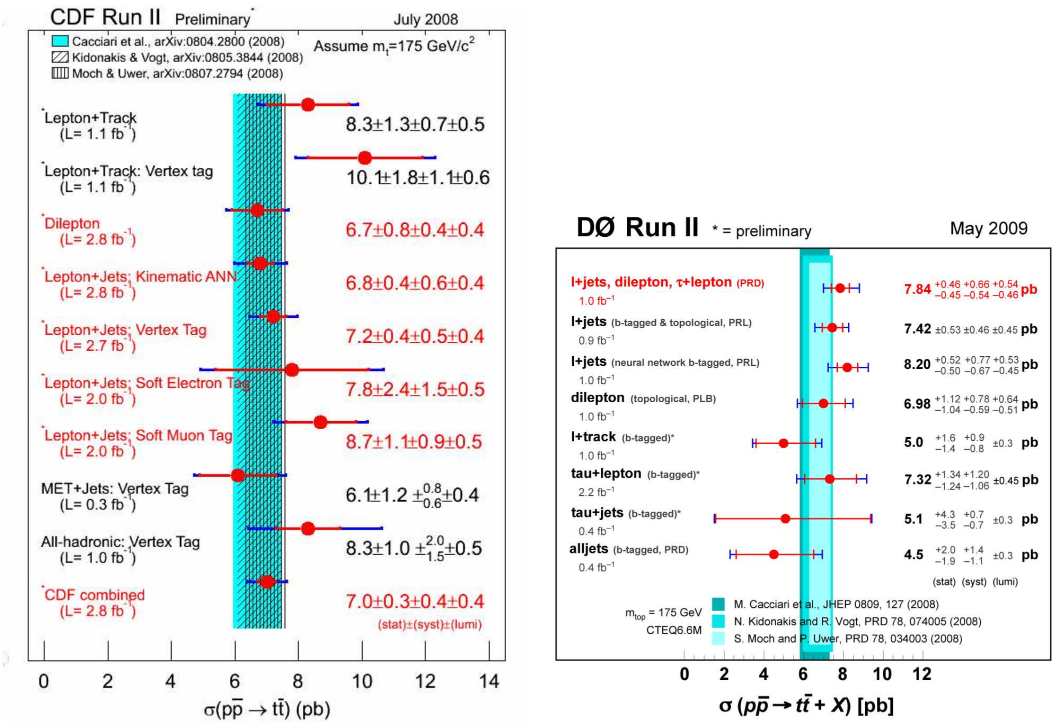

Figure 1: Summary of $t\bar{t}$ cross section measurements in different decay channels by the CDF (left) and the DØ Collaborations (right). The combination for each experiment is displayed, too.

lations into account. CDF combines 8 subchannels into a super-discriminant using a neural network trained with neuroevolution [14] which is shown in Fig. 2 (upper left). The CDF collaboration has an additional independent search channel [12, 15] that is designed to select events with missing transverse energy and jets and is orthogonal to the other channels. It accepts events in which the W boson decays into hadronically decaying τ leptons and recovers events lost due to electron or muon identification inefficiencies. The discriminant output of this analysis – shown in Fig. 2 (upper middle) – is combined to the super-discriminant to obtain the final result. DØ combines 12 subchannels into one BNN discriminant displayed in Fig. 2 (lower left).

CDF measures a cross section of $\sigma(p\bar{p} \rightarrow\ tb+X,\ tqb+X) = 2.3^{+0.6}_{-0.5}$ pb assuming a top quark mass of 175 GeV and DØ measures a cross section of $\sigma(p\bar{p} \rightarrow\ tb+X,\ tqb+X) = 3.94 \pm 0.88$ pb at a top quark mass of 170 GeV. Both measurements correspond to a 5.0 standard deviation (SD) significance for the observation. They are in agreement with the SM predictions. Both results are translated into a direct measurement of the amplitude of the CKM matrix element V_{tb} without making assumptions on the number of quark generations and the matrix unitarity. CDF obtains $|V_{tb}| = 0.91 \pm 0.13$, DØ derives $|V_{tb}| = 1.07 \pm 0.12$.

The DØ collaboration also reported direct evidence for the electroweak production of single top quarks through the t-channel exchange of a virtual W boson alone [16]. In the observation analyses the combined $s+t$ channel single top quark cross section was measured, assuming the SM ratio of the two production modes. This ratio is modified in several new physics scenarios, for example in models with additional quark generations, new heavy bosons, flavor-changing neutral

