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Top Quark Physics with CDF

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In this contributions to the proceedings of the HCP conference I will give a brief overview on the CDF upgrade for Run II relevant to top quark physics analyses. I will discuss the CDF top physics program, with particular emphasis to the search for single top quark production. This includes a review of single top quark analyses in Run I.

1 The CDF II Upgrade

The Collider Detector at Fermilab (CDF) underwent a major upgrade program for Run II, details are discussed in these proceedings [1]. Here I only highlight those parts of the upgrade which constitute substantial improvements for the top quark physics program.

CDF built a completely new silicon tracker which features full forward coverage up to pseudo-rapidities of $|\eta| < 2.0$. This will allow to substantially extend the acceptance for electron identification in the forward region (Among other criteria electrons are identified by requiring a track pointing to a cluster in the electromagnetic calorimeter.). To fully exploit the forward coverage of the silicon tracker in the region which is not covered by the central drift chamber (COT) CDF is developing a calorimeter seeded tracking algorithm. The transverse momentum of the electromagnetic cluster, the spacial information of the shower maximum detector and the primary vertex position are used to create seed tracks which are handed over to the standard outside-in silicon pattern recognition. A proof of principle of this algorithm has been delivered: In $15\,\mathrm{pb}^{-1}$ of data CDF found 160 $Z^0 \rightarrow e^+e^-$ candidates which have the electron and the positron in the forward region with $|\eta| > 1.2$. In Run II we expect 33% more identified high-p_t primary electrons from $t\bar{t}$ events compared to Run I. The new silicon tracker will also lead to a considerable improvement of the b-tagging efficiency in $t\bar{t}$ events, going up from $(50.5 \pm 5.1)\%$ in Run I [2] to 65% [3].

Further relevant upgrades for top quarks physics are the extension of the muon system and the new calorimeter endplugs. The muon coverage was extended in ϕ and in η yielding an increase of 12% in the geometrical acceptance for muons from $t\bar{t}$ events [3]. The plug calorimeter was completely replaced and is equipped with scintillation-tile fibers, thus being based on the same technology as the central calorimeter.

In total, CDF has roughly doubled its acceptance for $t\bar{t}$ events compared to Run I. The complete Run IIa data set of $2\,\mathrm{fb}^{-1}$ (Run I $105\,\mathrm{pb}^{-1}$) will yield about 800 $t\bar{t}$ events in the top mass sample.

2 The Top Physics Program of CDF

CDF has a very successful record in top quark physics, first and foremost with the top quark discovery in 1994/95. In this section I want to give a brief overview on the broad top quark physics program of CDF in Run II. Single top quark production and flavor changing neutral currents are discussed separately in section 3 and section 4.

2.1 $t\bar{t}$ Cross Section

The first measurements of CDF in Run II will be the $t\bar{t}$ cross section measurements in three different channels: $t\bar{t}$ events are experimentally classified according to the decay mode of the two W bosons coming from the top decays. If both W's decay to $e\nu$ or $\mu\nu$, the event is called a di-lepton event. If one W decays leptonically and the other W to two quarks, the event is a lepton plus jet event. The case where both W's decay hadronically, is called the all hadronic channel. $W \to \tau\nu$ events contribute to all three channels depending on the τ decay mode. The Run I cross section results are summarized in Table 1. The combined cross section of all three channels is $6.5^{+1.7}_{-1.4}$ pb.

Channel	cross section
Lepton + jets	$5.7^{+1.9}_{-1.5}$ pb
Di-lepton	$8.4^{+4.5}_{-3.5}$ pb
All-hadronic	$7.6^{+3.5}_{-2.7}$ pb
Combined	$6.5^{+1.7}_{-1.4}$ pb

Table 1. $t\bar{t}$ cross sections in different channels as measured by CDF in Run I.

