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Physics beyond the single top quark observation

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Summary. — In March 2009, the DØ Collaboration first observed the electroweak production of single top quarks at 5σ significance. We measured the cross section for the combined s-channel and t-channel production modes, and set a lower limit on the CKM matrix element $|V_{tb}|$. Since then, we have used the same dataset to measure the t-channel production mode independently, the combined cross section in the hadronically decaying tau lepton final state, and the width and lifetime of the top quark, and we have set upper limits on contributions from anomalous flavor-changing neutral currents. This paper describes these new measurements, as presented at the 3rd International Workshop on Top Quark Physics, held in Bruges, Belgium, May 31–June 4, 2010.

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1. – Introduction

The focus of this workshop, the top quark, is arguably the most interesting known particle of the standard model. Since the top quark decays before it can hadronize, many of its properties are directly accessible to experimenters, unlike for other quarks. But the main reason for our interest is that since the top quark is by far the heaviest of the elementary particles ($m_t = 173.3 \pm 1.1\,\mathrm{GeV}$ [1]), it may have properties and couplings not predicted by the standard model. Detailed study of its production and decay modes could thus provide a window to new physics.

Top quarks are mostly produced in particle-antiparticle pairs via the strong interaction from a very high energy virtual gluon. The cross section at the Tevatron 1.96 TeV proton-antiproton collider is about 7.5 pb [2]. They can also be produced singly from a highly energetic virtual W boson via the electroweak interaction [3]. If the W boson is in the s-channel, then it decays to a top quark and an antibottom quark or an antitop quark and a bottom quark, known together as "tb" production, with a cross section of ≈ 1 pb [4,5]. If the W boson is in the t-channel or u-channel, then it fuses with a bottom quark to produce the top quark, and there are an accompanying light quark and antibottom quark; this is known collectively as "tqb" or t-channel production, with a ≈ 2 pb cross section [4,5]. A third mode, $gb \to tW$, is negligible at the Tevatron. The labels "s," "t,"

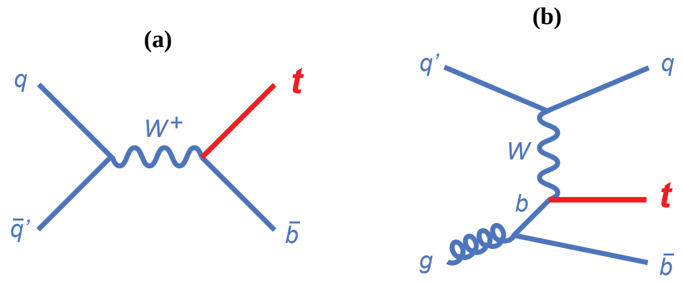

Fig. 1. – Representative leading-order Feynman diagrams for the electroweak production of single top quarks at the Tevatron: (a) s-channel tb production, and (b) t-channel tqb production.

and "u" are Mandelstam variables that describe the four-momenta of the interactions [6]. The main tree-level Feynman diagrams for single top quark production at the Tevatron are shown in fig. 1.

In the standard model there are only three generations of quarks, and in this situation, the CKM quark mixing matrix element V_{tb} is constrained indirectly to be very close to one. Therefore, the top quark decays almost 100% of the time to a W boson and a bottom quark. In the analyses presented here, we select events where the W boson decays leptonically to an electron, muon, or tau, and a neutrino.

2. – Single top quark observation

The new analyses presented here are based on the events selected for the observation measurement of single top quark production [7]. Many details of the measurement can be found in a recent long review paper [8] and proceedings paper [9]. The review paper also includes details of the simultaneous observation measurement by the CDF Collaboration [10] and the combination of DØ and CDF results [11].

