Single Top Quark Production at DØ

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We present new measurements of the single top quark production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\ TeV$ using data corresponding to 5.4 fb^{-1}of integrated luminosity collected by the DØ detector at the Fermilab Tevatron collider. The large mass of the top quark, close to the electroweak symmetry-breaking scale, makes it a good candidate for probing physics beyond the Standard Model, including possible anomalous couplings. We examine the data to study the Lorentz structure of the Wtb coupling, and find that the data prefer the left-handed vector coupling, and set upper limits on the anomalous couplings.

1 Introduction

At hadron colliders, top quarks are produced as $t\bar{t}$ pairs via the strong interaction or singly via the electroweak interaction [1,2]. Electroweak single top quark production was observed by the DØ and CDF collaborations [3] in 2009. Electroweak production of top quarks at the Tevatron proceeds mainly via the decay of a time-like virtual W boson accompanied by a bottom quark in the s-channel ($tb = t\bar{b} + \bar{t}b$) [4], or via the exchange of a space-like virtual W boson between a light quark and a bottom quark in the t-channel ($tqb = tq\bar{b} + \bar{t}qb$, where q refers to the light quark) [5]. A third process, usually called "associated production," in which the top quark is produced together with a W boson, has a negligible cross section at the Tevatron [2] and is therefore not considered in this analysis. For a top quark mass of 172.5 GeV, the Standard Model (SM) prediction of the single top production rates at next-to-leading order with soft-gluon contributions at next-to-next-to-leading order are 1.04 ± 0.04 pb (s-channel) and 2.26 ± 0.12 pb (t-channel) [2]. Single top quark production is distinct from $t\bar{t}$ pair production since it comes from an electroweak Wtb vertex instead of a strong gtt vertex and hence it provides a unique probe to study the interactions of the top quark with the W boson.

2 Event Selection

The results presented here uses 5.4 fb^{-1}of data collected with DØ detector between 2002 to 2009. The single top quark events are expected to contain at least one b quark jet from the decay of the top quark and a second b quark jet in the s-channel, or a light quark jet and a spectator b quark jet for the t-channel. In both cases, gluon radiation can give rise to additional jets. Events are selected that contain one jet with transverse momentum $p_T > 25$ GeV and at least a second jet with $p_T > 15$ GeV, both within pseudorapidity $|\eta| < 3.4$. Events are also required to contain exactly one isolated high-p_T electron or muon that originates from the $p\bar{p}$ interaction vertex and satisfies the following acceptance criteria: for the electron $|\eta| < 1.1$ and $p_T > 15(20)$ GeV for events with 2 (3 or 4) jets; for the muon $|\eta| < 2.0$ and $p_T > 15$ GeV. The $\not\!\!E_T$ is required to be in the range of $(20, 200)$ GeV for events with 2 jets and $(25, 200)$ GeV for events with 3 or 4 jets. The SM predicts a purely left-handed vector coupling (f_{L_V}) at the Wtb vertex, while the most general, lowest dimension Lagrangian [6] allows right-handed vector (f_{R_V}) and left-handed tensor (f_{L_T}) or right-handed tensor (f_{R_T}) couplings as well. Single top quark signal events with the SM and anomalous Wtb couplings are modeled using the COMPHEP-based MC event generator SINGLETOP [7]. The anomalous Wtb couplings are taken into account in both production and decay in the generated samples. The theoretical cross sections for anomalous single top quark production (s+t-channel) with $|V_{tb}| \simeq 1$ are 3.1 ± 0.3 pb if $f_{R_V} = 1$, 9.4 ± 1.4 pb if $f_{L_T} = 1$ or $f_{R_T} = 1$, and 10.6 ± 0.8 pb if $f_{L_T} = f_{L_V} = 1$ [8], all other couplings are set to zero when calculating these cross sections. The $t\bar{t}$, W+jets, and Z+jets backgrounds are simulated using the ALPGEN leading-log MC event generator [9], with PYTHIA [10] used to model hadronization. The main contributions to the systematic uncertainty on the predicted number of events arise from the signal modeling, the jet energy scale (JES), jet energy resolution (JER), corrections to b-tagging efficiency and the correction for jet-flavor composition in W+jets events. The total systematic uncertainty on the background is 11%. Table 1 lists the numbers of events expected and observed for each process as a function of jet multiplicity.