Fig. 1 shows a comparison of the CDF measurement with theoretical predictions [6,7,5]. Within the large errors there is good agreement. It is apparent that in order to stringently test the QCD predictions both measurements, the cross section and the mass measurement, have to be improved. In Run

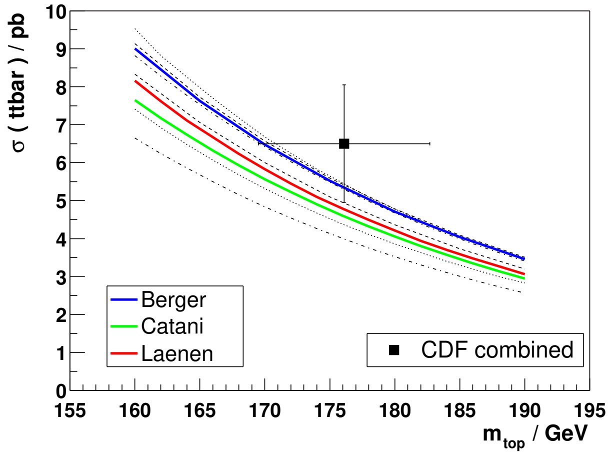

Fig. 1. Comparison of the CDF cross section measurement (and top mass measurement) with theoretical predictions.

IIa the relative precision will be improved to about 7% (Run I 26%). Since the center-of-mass energy increased from $\sqrt{s} = 1.80\,\mathrm{TeV}$ to $\sqrt{s} = 1.96\,\mathrm{TeV}$, the cross section will significantly increase by about +30%. Predictions are available for $\sqrt{s} = 2.00\,\mathrm{TeV}$ (the center-of-mass energy originally anticipated for Run I) from two different groups: $7.56^{+0.10}_{-0.55}\,\mathrm{pb}$ [7] and $6.97^{+0.15}_{-0.47}\,\mathrm{pb}$ [6]. In Run II CDF has not made a cross section measurement yet. However, there are first candidate events in the di-lepton sample. One of those is shown in Fig. 2.

2.2 Top Mass Measurement

The measurement of m_{top} is a crucial input to test the Standard Model, in particular, to derive limits on the Higgs mass. In Run I CDF measured $m_{top} = (176.1 \pm 6.6)\,\mathrm{GeV}/c^2$. The dominating systematic uncertainty is the jet energy scale and the modeling of initial-state and final-state radiation. In Run II it is expected that these uncertainties can be significantly reduced by analyzing control samples like $Z+$ jets, $Z \to b\overline{b}$ and $W \to q\overline{q}$ as well as studying soft gluon radiation in top quark events experimentally. The systematic error on the top mass in Run II is expected to be about 2 GeV, the statistical uncertainty to be well below 1 GeV. At the end of Run IIa the total error will thus be between 2 and 3 GeV.

2.3 Physics with $t\overline{t}$ events

The sample of top quark events is used for various interesting analyses. Here I can only briefly mention the various topics:

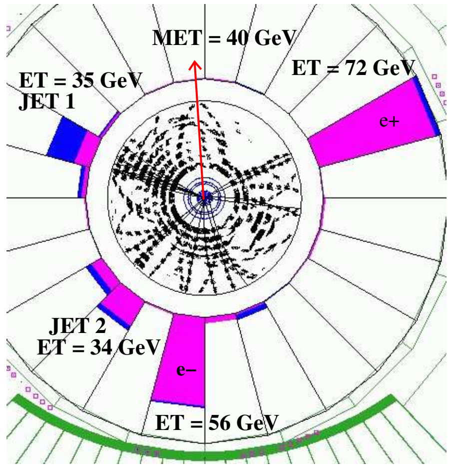

Fig. 2. $t\bar{t}$ di-lepton candidate event of CDF (Run 136286). The invariant mass of the electron and the positron is 118 GeV/c^2. The scalar sum of transverse energies is $H_t = 255\,\mathrm{GeV}$.