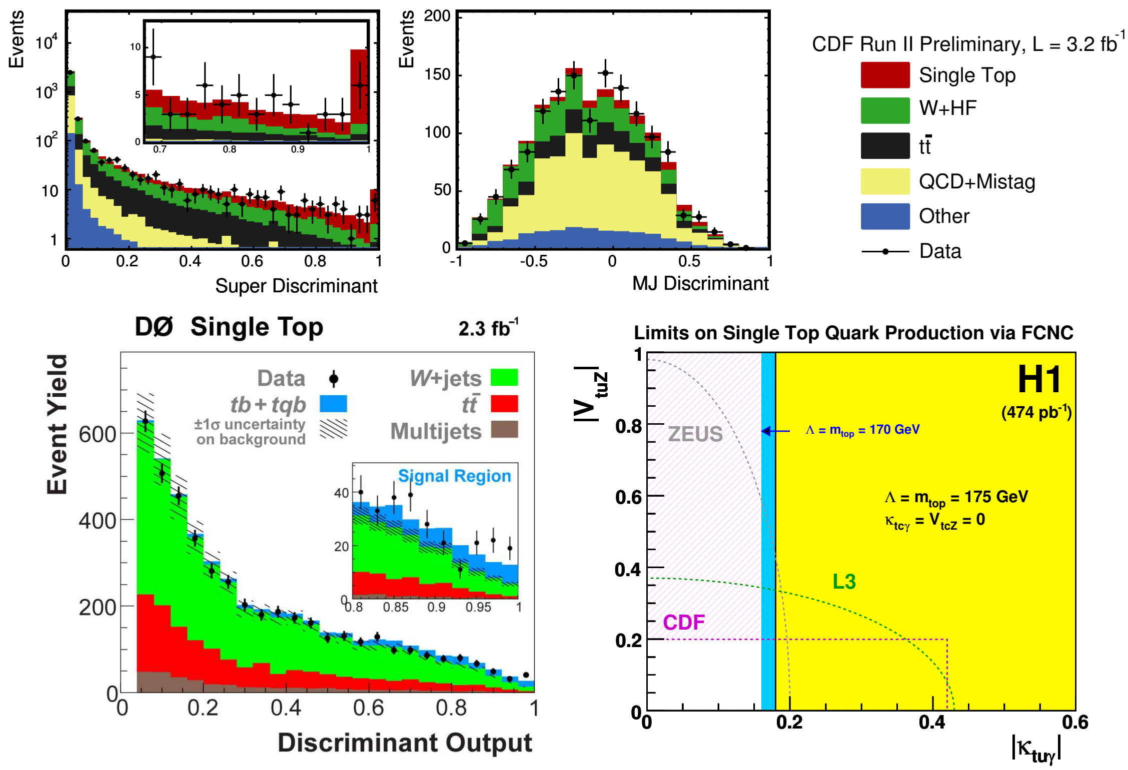

Figure 2: Output discriminants for single top quark observation. Displayed are the CDF super-discriminant output (upper left), the CDF discriminant output for the analysis using a missing transverse momentum and jets selection (upper middle) and the DØ BNN discriminant (lower left). The lower right plot shows upper limits at 95% CL on the anomalous $\kappa_{tu\gamma}$ and V_{tuZ} couplings obtained by the H1 Collaboration.

currents, or anomalous top quark couplings. Therefore it is interesting to remove this constraint and to use the t-channel characteristics to measure the t-channel and s-channel cross sections simultaneously which provides a t-channel measurement independent of the s-channel cross section model.

The measured cross section is $\sigma(t-\text{channel}) = 3.14^{+0.94}_{-0.81}$ pb, has a significance of 4.8 SD and is consistent with the SM prediction. This is the first analysis to isolate an individual single top quark production channel.

2.1.3 Single Top Production at HERA

In $e^{\pm}p$ collisions at HERA the production of single top quarks is kinematically possible due to the large center-of-mass energy of up to $\sqrt{s} = 319$ GeV. Within the SM the production of top quarks at HERA is however strongly suppressed. Therefore the observation of single top quark production would be a clear indication of new physics. In several extensions of the SM the top quark is predicted to undergo flavor changing neutral current (FCNC) interactions, which may lead to a sizeable top quark production cross section at HERA [17].

A search for single top quark production is performed using the full $e^{\pm}p$ data sample collected by the H1 experiment at HERA [18]. The data correspond to an integrated luminosity of 474 pb^{-1} including 36 pb^{-1} of data taken at $\sqrt{s} = 301$ GeV. Decays of top quarks into a b quark and a W

boson with subsequent leptonic or hadronic decay of the W are investigated. A multivariate analysis is performed to discriminate top quark production from SM background processes. An upper limit on the top quark production cross section via flavor changing neutral current processes $\sigma(ep \rightarrow etX) < 0.25$ pb is derived at 95% CL. Limits on the anomalous couplings $\kappa_{tu\gamma}$ and V_{tuZ} are derived for $m_t = 175$ GeV as depicted in Fig. 2 (lower right). The domain excluded by H1 is represented by the light shaded area. The dark shaded band shows the region additionally excluded if m_t is varied to 170 GeV. The hatched area corresponds to the domain excluded at the Tevatron by the CDF experiment ($\sqrt{s} = 1.96$ TeV, $\mathscr{L} = 1.9$ fb^{-1}) [19]. Also shown are limits obtained at the Large Electron Positron (LEP) Collider by the L3 experiment ($\sqrt{s} = 189 - 209$ GeV, $\mathscr{L} = 634$ pb^{-1}) [20] and at HERA by the ZEUS experiment($\sqrt{s} = 300 - 318$ GeV, $\mathscr{L} = 130.1$ pb^{-1}) [21]. This shows nicely the complementarity of the results obtained at different colliders.