A brief summary of the event selection and analysis is given here. From $2.3\,\mathrm{fb}^{-1}$ of data, 1.2 billion events were selected that passed any reasonable trigger and contained an electron or muon. We chose from this dataset 4519 events that passed offline electron or muon identification, had large missing transverse energy (to indicate the presence of a neutrino), and that had two, three, or four jets, where one or two of the jets were identified as having originated from the decay of a b hadron. We built a detailed model of the expected background processes and verified that it reproduced all aspects of the data in regions not expected to contain signal. We used three multivariate discrimination tools trained on an independent subset of the signal and background models to separate signal from background, and used a combination of them in a binned likelihood calculation to extract the single top quark production cross section and a limit on $|V_{tb}|$ at $m_t = 170\,\mathrm{GeV}$:

$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88\,\mathrm{pb}$$
$$0.78 < |V_{tb}| \leq 1 \quad \text{at 95\% CL.}$$

The NLO theory prediction at this mass is $3.46\,\mathrm{pb} \pm 5\%$ [5].

Of the 22% total uncertainty on the cross section measurement, 18% came from the data statistics of the measurement, and we inferred that the systematic uncertainties contributed the remaining 13% (when combined in quadrature). The main components of the systematic uncertainty came from the modeling of the b jet identification in Monte Carlo events, the modeling of the jet energy scale, and the fraction of W+heavy flavor jets in the W+jets background model.

3. – Single top quark production in the t-channel

For the observation analysis, s-channel and t-channel single top processes were combined as signal in order to maximize the chance to reach 5σ significance. However, it is more interesting to measure the cross section of each process separately, since they can be affected by physics beyond the standard model in different ways. Nonstandard couplings would change the kinematics and angular distributions for example. The existence of a fourth generation of quarks would affect $|V_{tb}|$ and hence the b-tagged fraction of jets. Resonances such as a heavy W' boson, charged Higgs boson, Kaluza-Klein excited W boson, technipion, or a top-flavor X particle would change the s-channel cross section only. And flavor-changing neutral currents would affect both channels, although dominantly the s-channel.

To measure the t-channel cross section independently of any assumption about the ratio of s-channel to t-channel cross sections (note, the SM ratio was assumed in the observation analysis), we trained new discriminants on the background model and data from the observation analysis, using only t-channel single top quark Monte Carlo events as signal. Repeating all subsequent steps of the analysis as before, we measured the following cross sections for $m_t = 170\,\mathrm{GeV}$:

$$\begin{aligned}\sigma(p\bar{p} \to tqb + X) &= 3.14^{+0.94}_{-0.80}\,\mathrm{pb},\\ \sigma(p\bar{p} \to tb + X) &= 1.05 \pm 0.81\,\mathrm{pb},\\ \text{t-channel significance} &= 4.8\sigma.\end{aligned}$$

The NLO theory predictions are [5]: t-channel = 2.34 pb and s-channel = 1.12 pb, consistent with the measurements. The recently published results [12] are shown in fig. 2.

4. – Single top quark production in the tau decay channel

It is possible to add to the signal acceptance by searching in decay channels not included in the main observation analysis. This can provide additional sensitivity to reach 5σ significance if needed, as CDF has done with the inclusion of the $\not{E}_T$+jets channel in their observation result. DØ has performed a search for single top quark production in the tau-lepton decay channel. That is, the top quark decayed to a W boson and a b quark, the W boson decayed to a tau and a tau-neutrino, and the tau decayed hadronically to form a narrow low-track-multiplicity jet. A new tau-identification algorithm was developed for this search that is better tuned to find taus in events containing additional jets (whereas DØ's standard tau-ID is optimized for taus in $Z \to \tau\tau$ events, which are very clean). Hadronically decaying taus were classified into three types depending on the decay mode: Type 1 = calorimeter cluster + one track; Type 2 = calorimeter cluster + one track + electromagnetic energy; Type 3 = calorimeter cluster + two or three tracks. The algorithm used boosted decision trees to discriminate tau jets from other jets, gaining 8%, 20%, and 8% in efficiency for Types 1, 2, and 3 taus over the efficiencies obtained with the previous neural-networked-based algorithm. The tau-ID efficiencies

