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S. Kim
For the CDF and D0 Collaborations

University of Tsukuba
Tsukuba, Ibaraki, 305, Japan

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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TOP QUARK PHYSICS AT THE TEVATRON

SHINHONG KIM
For the CDF and DØ Collaborations
University of Tsukuba, Tsukuba, Ibaraki, 305, Japan

We present the recent results and future prospects on top quark physics at the Tevatron. We describe the measurements of the top quark mass and the search for single top quark production in 1.8-TeV $p\bar{p}$ collisions. The CDF and DØ combined results yield a top quark mass of 174.3±5.1 GeV/c^2. The upper limit at 95% C.L. of the single top production cross section is found to be 16.0 pb and 15.6 pb for the W-gluon fusion process and s-channel W^* process, respectively.

1 Introduction

In Tevatron Run1 (1992-1995), CDF and DØ collected data corresponding to an integrated luminosity of 106 pb^{-1} and 125 pb^{-1}, respectively, and we had over 10^{13} $p\bar{p}$ collisions. About 1,000 top quark pairs were produced in Run1. The Tevatron is currently the only accelerator in the world where one can study top quark physics.

Since the discovery of the bottom quark in 1977 [1], a top quark which is a weak-isospin partner of the bottom quark has been searched for at various collider experiments. In April 1994, the CDF collaboration reported the first evidence for top quark production [2] where 15 $t\bar{t}$ candidates events were found against 6.0 background events expected. It corresponded to 2.8σ excess. CDF measured the top quark mass M_{top} to be 174±16 GeV/c^2 and the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ to be $13.9^{+6.1}_{-4.8}$ pb. In February 1995, CDF and DØ observed top quark production [3,4]. CDF reported that $t\bar{t}$ signals had 4.8σ excess, M_{top}=176±8(stat)±10(syst) GeV/c^2 and $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb. DØ reported that $t\bar{t}$ signals had 4.6 σ excess, $M_{top} = 199^{+19}_{-21}(\mathrm{stat})^{+14}_{-21}(\mathrm{syst})$ GeV/c^2 and $\sigma_{t\bar{t}}$ = 6.4±2.2 pb. We will present the latest measurements of the top quark mass and the search for single top quark production with the full Run1 data sample. We will also present the future prospects on top quark physics in the coming Run2.

2 Top Quark Physics

2.1 $t\bar{t}$ Production Cross Section and Top Quark Mass

Within the standard model, the top quark decays predominantly to Wb. We categorize the decays of $t\bar{t}$ pairs into the following three channels by the decay of the two W bosons:

- Dilepton channel: Both W bosons decay leptonically. The final state is $l^+\nu l^-\bar{\nu}b\bar{b}$ ($l = e$ or μ; BR = 5%).
- Lepton+jets channel: One W decays hadronically and another decays leptonically. The final state is $l^+\nu q\bar{q}'b\bar{b}$ ($l = e$ or μ; BR = 30%).

- All-hadronic channel: Both W bosons decay hadronically. The final state is $q\bar{q}^{'}q\bar{q}^{'}b\bar{b}$ (BR = 44%)

Together, CDF and D0 had 13, 60 and 60 candidate $t\bar{t}$ events in the dilepton, lepton+jets and all-hadronic channels, respectively.

In the lepton+jets channel, we require one isolated high P_T lepton (e or μ) with $P_T > 20$ GeV/c, high missing transverse energy ($\not{E}_T > 20$ GeV) from a neutrino and 3 or more jets with $E_T > 15$ GeV in $|\eta| < 2.0$. In order to separate the $t\bar{t}$ events in the lepton+jets channel from the large W+jets background, CDF requires that one of the jets be identified as a b-quark jet. We tag b-jets by reconstructing displaced vertices from b-quark decay using the silicon vertex detector SVX (SVX tagging), or identifying an additional lepton from a semileptonic b decay (SLT tagging). Details of the SVX and SLT tagging algorithms are described in reference [3].

CDF and D0 measure the $t\bar{t}$ production cross section [5] which tests both the production and decay mechanisms of the standard model. Recent calculations based on Quantum Chromodynamics (QCD) [6] have led to predictions for the cross section from 4.8 to 5.5 pb at a top quark mass of 175 GeV/c^2 with a theoretical uncertainty of less than 15%.