2.2 Top Quark Properties

In order to make sure that the discovered top quark is really the top quark as predicted by the SM its properties have to be measured as precisely as possible. A few examples of top property measurements are presented here.

2.2.1 Top Quark Mass

The mass of the top quark, which is by far the heaviest of all quarks, plays an important role in electroweak radiative corrections and therefore in constraining the mass of the Higgs boson. Precise measurements of the top quark mass provide a crucial test of the consistency of the SM and could indicate a hint of physics beyond.

Different methods to measure the top quark mass are discussed. “Template Methods” [9] have the advantage of being more straightforward and transparent but are statistically less accurate. To maximize the statistical information on the top quark mass extracted from the event sample, more elaborated but also more complex methods exist as for example the “matrix method” [22, 23]. An alternative method uses the cross section measurement to extract the top quark mass [24]. Some example analyses are presented here.

Distributions of variables that are strongly correlated with the top quark mass are derived as templates in MC simulations for different top mass hypotheses. They are compared to the measured distribution in order to extract the top quark mass from data. One example is the extraction of the top quark mass with simultaneous (in situ) calibration of the JES in the all-hadronic channel using the reconstructed top quark and W boson masses as templates. The result is $m_t = 174.8 \pm 2.4(\mathrm{stat}+\mathrm{JES})^{+1.2}_{-1.0}(\mathrm{syst})$ GeV.

However, the currently best measurements use matrix elements to calculate a probability for each event as a function of the assumed top quark mass m_t and an overall multiplicative scale factor JES for jet energies in ℓ+jets final states. The factor JES is fitted *in situ* in data, simultaneously with the top quark mass by using information from the invariant mass of the hadronically decaying W boson. For every event, this mass is constrained to be equal to the known value for the W mass. The probabilities from all events in the sample are then combined to obtain a probability as a function of m_t and JES, and the top quark mass is extracted by finding the values that maximize this probability.

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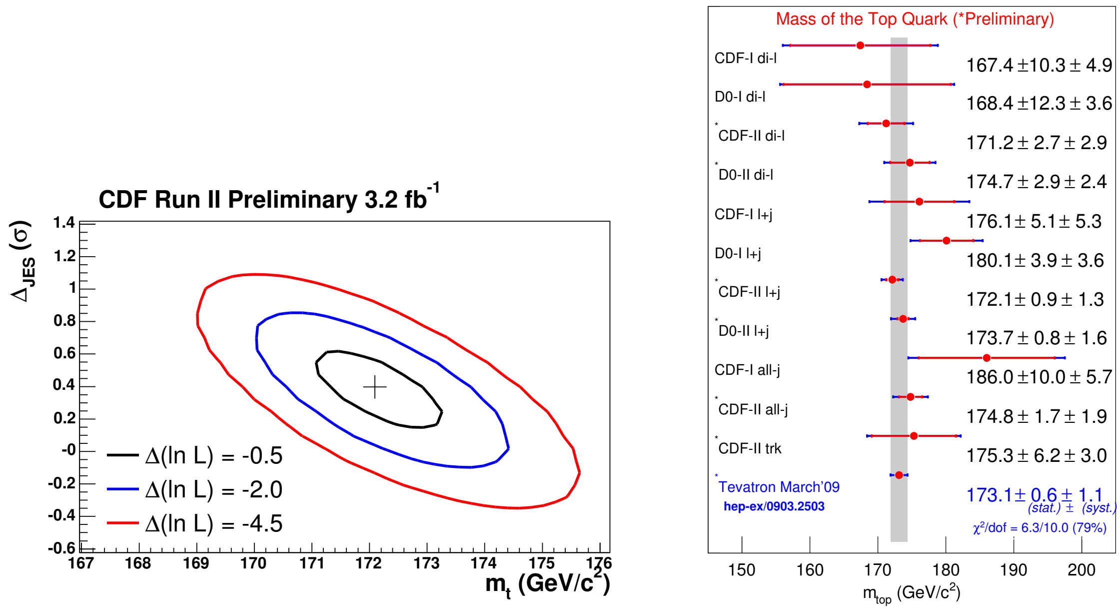

Figure 3: 2D-likelihood on data events including the 1σ, 2σ and 3σ uncertainties for the CDF matrix element method (left). Summary of all mass measurements that are included into the Tevatron combination (right).