Table 1: Numbers of expected and observed events in 5.4 fb^{-1} of integrated luminosity, with uncertainties including both statistical and systematic components. The single top quark contributions are normalized to their theoretical predictions.

Source	2 jets			3 jets			4 jets		
tb ($f_{L_T} = 1$)	730	±	38	316	±	25	92	±	14
tqb ($f_{L_T} = 1$)	117	±	6.2	86	±	8.6	40	±	5.8
tb ($f_{L_V} = f_{L_T} = 1$)	607	±	31	284	±	21	86	±	13
tqb ($f_{L_V} = f_{L_T} = 1$)	268	±	15	167	±	16	67	±	10
tb ($f_{R_V} = 1$)	105	±	6.0	43	±	3.8	12	±	1.9
tqb ($f_{R_V} = 1$)	122	±	7.2	61	±	5.3	22	±	3.7
tb ($f_{R_T} = 1$)	756	±	42	344	±	27	103	±	15
tqb ($f_{R_T} = 1$)	103	±	5.8	67	±	6.3	28	±	4.4
tb (SM, $f_{L_V} = 1$)	104	±	16	44	±	7.8	13	±	3.5
tqb (SM, $f_{L_V} = 1$)	140	±	13	72	±	9.4	26	±	6.4
$t\bar{t}$	433	±	87	830	±	133	860	±	163
W+jets	3,560	±	354	1,099	±	169	284	±	76
Z+jets and dibosons	400	±	55	142	±	41	35	±	18
Multijets	277	±	34	130	±	17	43	±	5.2
Total SM prediction	4,914	±	558	2,317	±	377	1,261	±	272
Data	4,881			2,307			1,283		

3 Single Top Quark Production Cross Section Measurement

Since the expected single top quark contribution is smaller than the uncertainty on the background count prediction, multivariate analysis (MVA) methods are used to improve the discrimination between signal and background events. Three different MVA techniques are used for the cross section extraction: (i) boosted decision trees (BDT) [11], (ii) bayesian neural networks (BNN) [12], and (iii) neuroevolution of augmented topologies (NEAT) [13]. All the three methods use the same data and background model considering the same sources of systematic uncertainties. Each MVA method is trained separately for the two single top quark production channels: for the tb (tqb) discriminants, with tb (tqb) considered signal and tqb (tb) treated as a part of the background. To achieve the maximum sensitivity, the three methods are combined to construct a new discriminant using a seccond BNN for each channel, for tb, tqb, and $tb + tqb$ events. The combined $tb + tqb$ discriminant is constructed by taking input from the six discriminant outputs of BDT, BNN and NEAT that are trained separately for the tb and tqb signal. The single top quark production cross section is measured using a Bayesian inference approach [14,15]. To measure the individual tb (tqb) production cross section, a one-dimensional (1D) posterior probability density function is constructed with the tqb (tb) contribution normalized with Gaussian priors centered in the predicted SM cross section for each individual MVA method and also for their combination. To measure the total single top quark production cross section of tb+tqb, a 1D posterior probability density function is constructed assuming the production ratio of tb and tqb predicted by the SM. Fig. 1 shows the resulting expected and observed posterior density distributions for tb, tqb and $tb + tqb$ for the combined discriminants.

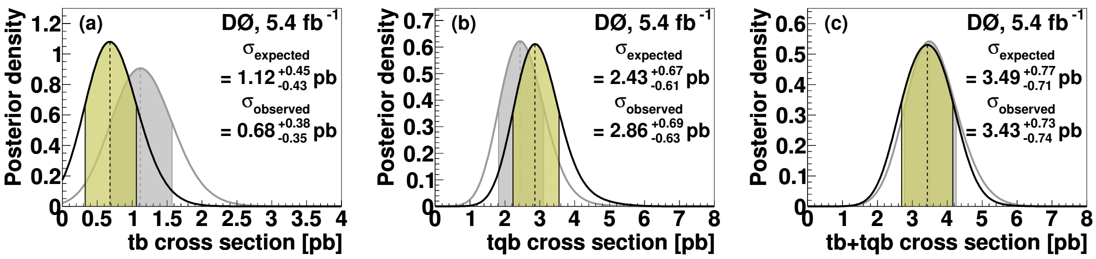

Figure 1: The expected (grey) and observed (black) posterior probability densities for (a) tb, (b) tqb, and (c) tb+tqb production. The shaded bands indicate the 68% C.L.s from the peak values.