The latest CDF $t\bar{t}$ production cross section is $6.5^{+1.7}_{-1.4}$ pb[7] obtained by combining the results in the dilepton, lepton+jet and all-hadronic channels, where the quoted uncertainty includes both statistical (± 1.2 pb) and systematic uncertainties. This result includes recent reevaluation of the SVX b-tagging efficiency. D0 obtains the $t\bar{t}$ production cross section to be $5.9^{+1.8}_{-1.7}$ pb by combining the results in the dilepton, lepton+jet and all-hadronic channels. Both results are consistent with the theoretical prediction.

The top quark mass is a fundamental parameter of the standard model. The CDF measurement of the top quark mass in the lepton+jets channel[8] was performed as follows: CDF requires an additional jet with $E_T > 8$ GeV and $|\eta| < 2.4$ in the $W+ \geq 3$ jet event sample to make a $W+ \geq 4$ jet sample for the top quark mass analysis. Imposing $m(j_1 j_2) = m(\ell\nu) = M_W$ and $m(j_1 j_2 j_3) = m(\ell\nu j_4) = M_{rec}$, a 2-C constrained fit is done event by event where j_i means one of jets. The output of each event fit is a reconstructed top mass M_{rec} and a χ^2 value quantifying how well the event is described by the $t\bar{t}$ hypothesis.

Next CDF extracts a measured top mass from a sample of $t\bar{t}$ candidates with a likelihood method. The M_{rec} distribution for the $t\bar{t}$ candidate events is fitted to a sum of those for the Monte Carlo $t\bar{t}$ signal and backgrounds which we call templates. The $t\bar{t}$ signal templates are determined by a simultaneous fit to eighteen reconstructed mass distributions corresponding to input top mass ranging from 120 to 220 GeV/c^2 calculated with the HERWIG [9] program. The background template is generated with the VECBOS [10] W+jets Monte Carlo program. By maximizing this likelihood with respect to M_{top}, the background fraction and the template parameters, M_{top} and $\sigma_{M_{top}}$ are obtained.

Thus CDF measures the top quark mass to be 176.0±4.0(stat)±5.1(syst) GeV/c^2 in the lepton+jets channel. The largest systematic uncertainty on the top quark mass of 4.4 GeV/c^2 comes from the jet energy scale. This measurement is combined with measurements from the all-hadronic and dilepton channels, from which we obtain a top quark mass of 176.0±6.5 GeV/c^2 [11]. D0 measures the top quark

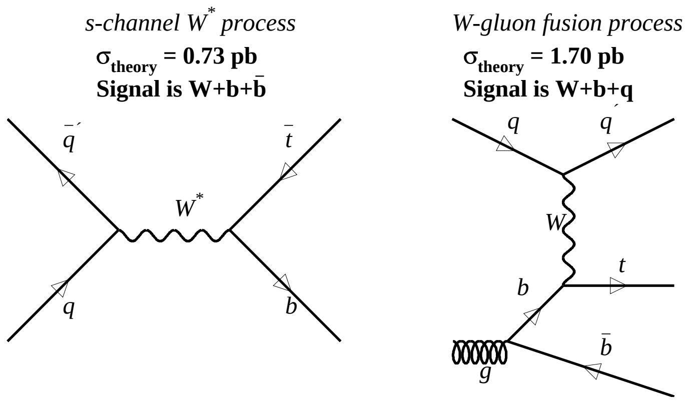

Figure 1: Two processes of single top quark production.

mass to be 172.1±7.1 GeV/c^2 [12]. The CDF and DØ combined top mass is 174.3 ± 3.2(stat) $\pm\, 4.0$(syst) GeV/c^2 or 174.3 ± 5.1 GeV/c^2 [13]. A top quark mass together with a W mass yields a constraint on a Higgs mass in the standard model. The present allowed Higgs mass is 76^{+87}_{-74} GeV/c^2 and less than 262 GeV/c^2 at 95% confidence level [14] from the CDF results, the DØ results, the LEP results and other electroweak results.