The analyses performed by the CDF [22] and DØ [23] experiments are very similar. As a result the top quark mass is measured to $m_t = 173.7 \pm 0.8(\text{stat}) \pm 1.6(\text{syst})$ GeV by DØ and $m_t = 172.1 \pm 0.9(\text{stat}) \pm 1.3(\text{syst})$ GeV by CDF. For the latter measurement, the contours of the log likelihood function for the data are shown as a function of the top quark mass and JES in Fig. 3 (left). The total uncertainties are $\pm 1.0\%$ (DØ) and $\pm 0.9\%$ (CDF), respectively. They are systematically limited. The largest sources of systematic uncertainties apart from the simultaneous inclusion of JES are given by residual JES, in particular of *b*-jets, and theoretical uncertainties in signal and background modeling. Currently both experiments are undertaking large efforts to get a uniform treatment of all uncertainties where ever possible.

Taking correlated uncertainties properly into account the CDF and DØ collaborations have derived a combination of published Run-I (1992–1996) measurements with the most recent preliminary Run-II (2001–present) measurements using up to 3.6 fb^{-1} of data as represented in Fig. 3 (right). A new world average [25] of $m_{\text{top}} = 173.1 \pm 0.6(\text{stat}) \pm 1.1(\text{syst})$ GeV was obtained. This corresponds to a total precision of 1.3 GeV and a relative precision of 0.75% on the top quark mass.

2.2.2 Top Antitop Quark Mass Difference

The CPT theorem, which is fundamental to any local Lorentz-invariant quantum field theory, requires that the mass of a particle and that of its antiparticle be identical. The DØ collaboration reported a measurement of the difference between the mass of the top quark and that of its antiparticle based on data corresponding to 1 fb^{-1} of integrated luminosity [26].

This analysis uses a similar matrix element method as the analyses described in the previous section. Here the jet energies are scaled by an overall JES calibration factor and the mass of the top quark and the mass of the antitop quark, which are not constrained to be equal anymore, are extracted simultaneously. This is shown in Fig. 4 (left) for the e+jets channel. The mass difference for the combined ℓ+jets channels was obtained to be $m_t - m_{\bar{t}} = 3.8 \pm 3.7$ GeV. This is the first direct measurement of a mass difference between a bare quark and its antiquark partner.

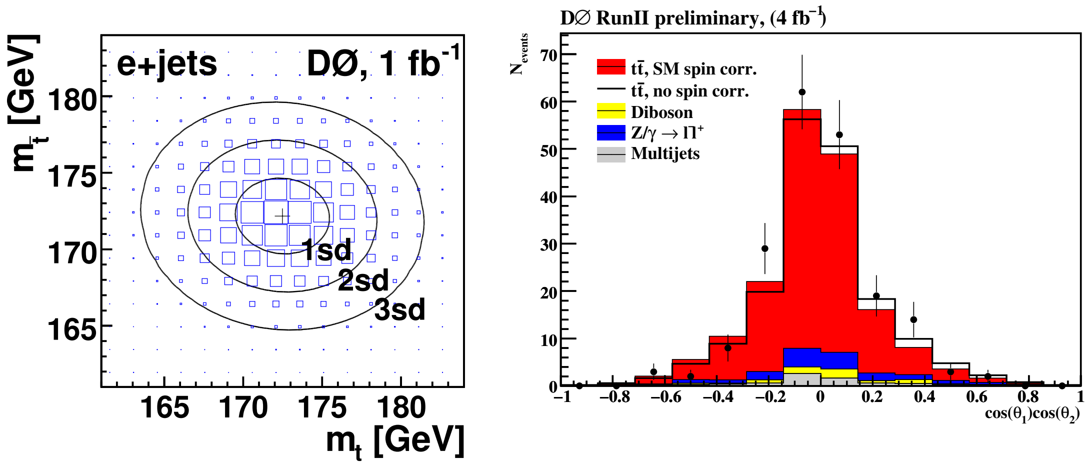

Figure 4: Left: fitted contours of equal probability for the two-dimensional likelihoods as a function of m_t and $m_{\bar{t}}$ in e+jets data. The boxes, representing the bins in the two-dimensional histograms of the likelihoods, have areas proportional to the bin contents, set equal to the value of the likelihood evaluated at the bin center. Right: the $\cos(\theta_1)\cos(\theta_2)$ distribution for a dilepton event sample. The sum of $t\bar{t}$ signal including NLO QCD spin correlation ($C = 0.78$) (red) and multijet (grey), di-boson (yellow) and Drell-Yan (blue) background is compared to data. The open black histogram shows the prediction without $t\bar{t}$ spin correlation ($C = 0$).