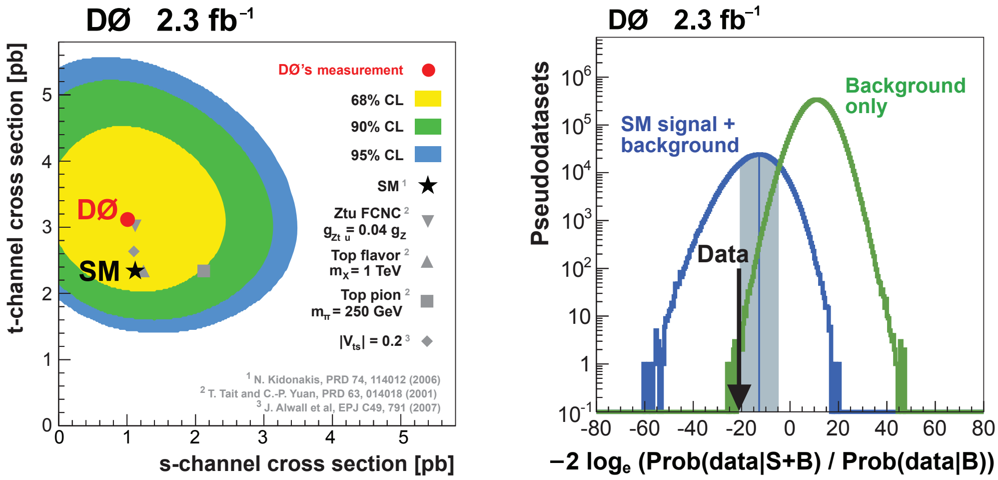

Fig. 2. – Left plot: posterior probability density for t-channel and s-channel single top quark production in contours of equal probability density. Also shown are the measured cross sections, standard model expectation, and several representative new physics scenarios [13]. Right plot: log-likelihood ratio plot used to determine the significance of the t-channel measurement.

obtained are 76%, 69%, and 59%, for 98% background rejection. Taus that decayed to electrons, and events with direct W boson decay to electrons that failed the main electron identification, were also selected by the Type 2 algorithm in this analysis. The tau classifications are illustrated in fig. 3.

The analysis required one identified tau, missing transverse energy, and two or three jets, with one or two of the jets identified as having come from a b decay. The dominant background, as one might expect, was from multijet events where a jet was misidentified as a tau. If the other jets were from light quarks or gluons, then something had been misreconstructed to generated fake missing transverse energy, and the b-tagged jets had fake tags. If there was a $b\bar{b}$ pair in the event, then this could generate both real $\not\!\!E_T$ and b tags. Boosted decision trees were used in each analysis channel to separate signal from

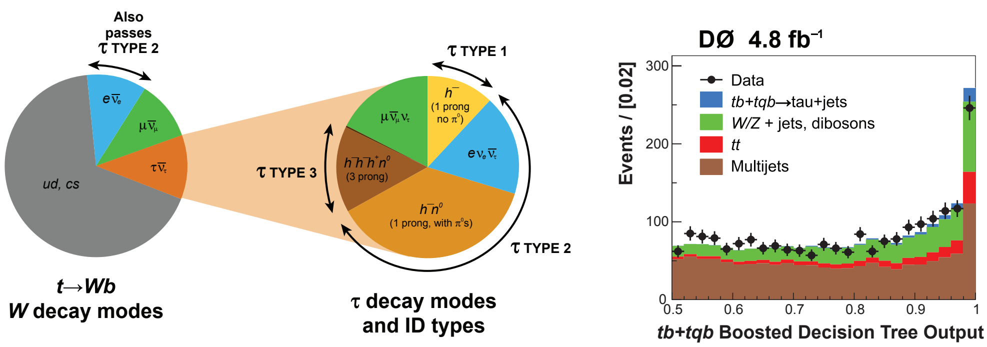

Fig. 3. – Left image: tau identification by decay type. Right plot: tau decay channel final boosted decision tree discriminant, with all analysis channels combined.

background. A binned likelihood calculation gave the following recently published [14] cross section results for $m_t = 170\,\mathrm{GeV}$:

$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.4^{+2.0}_{-1.8}\,\mathrm{pb} \quad \text{(using tau+jets events)},$$
$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.84^{+0.89}_{-0.83}\,\mathrm{pb} \quad \text{(all channels combined)}.$$