1. Measurement of the ratio $R_{tb} = \mathrm{BR}(t \to W + b)/\mathrm{BR}(t \to W + q)$. In the Standard Model R_{tb} is expected to be close to 1. In Run I CDF has measured $|R_{tb}| = 0.94^{+0.31}_{-0.24}$ [4] using a maximum likelihood fit to the b-tagging multiplicity distribution in the lepton+jets and di-lepton sample. This measurement translates into a lower limit of $|R_{tb}| > 0.56$ at 95% confidence level. The expectation for Run IIa is to measure $|R_{tb}|$ with a relative precision of 3% [3].
2. CDF investigated the helicity of W bosons from top quark decays [8].
3. CDF measured the top quark p_t distribution [9].
4. In Run II CDF will measure the spin correlation between the top quark and the anti-top quark in $t\bar{t}$ events.
5. Soft gluon radiation from $t\bar{t}$ events will be studied to improve the uncertainty on the top mass, as mentioned above. A first proof of principle of the method has been given using Run I data.
6. CDF has searched for top quark decays to charged Higgs bosons [10].

3 Single Top Quark Production

In hadron collisions top quarks are not only produced as $t\bar{t}$ pairs via the strong interaction but can also be produced via electroweak charged current interactions as single quarks. Single top quark production always involves a $W - tb$ vertex. There are three production modes which are distinguished by the virtuality of the W boson:

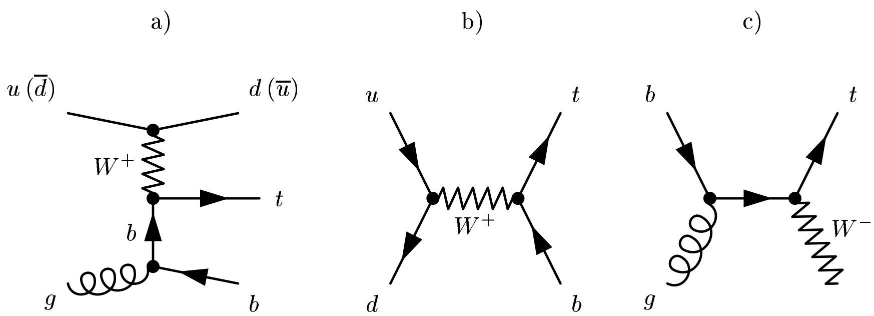

Fig. 3. Representative Feynman diagrams for the three single top production modes. a) shows the dominating W-gluon fusion graph, b) the s-channel process and c) associated production. We chose to draw the graphs in a) and b) with the (u, d) weak-isospin doublet coupling to the W. This is by far the dominating contribution. In general, also the (c, s) doublet contributes, but the respective PDFs are strongly suppressed. The graphs show top quark production, the diagrams for single anti-top quark production can be obtained by interchanging quarks and anti-quarks.

1. the **t-channel**: A virtual W strikes a b-quark (a sea quark) inside the proton. The W boson is spacelike ($q^2 < 0$). This mode is also known as **W-gluon fusion**, since the b-quark originates from a gluon splitting into a $b\bar{b}$ pair. A Feynman diagram representing this process is shown in Fig. 3a. W-gluon fusion is the dominant production mode, both at the Tevatron and the LHC. The experimental signature is a W and a b-jet from the top quark decay and in addition a light quark jet which is usually at high η. The second b-jet from the gluon splitting is soft and has low E_t. In most cases it goes undetected
2. the **s-channel**: This production mode is of Drell-Yan type. A timelike W boson, $q^2 \geq (m_t+m_b)^2$, is produced by the fusion of two quarks belonging to a SU(2) isospin doublet. See Fig. 3b for the Feynman diagram. The signature of the s-channel is two hard b-jets and a W boson.
3. **associated production**: The top quark is produced in association with a real, on shell, W boson ($q^2 = M_W^2$). The initial b-quark is a sea quark inside the proton. Fig. 3c shows the Feynman diagram. The cross section is negligible at the Tevatron ($< 0.1\,\mathrm{pb}$), but of considerable size ($51\,\mathrm{pb}$) at LHC energies where it even supercedes the s-channel.