2.2.3 Top Antitop Quark Spin Correlation

One of the most important properties of the top quark, its spin, is still basically unexplored. While the top quarks and antiquarks produced at hadron collider are unpolarized, their spins are correlated [27, 28]. Since at the Tevatron top pair production is dominated by $q\bar{q}$ scattering, a different spin correlation is analyzed compared to the LHC where top pair production is dominated by gg scattering.

The SM predicts that the top quark decays before its spin flips [29], in contrast to the lighter quarks, which are depolarized by QCD interactions long before they fragment [30]. The spin of the top quark is therefore reflected by its decay products. In the following analyses it is assumed that top quarks decay exactly as predicted by the SM. Then the charged lepton from a leptonic top quark decay has a spin analyzing power of 1 at the tree level [31]. Therefore, the dilepton final states have the highest sensitivity to measure the correlation between the spins of pair-produced top and antitop quarks.

The only measurement of spin correlations between top and antitop quarks so far was performed by the DØ Collaboration using an integrated luminosity of approximately 125 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV during Run-I of the Tevatron collider [32]. The 68% confidence level given on a correlation coefficient was in agreement with the SM prediction. However, since the sample used for the measurement contained only six events the sensitivity was too low to distinguish between a hypothesis of no correlation between the spins of top and antitop quarks and the correlation predicted by the SM.

The CDF and DØ collaborations have measured the spin correlations between t and $\bar{t}$ now for the first time in proton antiproton scattering at a center of mass energy of $\sqrt{s} = 1.96$ TeV using data of an integrated luminosity of 2.8 fb^{-1} (CDF) and up to 4.2 fb^{-1} (DØ), respectively.

The following double differential distribution is used:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)\ , \tag{2.1}$$

where σ denotes the cross section of the channel under consideration and C is a free parameter between -1 and 1 that depends on the choice of the spin basis. At tree level in the SM C represents the number of events where the t and $\bar{t}$ spins are parallel minus the number of events where they are anti-parallel normalized by the total number of events. θ_1 (θ_2) describes the angle between the direction of flight of the lepton ℓ^+ (ℓ'^-) in the t ($\bar{t}$) rest frame and a reference direction $\hat{\mathbf{a}}$ ($\hat{\mathbf{b}}$). The choice of the spin basis determines the extent to which the spins of the top quarks are correlated. For the Tevatron it has been shown that an almost optimal choice for the spin basis is given by the beam basis [33].

Templates are generated for different values of C by reweighting generated MC events at parton level. DØ uses the distribution (2.1) which is shown in Fig. 4 (right) for background and $t\bar{t}$ signal without and with NLO QCD spin correlation. CDF uses the double-differential $(\cos\theta_1, \cos\theta_2)$ and $(\cos\theta_b, \cos\theta_{\bar{b}})$ distributions where for the latter the flight directions of ℓ^+ (ℓ'^-) are replaced by those of the b quark (anti-b quark). DØ uses the beam axis as the quantization axis and CDF the off-diagonal basis.

The extracted result is $C_{\text{beam}} = -0.17^{+0.64}_{-0.53}\,(\text{stat}+\text{syst})$ in case of the DØ collaboration and $C_{\text{off-diagonal}} = 0.32^{+0.55}_{-0.78}\,(\text{stat}+\text{syst})$ for CDF. This agrees with the NLO QCD value of $C = C_{\text{beam}} = C_{\text{off-diagonal}} = 0.78$ within 2 SD.

2.3 Searches for New Physics in Top Production and Decay

The fact that the top quark has by far the largest mass of all known elementary particles suggests that the it may play a special role in the dynamics of electroweak symmetry breaking. This makes searches for new physics in the top quark sector very attractive. In the following a few examples are presented for searches for new physics in the production and decay of top quarks.

2.3.1 Search for $t\bar{t}$ Resonances

One of the various models incorporating the possibility of a special role of the top quark in the dynamics of electroweak symmetry breaking is topcolor [34], where the large top quark mass can be generated through a dynamical $t\bar{t}$ condensate, X, which is formed by a new strong gauge force preferentially coupled to the third generation of fermions. In one particular model, topcolor-assisted technicolor [35], X couples weakly and symmetrically to the first and second generations and strongly to the third generation of quarks, and has no couplings to leptons, resulting in a predicted cross section for $t\bar{t}$ production larger than SM prediction.