2.2 Search for Single Top Quark Production

There are two processes where a single top quark is produced as shown in Fig. 1, the s-channel W^* process and the W-gluon fusion process. The theoretical prediction of the production cross sections are 0.73±0.10 pb [15] and 1.70±0.30 pb [16] for the s-channel W^* process and the W-gluon fusion process, respectively. It is important to study the single top quark production because it yields the best measurement of the top quark decay width Γ_{top} and the CKM matrix elements V_{tb} at the Tevatron and is sensitive to new physics which give anomalous t-W-b couplings.

CDF searches for single top quark production, requiring a high P_T lepton (e or μ) with $P_T > 20$ GeV/c, high missing transverse energy ($\not\!\!E_{\rm T} > 20$ GeV) to account for the presence of an undetected neutrino and two jets with $E_T > 15$ GeV and $|\eta| < 2.0$. CDF also removes dilepton events coming from Z and Drell-Yan, and additionally requires at least one b-tagged jet for the s-channel W^* process, and only one b-tagged jet for the W-gluon fusion process. Main backgrounds for both processes come from QCD W+jets processes with tagged jets such as $Wb\bar{b}$, $Wc\bar{c}$,Wc, and W+2jets with mistags. Another background comes from $t\bar{t}$ production. CDF reconstructs a top quark mass with the four-momenta of the e or μ, ν and one of the jets, by taking the solution with the smallest absolute value for the neutrino P_z

from the W-mass constraint.

In the W-gluon fusion single top search, CDF further applies a top mass window cut ($145\mathrm{GeV/c}^2 < M_{\ell\nu b} < 205\mathrm{GeV/c}^2$). The expected and observed number of events are shown in Table 1. The charge of the top quark, or the lepton charge Q (=±1), is correlated with the untagged jet pseudorapidity η in the W-gluon fusion single top production, while it is not in the QCD W+jets, $t\bar{t}$ and s-channel W^* processes. To make use of this difference, a likelihood fit of the Q$\times\eta$ distribution is performed with background constraints to the expected number of events. The Q$\times\eta$ distribution is shown together with a fitted histogram of background plus signal in Fig. 2. This fit yields 13.1±1.9 fitted background events and $1.4^{+4.2}_{-3.4}$ fitted signal events. Including the systematic uncertainty, CDF obtains the upper limit at 95% C.L. of the single top production cross section to be 16.0 pb in the W-gluon fusion process.

Source	QCD	$t\bar{t}$	W^*	W-g	Observed
Number of Events	10.2±1.9	2.2±0.6	0.5±0.1	1.2±0.3	15

Table 1: The expected and observed number of events after selection of the single top events in W-gluon fusion process.

In the s-channel W^* single top search, CDF obtains the expected and observed number of events as listed in Table 2. Since the b-jet from a top quark decay tends to go along the proton direction, we define a jet with larger (smaller) η as a b-jet from a top (anti-top) quark decay. This b-jet assignment is right at a rate of 64%. A likelihood fit of the reconstructed top mass distribution is performed as shown in Fig. 2, which yields $33.0^{+4.4}_{-4.3}$ fitted background events and $6.6^{+7.3}_{-6.5}$ fitted signal events. Including the systematic uncertainty, CDF obtains the upper limit at 95% C.L. of the single top production cross section to be 15.6 pb in the s-channel W^* process.

Source	QCD	$t\bar{t}$	W-g	W^*	Observed
Number of Events	24.0±4.5	5.7±1.3	1.5±0.3	1.0±0.2	42

Table 2: The expected and observed number of events after selection of the single top events in s-channel W^* process.