4 Anomalous Wtb Couplings

As discussed earlier, by studying single top quark production, we can test whether the Wtb coupling is pure left-handed vector in form, or whether there are right-handed vector, or left- or right-handed tensor components present. Assuming single top quarks are produced only via W boson exchange, the single top quark cross section is directly proportional to the square of the effective Wtb coupling. Moreover, the event kinematics and angular distributions are also sensitive to the existence of anomalous top quark couplings [8]. Therefore, direct constraints on anomalous couplings can be obtained by measuring single top quark production. An analysis has been performed using the same dataset, event selection and background as the cross section measurement analysis, between SM background (including SM single top quark) and anomalous single top quark production as a signal, to set limits on the Wtb coupling for other than a pure left-handed vector form [16]. A BNN is used to discriminate between signal and background. A Bayesian statistical approach is followed to compare data to the signal predictions given by different anomalous couplings. A two-dimensional (2D) posterior probability density is computed as a function of $|V_{tb} \cdot f_{L_V}|^2$ and $|V_{tb} \cdot f_X|^2$, where f_X is any of the three nonstandard couplings and V_{tb} is the Cabibbo-Kobayashi-Maskawa matrix element [17]. The two dimensional (2D) limit contours are shown in Fig. 2. We measure upper limits $|V_{tb} \cdot f_{L_T}|^2 < 0.06$, $|V_{tb} \cdot f_{R_V}|^2 < 0.93$ and $|V_{tb} \cdot f_{R_T}|^2 < 0.13$ at 95% C.L. after integrating the 2D posterior over $|V_{tb} \cdot f_{L_V}|^2$.

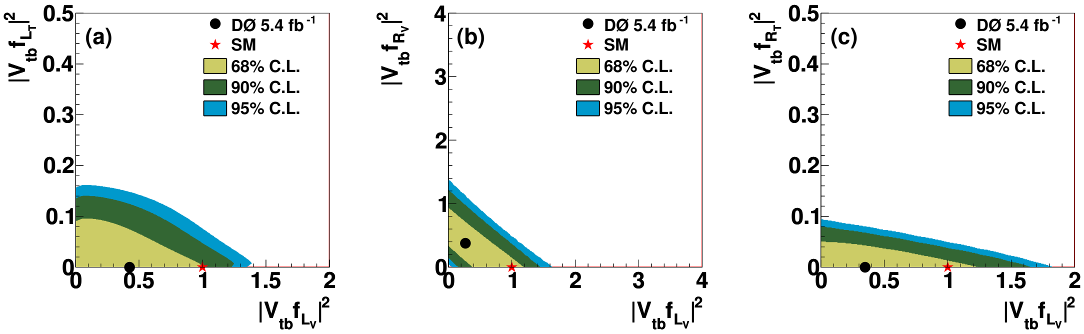

Figure 2: Two-dimensional posterior probability density distributions for the anomalous couplings. (a) (L_V,L_T) scenario, (b) (L_V,R_V) scenario, and (c) (L_V,R_T) scenario.

5 Summary

In summary, we have measured the single top quark production cross section using 5.4 fb^{-1} of data collected by the DØ experiment at the Fermilab Tevatron Collider. For $m_t = 172.5$ GeV, we measure the cross sections for tb and tqb production to be $0.68^{+0.38}_{-0.35}$ pb and $2.86^{+0.69}_{-0.63}$ pb assuming, respectively, tqb and tb production rates as predicted by the SM. The total $tb + tqb$ cross section, assuming the SM ratio between tb and tqb production is $3.43^{+0.73}_{-0.74}$ pb. Also, we searched for the anomalous Wtb couplings in single top quark production and found no evidence for them and set 95% C.L. limits on these couplings. This result represents the most stringent direct constraints on anomalous Wtb interactions.

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