5. – Top quark width and lifetime

In the standard model, the top quark's partial width is given at leading order by

$$\Gamma_{\mathrm{LO}}(t \to Wb) = \frac{G_F m_t^3}{8\pi\sqrt{2}} \times |V_{tb}|^2.$$

At next-to-leading order, and ignoring terms of order m_b^2/m_t^2, α_s^2, and $(\alpha_s/\pi)M_W^2/m_t^2$, the partial width becomes [15]

$$\begin{aligned}\Gamma_{\mathrm{LO}}(t \to Wb) &= \Gamma_{\mathrm{LO}}(t \to Wb)\left(1 - \frac{M_W^2}{m_t^2}\right)^2\left(1 + 2\frac{M_W^2}{m_t^2}\right)\left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]\\ &= 1.26\,\mathrm{GeV} \text{ for } m_t = 170\,\mathrm{GeV}.\end{aligned}$$

We have used our measured t-channel single top quark cross section to determine the top quark partial width, since both are proportional to $|V_{tb}|^2$ and hence proportional to each other, as proposed by Yuan [16]. First, we removed the assumption of three quark-generations from the t-channel measurement by scaling it by our measurement of the top quark branching fraction [17]:

$$\begin{aligned}\sigma(p\bar{p} \to tqb + X) \times \mathcal{B}(t \to Wb) &= 3.14^{+0.94}_{-0.80}\,\mathrm{pb},\\ \mathcal{B}(t \to Wb) &= 0.962^{+0.068}_{-0.066}(\mathrm{stat})^{+0.064}_{-0.052}(\mathrm{syst})\end{aligned}$$

and then we scaled the measured cross section by the standard model values for the partial width and the cross section [5] at $m_t = 170\,\mathrm{GeV}$:

$$\begin{aligned}\Gamma(t \to Wb) &= \sigma(p\bar{p} \to tqb + X) \times \frac{\Gamma_{\mathrm{NLO}}(t \to Wb)}{\sigma_{\mathrm{NLO}}(p\bar{p} \to tqb + X)},\\ \sigma_{\mathrm{NLO}}(p\bar{p} \to tqb + X) &= 2.14 \pm 0.18\,\mathrm{pb}.\end{aligned}$$

The calculation was performed using a Bayesian technique, with all statistical and systematic uncertainties and their correlations included. The most probable value for the partial width and its uncertainty, defined by the position of the peak of the posterior and its width, is

$$\Gamma(t \to Wb) = 1.92^{+0.58}_{-0.51}\,\mathrm{GeV}.$$

The total top quark width comes from the partial width using a similar Bayesian calculation:

$$\Gamma(t) = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)} = 1.99^{+0.69}_{-0.55}\,\mathrm{GeV}.$$

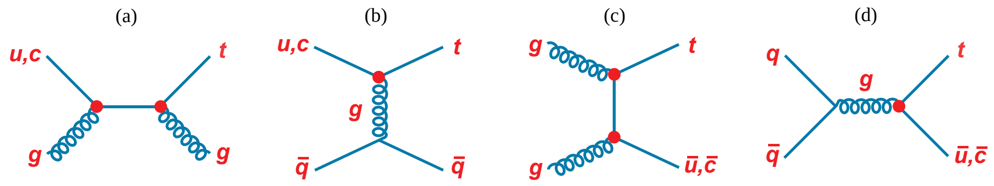

Fig. 4. – Leading-order Feynman diagrams for FCNC gluon coupling between an up or a charm quark and a top quark. The solid circles indicate the effective FCNC coupling, possible at either of the two vertices in (a) and (c) for which the amplitudes are properly summed.

This can be converted to the top quark lifetime using the reduced Planck constant:

$$\tau(t) = \frac{\hbar}{\Gamma(t)} = \left(3.3^{+1.3}_{-0.9}\right) \times 10^{-25}\,\mathrm{s},$$

close to the standard model predicted value [15] of 5.2×10^{-25} s for $m_t = 170$ GeV. These results have recently been submitted for publication [18].