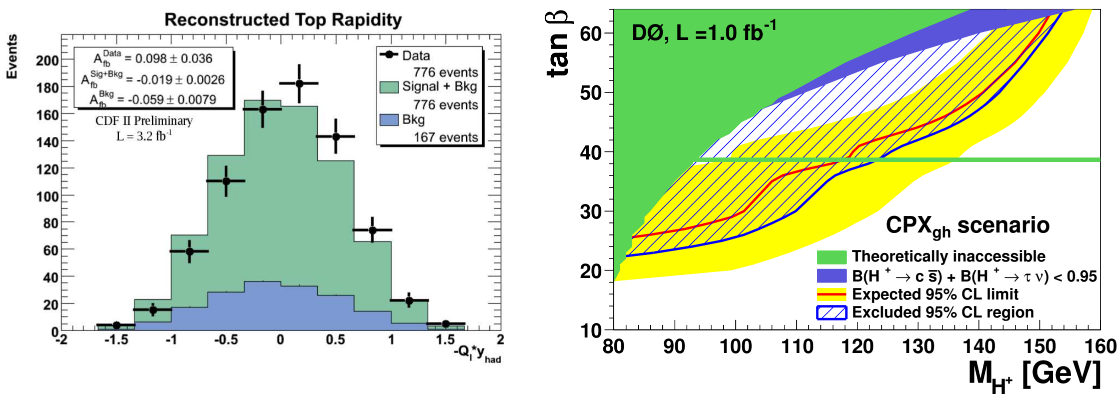

Figure 5: Left: the raw distribution $-Q_l \cdot y_{\text{had}}$ used for the forward-backward asymmetry measurement. Right: excluded regions in $\tan\beta$ and M_{H^+} in a CPX benchmark scenario of a strangephilic Higgs sector.

The CDF and DØ collaborations presented updated model-independent searches for a narrow-width heavy resonance X decaying into $t\bar{t}$ using 2.8 fb^{-1} of data in the all-hadronic final state (CDF) [36] and 3.6 fb^{-1} of data analyzing ℓ+jets final states (DØ) [37]. The search for resonant production is performed by examining the reconstructed $t\bar{t}$ invariant mass distribution resulting from a constrained kinematic fit to the $t\bar{t}$ hypothesis. No deviation from the SM prediction was observed. Within a top-color-assisted technicolor model, the existence of a leptophobic Z' boson with $M_{Z'} < 805$ GeV (CDF) and $M_{Z'} < 820$ GeV (DØ), respectively, and width around $\Gamma_{Z'} = 0.012 M_{Z'}$ is excluded at 95% CL.

2.3.2 Forward Backward Asymmetry

In LO QCD, the top quark production angle is symmetric with respect to the beam direction. At NLO, QCD predicts a small charge asymmetry, $A_{fb} = 0.050 \pm 0.015$ [38, 39], due to interference of initial-state radiation diagrams with final-state diagrams and “box diagrams” with Born processes.

The CDF collaboration has measured the forward-backward asymmetry of pair produced top quarks in a dataset of 3.2 fb^{-1} in ℓ+jets final states [40]. The $t\bar{t}$ events were reconstructed with a χ^2 based kinematic fitter. Then, in the $p\bar{p}$ laboratory frame, the rapidity y_{had} of the hadronically-decaying top (or antitop) system was studied, tagging the charge with the lepton sign Q_l from the leptonically decaying system. The raw distribution of $-Q_l \cdot y_{\text{had}}$ is shown in Fig 5 (left). Assuming CP-invariance the asymmetry

$$A_{fb} = \frac{N(-Q_l \cdot y_{\text{had}} > 0) - N(-Q_l \cdot y_{\text{had}} < 0)}{N(-Q_l \cdot y_{\text{had}} > 0) + N(-Q_l \cdot y_{\text{had}} < 0)} \tag{2.2}$$

is measured. A model-independent correction for acceptance and reconstruction dilutions is performed to be able to compare the asymmetry directly with theoretical predictions. The result is $A_{fb} = 0.193 \pm 0.065(\text{stat}) \pm 0.024(\text{syst})$ consistent with the prediction in NLO QCD. The DØ asymmetry measurement is also in agreement with the SM prediction [41].

2.3.3 Search for Charged Higgs Bosons in Top Quark Decays

In many extensions of the SM, including supersymmetry and grand unified theories, the existence of an additional Higgs doublet is required. Such models predict multiple physical Higgs particles, including three neutral and two charged Higgs bosons ($H^{\pm}$) [42]. If a charged Higgs boson is sufficiently light, it can appear in top quark decays $t \to H^+ b$ [1]. The decay modes of the charged Higgs boson depend on the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. For small values of $\tan\beta$ it is dominated by the decay to quarks, while for larger values of $\tan\beta$ it is dominated by the decay to a τ lepton and a neutrino.

The DØ Collaboration presented a search for charged Higgs bosons in top quark decays [43]. The e+jets, μ+jets, ee, $e\mu$, $\mu\mu$, τe and $\tau\mu$ final states from top quark pair production events were analyzed, using data from about 1 fb^{-1} of integrated luminosity. Different scenarios of possible charged Higgs boson decays were considered, one where the charged Higgs boson decays purely hadronically into a charm and a strange quark, another where it decays into a τ lepton and a τ neutrino and a third one where both decays appear. For a non-zero branching ratio $B(t \to H^+ b \to c\bar{s}b)$ the number of events decreases in the ℓ+jets, $\ell\ell$ and $\tau\ell$ final states. In case of a non-zero branching ratio $B(t \to H^+ b \to \tau^+ \nu b)$ the number of predicted events increases in the $\tau\ell$ channel while it decreases in all other channels.