3 Future Prospects at the Tevatron

The Tevatron is now being upgraded to have a main injector ring and a $\bar{p}$ recycler ring for Run2 operation which will start in spring 2000. By this improvement, the number of bunches will increase from 6 to 36 ∼ 108 which results in the decrease in a bunch period from 3.5μs to 396 ∼ 132 ns. The instantaneous luminosity will increase from 2.5×10^{31} cm^{-2}sec^{-1} to $5\times10^{31} \sim 2\times10^{32}$cm^{-2}sec^{-1}. To meet these accelerator upgrades which include a much shorter bunch spacing, we need to up-

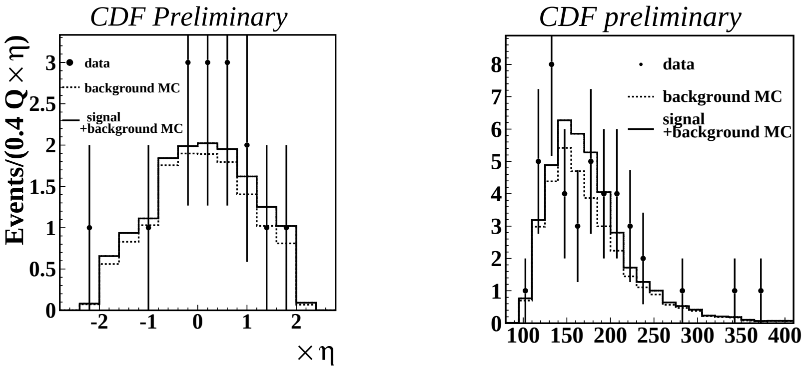

Figure 2: Q×η distribution for the W-gluon fusion single top production (Left). Reconstructed top mass distribution for the s-channel W'' single top production (Right).

grade the detectors with faster response times. The upgraded detectors[17,18] will also have a wider geometrical acceptance for leptons and b-jets than their predecessors.

By the accelerator upgrade, the center-of-mass energy will increase from 1.8 TeV to 2.0 TeV ($\sigma_{t\bar{t}}$ becomes higher by a factor of 1.4) and the integrated luminosity will increase from 0.1 fb^{-1} to 2 fb^{-1} by a factor of 20. By the CDF detector upgrade, the acceptance for $t\bar{t} \rightarrow W(\rightarrow \ell\nu)+ \geq 3$ jet events will increase from 8.7% to 10% (by a factor of 1.15) and the b-tagging efficiency for b-jets will increase from 52% to 86% (by a factor of 1.65). From the above, CDF has 50 times higher rate of $t\bar{t} \rightarrow W(\rightarrow \ell\nu)+ \geq 3$ jet events with one b-tagged jet in Run2. Thus in Run2, both CDF and DØ expect 1,000 $t\bar{t}$ candidates in the $W(\rightarrow \ell\nu)+ \geq 4$ jet sample with one b-tagged jet, and 500 in the $W(\rightarrow \ell\nu)+ \geq 4$ jet sample with two b-tagged jets.

We will study the following subjects on top quark physics in Run2 [19]: Each of CDF and DØ will measure the top quark mass with an uncertainty ΔM_{top} around 3 GeV/c^2 which, together with new measurements of the W mass, will yield a tighter constraint on the Higgs mass. From M_{top}(Tevatron Run2), M_W(Tevatron Run2,LEPII) and other electroweak results at LEP and SLC, Higgs mass will be determined with $\Delta M_H/M_H$ around 30%. It will also measure the $t\bar{t}$ production cross section with $\Delta\sigma/\sigma \sim 9\%$ and the top quark decay width Γ_{top} from $q\bar{q} \rightarrow W^* \rightarrow t\bar{b}$ with $\Delta\Gamma/\Gamma \sim 25\%$. It also yields a V_{tb} measurement with $\Delta|V_{tb}|/|V_{tb}|$ around 13%. We will search for new particles such as $X \rightarrow t\bar{t}$ where X is a color octet vector meson, Z' or something else, and make more precise measurements of $t\bar{t}$ kinematics.

4 Summary

Top quark production and decay have been studied at the Tevatron since its discovery almost five years ago. CDF and DØ have measured the top quark mass in the dilepton, lepton+jets and all-hadronic channels, and obtained combined masses of 176.0±6.5 GeV/c^2 and 172.1±7.1 GeV/c^2, respectively. The CDF and DØ combined top quark mass is 174.3±5.1 GeV/c^2. The upper limit at 95% C.L. of the single top production cross section was measured by CDF to be 16.0 pb and 15.6 pb via W-gluon fusion process and s-channel W^* process, respectively. In the next run of the Fermilab Collider, we will measure the top quark mass more accurately which, together with new measurements of the W mass, will yield a more stringent Higgs mass limit.

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