Theoretical cross section predictions for single top quark production are available at next-to-leading order (NLO) in perturbation theory, see Table 2 [11,12].

In total the t- and s-channel have a cross section that amounts to about 40% of the $t\bar{t}$ production cross section. However, the detection is much more difficult because one has to discriminate against a large QCD background of W + two jet production. The single top quark production cross section is proportional to the square of the CKM matrix element $|V_{tb}|$ and thereby

$\sqrt{s}$	W-gluon fusion	s-channel
1.8 TeV	(1.70 ± 0.09) pb	(0.73 ± 0.04) pb
2.0 TeV	(2.44 ± 0.12) pb	(0.88 ± 0.05) pb
14.0 TeV	(245 ± 12) pb	(10.2 ± 0.6) pb

Table 2. Predicted total cross sections for single top quark production modes at NLO [11,12]. The cross sections are given for $p\overline{p}$ collisions at the Tevatron ($\sqrt{s} =$ 1.8 TeV and $\sqrt{s} = 2.0$ TeV), pp collisions at the LHC ($\sqrt{s} = 14$ TeV). The cross sections are given for a top quark mass of $m_{top} = 175$ GeV.

allows its direct determination. Furthermore, it has to be noted that the observation of the s-channel process at the Tevatron will be crucial, since at the LHC this production mode will be even more suppressed with respect to other top quark production modes.

In Run I three analyses were performed to search for single top production at CDF. The first two use maximum likelihood techniques and the results were published in 2002 [13]. The third analysis is a neural net search for which only preliminary results are available.

The basic pre-selection is common to all three analyses: The W from the top quark decay is identified by demanding an isolated electron or muon of at least 20 GeV transverse energy (in case of the electron) or transverse momentum (muon). Missing transverse energy, $\not{E}_T$, is used to detect the neutrino. $\not{E}_T$ is required to be above 20 GeV. Events which are compatible with a Z^0 decay into muons or electrons or have a $t\bar{t}$ di-lepton signature are vetoed. At least one b-tagged jet with a transverse energy above 15 GeV is required.

The first analysis is a combined search for both single top production modes. We accept events with one, two or three jets with $E_t > 15\,\mathrm{GeV}$. We calculate the invariant mass $M_{\ell\nu b}$ of the charged lepton, the missing transverse energy (neutrino) and the b-quark. The invariant mass of the lepton and the missing transverse energy vector is constraint to be the mass of the W boson. Only events with $M_{\ell\nu b}$ in the top quark mass range are accepted: $140\,\mathrm{GeV} < M_{\ell\nu b} < 210\,\mathrm{GeV}$. After the cuts CDF observes 65 candidate events. The Standard Model expectation is 67 ± 12 events (3.0 W-gluon fusion, 1.3 s-channel, 8.4 $t\bar{t}$ and 54 non-top background events). To fit for the composition of the data sample we calculate the scalar sum of tranverse momenta: $H_t \equiv |\not{E}_T| + |E_t(\ell)| + \sum |E_t(\text{all jets})|$. Performing an unbinned maximum likelihood fit to the H_t distribution yields an upper limit of 14 pb on the cross section for single top quark production.