No indication for charged Higgs boson production in the tauonic or leptophobic model is found. Comparing the number of predicted and observed events in the various $t\bar{t}$ final states, limits on the branching ratio $B(t \to H^+ b)$ were extracted for all these models. Two methods were used, one where the $t\bar{t}$ production cross section is fixed, and one where the cross section is fitted simultaneously with $B(t \to H^+ b)$. Based on the extracted limits, regions in the charged Higgs boson mass and $\tan\beta$ were excluded for different scenarios of the minimal supersymmetric standard model.

As an example a specific CP-violating benchmark scenario (CPX) with large threshold corrections [44] is presented where values of $B(H^+ \to \tau^+\nu) + B(H^+ \to c\bar{s}) \approx 1$ can be realized introducing an additional mass hierarchy between the first two and the third generation of sfermions. Figure 5 (right) shows the excluded region in the $[\tan\beta, M_{H^+}]$ parameter space. Theoretically inaccessible regions indicate parts of the parameter space where perturbative calculations can not be performed reliably. In the $[\tan\beta, M_{H^+}]$ region analyzed here, the sum of the branching ratios was found to be $B(H^+ \to \tau^+\nu) + B(H^+ \to c\bar{s}) > 0.99$ except for values very close to the blue region which indicates $B(H^+ \to \tau^+\nu) + B(H^+ \to c\bar{s}) < 0.95$. The charged Higgs decay $H^+ \to \tau^+\nu$ dominates for $\tan\beta$ below 22 and above 55. For the rest of the $[\tan\beta, M_{H^+}]$ parameter space both the hadronic and the tauonic decays of charged Higgs bosons are important. In the region $38 \le \tan\beta \le 40$, the hadronic decays of the charged Higgs boson dominate and $B(H^+ \to c\bar{s}) > 0.95$. Here the Higgs sector is strangephilic. The neutral Higgs boson would preferably decay into an $s\bar{s}$ pair and therefore be missed in searches using either b-tagging or tau identification. In this case only strangephilic charged Higgs bosons from top decays as analyzed here could be easily discovered. For large values of $\tan\beta$, M_{H^+} up to 154 GeV are excluded. For low charged Higgs masses, $\tan\beta$ values down to 23 are excluded. These are the first Tevatron limits on a CP-violating MSSM scenario derived from the charged Higgs sector.

3. Prospects at the LHC

At the time of this conference it was clear that the Large Hadron Collider (LHC) at CERN would soon start the first proton-proton collisions at a center of mass energy never reached before.

[1] Throughout the paper, H^+ also refers to the charge conjugate.

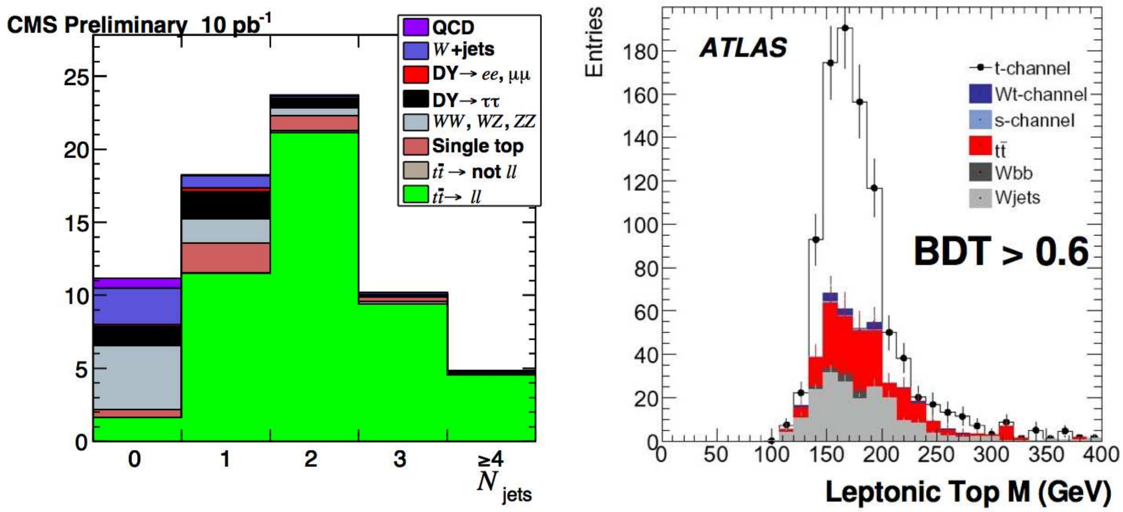

Figure 6: Left: number of jets in a dilepton selection with a dataset of 10 pb^{-1} at $\sqrt{s} = 10$ TeV as expected by CMS. Right: reconstructed mass of leptonically decaying single top quarks produced by t-channel W exchange with a dataset of 1 fb^{-1} at $\sqrt{s} = 14$ TeV as expected by ATLAS.