6. – Flavor-changing neutral currents tgq

If flavor-changing neutral currents (FCNC) were to exist, then it would be possible for the top quark to couple to a lighter up-type quark and a gluon. This is illustrated in fig. 4. The process in fig. 4(a) forms 83% of the total rate when the up-type quark is an up quark and 66% when it is charm quark.

We have recently completed a search for the production of single top quarks together with a light quark or gluon, instead of a bottom quark. (Note that the simpler process $qg \to t$ has only one jet in the final state, from the top quark decay, so does not pass our observation analysis requirement of at least two jets. The CDF Collaboration used this production mode with one jet for their FCNC analysis [19].) For this new analysis, we used the 2.3 fb^{-1} dataset and background model from the observation analysis, which is ten times larger than used in our first analysis [20]. The selection criteria were the same as in the observation, except that we required exactly one b-tagged jet to identify the b from the top quark decay. Bayesian neural networks (BNN) were used to separate signal from background with about 24 variables per channel, for a total of 54 variables. These include individual object and event kinematics, top quark reconstruction, jet widths, and angular correlations. We used a binned likelihood calculation with the discriminant outputs to set limits on the anomalous coupling constants, the signal cross sections, and the top quark branching fraction to gq. The results are shown in table I and illustrated in fig. 5. They have been submitted for publication [21].

TABLE I. – *Observed 95% CL upper one-dimensional limits on the FCNC cross sections, couplings, and branching fractions.*

	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgq}/Λ	0.013 TeV^{-1}	0.057 TeV^{-1}
$\mathcal{B}(t \to gq)$	2.0×10^{-4}	3.9×10^{-3}

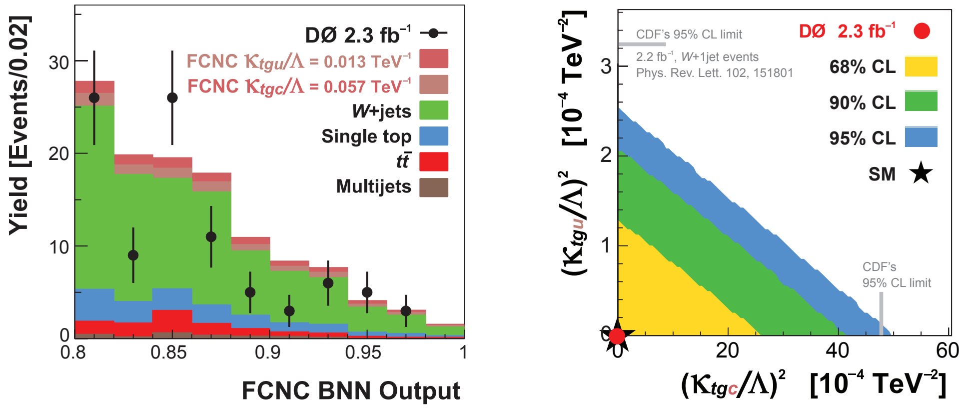

Fig. 5. – Left plot: close-up of the Bayesian neural network signal region. Right plot: two-dimensional Bayesian posterior probability as a function of the square of the couplings.

7. – Conclusions

Since DØ's observation of single top quark production in March 2009, we have produced four new publications using the same dataset. We have measured t-channel tqb production separately from s-channel tb production, with 4.8σ significance for the t-channel signal [12]. We developed a new more efficient tau identification and measured the single top quark cross section in the hadronic tau decay channel [14]. We used the t-channel cross section measurement together with our value for the branching fraction for top to decay to Wb in top pair events to determine the partial and total widths of the top quark and its lifetime [18]. And we have searched for single top quark production via flavor-changing neutral currents with tgq couplings [21]. The possibilities do not end here. We recently completed a search for heavy W' resonant production with decay to tb that will be submitted for publication shortly, and we expect to finish a new analysis of a dataset over twice as large as the observation one in the near future. DØ should collect $10\,\text{fb}^{-1}$ of data by the end of September 2011, and there is a possibility under discussion that the Tevatron will run for a further three years to give an additional $7\,\text{fb}^{-1}$ for each experiment. We are excited at the physics prospects in store for us.

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