The second analysis derives separate limits for W-gluon fusion and the s-channel. Only the W plus two jet sample is used for this analysis. The sample is subdivided into two sub-samples by requiring either exactly one or exactly 2 b-tagged jets. For the single tagged events the reconstructed top mass has to fall in the region $145\,\mathrm{GeV} < M_{\ell\nu b} < 205\,\mathrm{GeV}$. The single tag sample contains 15 events, the expectation is 14 ± 2. There are 6 double-tagged events compared to an expectation of 2.7 ± 0.5. In the first sub-sample the expectation of W-gluon fusion events is 2.5 times larger than for s-channel events, in the second sub-sample the expectation of s-channel events is 7.5 times larger than for W-gluon fusion. The acceptance times branching ratio is 1.0% for W-gluon fusion and 1.5% for the s-channel. For the single-tag sample we calculate the product $Q \times \eta$, where Q is the charge of the lepton from the W decay and η the pseudo-rapidity of the light-quark jet. For the double-tag sample we calculate the invariant mass $M_{\ell\nu b}$. A combined binned maximum likelihood fit is applied to these two distributions. The result is a single top content in the data of $-0.6^{+4.8}_{-4.0}$ W-gluon fusion events and $7.6^{+5.9}_{-4.8}$ s-channel events. This yields upper limits of 13 pb for W-gluon fusion and 18 pb for the s-channel.

Results of the third analysis are still preliminary and not yet published. Refined jet multiplicity cuts are used: If there is exactly one hard jet ($|E_t| > 15\,\mathrm{GeV}$), at least one additional soft jet with $|E_t| > 8\,\mathrm{GeV}$ is required. Events with exactly two hard jets are accepted. Events with exactly three hard jets are only accepted if there is no additional soft jet with $|E_t| > 8\,\mathrm{GeV}$. CDF observes 64 events after cuts. The neural network determines the sample composition and finds a signal content of 22.9 ± 7.6 single top quark events, that is a $2.5\,\sigma$ access over the Standard Model expectation of 4.2 events. Further cross checks on this result are ongoing. The observed access is statistically still compatible with the limits derived in the previous analysis due to the large errors. However, the neural network result also underlines the importance to look for single top quark production in Run IIa with more data and an improved background simulation due to new Monte Carlo generators like Alpgen and Grappa.

In the complete data set for Run IIa, $2\,\mathrm{fb}^{-1}$, CDF expects to find 100 to 150 single top quark events. This will allow to measure $|V_{tb}|$ with a precision of 10 to 15%.

4 Search for FCNC in the Top Sector

In the Standard Model flavor-changing neutral current (FCNC) decays of top quarks are strongly GIM suppressed. Branching ratios for $t \to c + Z/\gamma/g$ are predicted to be below 10^{-10} [17] and thus experimentally out of reach, even for the LHC. Any observation of such decays will signal new physics. However, there is plenty of phenomenological models describing physics beyond the Standard Model which predict a large enhancement of FCNC in the top sector, see for instance Ref. [14–16].

In Run I the CDF collaboration has set limits on the branching ratios of anomalous top quark decays: $\mathrm{BR}(t \to u/c + \gamma) < 3.2\%$ and $\mathrm{BR}(t \to$

$u/c + Z^0) < 33\%$ [18]. In the analysis we searched for $t\bar{t}$ events where one top quark decays into $W + b$ and the second top quark decays anomalously to $u/c+\gamma/Z^0$. For the Z^0 channel only decays $Z^0 \to e^+e^-/\mu^+\mu^-$ were used. In Run IIa we plan to also use $Z^0 \to b\bar{b}$ decays and thereby improve the sensitivity for the Z^0 channel. The sensitivity projections for Run IIa are $\mathrm{BR}(t \to u/c + \gamma) < 0.3\%$ and $\mathrm{BR}(t \to u/c + Z^0) < 1.5\%$ [3]. The sensitivity for the anomalous coupling constants will be $\kappa_\gamma < 0.13$ and $\kappa_Z < 0.15$, respectively.

5 Conclusions

Since February 2002 the Collider Detector at Fermilab is back taking physics quality data in Run II of the Tevatron. First $t\bar{t}$ cross section measurements at $\sqrt{s} = 1.96\,\mathrm{TeV}$ are expected in Spring 2003. Many interesting physics topics in top quark physics will attacked in the coming years. One of the hot topics is the first observation of single top quark production, a process which was not accessible in Run I due to the limited amount of data.

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