The investigation of the physics of the top quark will be a fundamental element of the early analysis program. A few highlights of the expectations of top quark measurements at the ATLAS and CMS experiments are given in the following.

It is expected that at a luminosity of $10^{32}\text{cm}^{-2}\text{s}^{-1}$ and a center-of-mass energy of 10 TeV, a few weeks will be sufficient to rediscover the top quark and to collect a sample large enough to check SM predictions, but also to test the validity of lepton identification, jet identification, b-tagging and many other analysis tools in general.

As a first step the top pair production will be measured [45, 46]. As an example, the CMS collaboration expects to measure the $t\bar{t}$ cross section with an uncertainty of $\Delta\sigma_{t\bar{t}} = 15\%(\text{stat}) \pm 10\%(\text{syst}) \pm 10\%(\text{lumi})$ with a dataset of 10 pb^{-1} at $\sqrt{s} = 10$ TeV [46]. Figure 6 shows the expected distribution of the number of jets for the $t\bar{t}$ signal and the different sources of background.

ATLAS and CMS also evaluated the prospects for the measurement of the single top cross section and the direct extraction of V_{tb} [47, 48]. As an example, ATLAS studied the measurement of V_{tb} in the t-channel based on a multivariate Boosted Decision Tree (BDT) technique [47]. Figure 6 shows the expected reconstructed mass of the leptonically decaying top quark for large values of the BDT discriminant where the signal is enhanced. Assuming a center-of-mass energy of 14 TeV and an integrated luminosity of 1 fb^{-1}, the expected accuracy is $\Delta V_{tb} = 12\%(\text{stat}+\text{syst}+\text{theo})$ which is dominated by systematic uncertainties due to b-tagging, JES and luminosity. This compares to the current measurements of $\Delta V_{tb} = 14\%$ (CDF) and $\Delta V_{tb} = 11\%$ (DØ) at the Tevatron.

In general, it will be difficult for the LHC experiments to beat systematically limited Tevatron measurements of properties such as the top quark mass. Here the expectation of an accuracy of 1 GeV at the LHC is very close to the current Tevatron accuracy of 1.3 GeV which will further improve with more data and an even better understanding of the detectors. However, the LHC will be able to measure basic quantities such as spin, charge and the couplings of the top quark with a very high precision in the future. Most interestingly, some quantities will be measured for the first time. One example is the spin correlation between top and antitop quarks where the LHC measures a different quantity compared to the Tevatron, because the top pairs are mostly produced by gluon fusion while $q\bar{q}$ annihilation dominates at the Tevatron. The ATLAS collaboration has presented a study for the ℓ+jets channel which shows an expected accuracy of 53% for a dataset of only 220 pb^{-1} at $\sqrt{s} = 14$ TeV [47].

In many searches for new physics the LHC experiments have a much better expected sensitivity even with early data compared to the Tevatron analyses. One example is the search for FCNC where the expected limit in absence of a signal will exceed all LEP, HERA and Tevatron limits shown in Fig. 2 (lower right) by several factors using ATLAS data corresponding to an integrated luminosity of only 1 fb^{-1} at $\sqrt{s} = 14$ TeV [47].

Furthermore, exciting new developments were presented such as a method for the discrimination of boosted hadronically decaying top jets against light quark and gluon jets using jet substructure. The procedure presented by the CMS collaboration involves parsing the jet cluster to resolve its subjets, and then imposing kinematic constraints due to for example the top quark or W boson masses. With this method, light quark or gluon jets with a transverse momentum of around 1 TeV can be rejected with an efficiency of around 99% while retaining up to 40% of top jets [49].

4. Conclusions

Recent highlights in top quark physics analyses from the HERA and Tevatron colliders and prospects from the LHC are reviewed. Among many impressive results from the Tevatron, the observation of single top quark production via the electroweak interaction and the direct measurement of the CKM matrix element V_{tb} by the CDF and DØ Collaborations is outstanding.

Analyzing datasets corresponding to an integrated luminosity of up to 3.6 fb^{-1} the Tevatron experiments can now perform several high precision measurements, most of all of the top quark mass which is known to an accuracy of 0.75% in its current world average. For the first time, sensitive measurements of important and previously unexplored properties such as $t\bar{t}$ spin correlations could be performed. In all presented analyses, so far, there is no hint for new physics beyond the SM in the top sector. Excellent prospects for top physics investigations can be expected with more integrated luminosity at the Tevatron and by the upcoming LHC physics run.

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