Single top quark production at D0

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Updates of electroweak single top quark production measurements by the D0 collaboration are presented using 5.4 fb$^{-1}$ of proton-antiproton collision data from the Tevatron at Fermilab. Measurements of the $t$-channel, $s$-channel and combined single top quark production cross section are presented, including an updated lower limit on the CKM matrix element $|V_{tb}|$. Also reported are results from searches for gluon-quark flavor-changing neutral currents and $W'$ boson production.

I. INTRODUCTION

The production of single top quark events via the electroweak interaction was reported in 2009 by the D0 [1] and CDF [2] collaborations. A measurement of the single top quark production cross section provides a direct measurement of the quark mixing matrix element $|V_{tb}|$ [3]. It also serves as a probe of the $Wtb$ coupling [4–8] and is sensitive to several models of new physics [9]. Single top quark production proceeds via the $t$-channel exchange of a virtual $W$ boson between a light quark line and a heavy quark line ($tqb$) and the $s$-channel production and decay of a virtual $W$ boson ($tb$), shown in Fig. 1.

Here we present an updated measurement of the combined single top quark production cross section using 5.4 fb$^{-1}$ of data collected by the D0 experiment at the Tevatron proton-antiproton collider at Fermilab [10]. The $s$-channel and $t$-channel modes are measured separately and the first observation of $t$-channel production is reported [11].

II. SM SINGLE TOP QUARK MEASUREMENT

A. Event selection

The single top quark final state consists of a lepton (electron or muon) and a neutrino from the $W$ boson decay, a $b$ quark from the top quark decay and an additional light quark ($t$-channel) or $b$ quark ($s$-channel). The event selection for all analysis channels requires large $E_T$ and two to four jets, at least one of which is $b$-tagged.

The backgrounds to this signature are dominated by $W$ bosons produced in association with jets ($W$+jets), with smaller contributions from $t\bar{t}$ pairs. Multijet events also contribute to the background when a jet is misidentified as an isolated electron or a heavy-flavor quark decay results in an isolated lepton. Diboson ($WW$, $WZ$, $ZZ$) and $Z$+jets contribute smaller backgrounds. In total, about 8,000 events are selected with an expected SM signal of about 400 events.

In addition to the single top analysis sample, several cross-check samples are defined: a without any $b$-tag requirements; a sample containing exactly two jets and sum of transverse momenta of all objects $H_T < 175$ GeV;
and a sample containing exactly four jets and requiring $H_T > 300$ GeV. Figure 2 shows a comparison between the data and the signal+background model for several discriminating variables used in the analysis in the different samples.

**FIG. 2:** Comparisons between the data and the background model for (a) $E_T$, (b) $W$ boson transverse mass, (c) light quark jet pseudorapidity multiplied by lepton charge, (d–f) reconstructed top quark mass. Subfigures (a) and (b) are before $b$-tagging, (c) and (d) are after $b$-tagging, (e) is a control sample dominated by $W$+jets, and (f) is a control sample dominated by $t\bar{t}$ pair events. The hatched bands show the ±1σ uncertainty on the background prediction for distributions obtained after $b$-jet identification (c–f).

### B. Multivariate analysis

The expected single top quark signal is small compared to the statistical data uncertainty and the uncertainty on the background prediction. Thus, multivariate analysis methods are employed to extract the single top quark signal. Several different multivariate methods (Boosted decision trees, Bayesian neural networks and a Neuro-evolution network) are trained and then combined into one filter. This training is done separately for the combined single top analysis and for the dedicated $t$-channel and $s$-channel analyses. The resulting discriminants are shown in Fig. 3.
The cross section is measured using a Bayesian approach, including all systematic uncertainties and their correlations \[12\]. The expected and observed cross section measurements are given in Table \[1\]. The separate $t$-channel and $s$-channel cross sections are extracted assuming the SM contribution for the $s$-channel and $t$-channel, respectively.

The $t$-channel signal is observed with a significance of more than five standard deviations, and the combined single top measurement is the most precise measurement to date.

D. $V_{tb}$

The single top quark production cross section is proportional to the CKM matrix element $|V_{tb}|^2$, allowing for a $|V_{tb}|$ measurement without having to assume three quark generations or CKM matrix unitarity. We only assume that SM sources for single top quark production and that top quarks decay exclusively to $Wb$, as well as that the $Wtb$ interaction is CP-conserving and of the $V-A$ type. We set a lower limit at the 95\% confidence
TABLE I: Expected and observed cross sections in pb for $tb$, $tqb$, and $tb+tqb$ production. All results assume a top quark mass of 172.5 GeV and the expected cross section normalize the single top signal to its theoretical prediction $^{13}$.

| Discriminant | Expected cross section | Observed cross section |
|--------------|------------------------|------------------------|
| $tb$         | $1.12^{+0.45}_{-0.33}$ pb | $0.68^{+0.38}_{-0.35}$ pb |
| $tqb$        | $2.43^{+0.67}_{-0.61}$ pb    | $2.86^{+0.69}_{-0.63}$ pb    |
| $tb+tqb$     | $3.49^{+0.77}_{-0.71}$ pb    | $3.43^{+0.73}_{-0.72}$ pb    |

FIG. 4: Distributions of the FCNC discriminant for (a) the full discriminant range and (b) the signal region.

level of $|V_{tb}| > 0.79$.

III. SEARCHES FOR NEW PHYSICS

A. Search for flavor-changing neutral currents

The $t$-channel final state is sensitive to flavor-changing neutral currents (FCNC) via quark-gluon couplings. In FCNC interactions a gluon vertex couples an up quark ($tgu$) or a charm quark ($tgc$) to the top quark. The rate for these events at the Tevatron is large because the initial state contains two light quarks. The D0 collaboration searched for FCNC interactions in 2.3 fb$^{-1}$ $^{14}$, using the single top quark observation analysis sample $^{1}$. A Bayesian Neural Network (BNN) is used to separate the FCNC signal from the large backgrounds. The BNN output distribution is shown in Fig. 4. The observed limits on the FCNC couplings are $\kappa_{tgu}/\Lambda < 0.013$ TeV$^{-1}$ and $\kappa_{tgc}/\Lambda < 0.057$ TeV$^{-1}$, without making assumptions about the $tgc$ and $tgu$ couplings, respectively. These can be translated into limits on top quark decay branching fractions, which are $\mathcal{B}(t \rightarrow gu) < 2.0 \times 10^{-4}$ and $\mathcal{B}(t \rightarrow gc) < 3.9 \times 10^{-3}$.

B. Search for heavy $W'$ boson production

Models of new physics that introduce additional symmetries predict the existence of additional heavy charged bosons, generally called $W'$. The D0 collaboration has performed a search for $W'$ boson production in 2.3 fb$^{-1}$ of data $^{15}$, using the same event selection and background modeling as the single top quark observation analysis $^{1}$. This analysis explores the full parameter space of both SM-like left-handed couplings ($aL$) and right-handed couplings ($aR$) and a mixture of both for the $W'$ boson. For each $W'$ boson mass under consideration, a Boosted Decision Tree (BDT) is trained to separate the $W'$ boson signal from the backgrounds. The BDT output for one mass is shown in Fig. 5(a).

The resulting limits on the $W'$ boson mass as a function of the two couplings are shown in Fig. 5(b). For SM-like left-handed $W'$ couplings, the limit on the $W'$ boson mass is $M(W') > 863$ GeV. For purely right-handed couplings it depends on whether a right-handed neutrino ($\nu_R$) exists and is lighter than the $W'$ boson, the limit is $M(W') > 885$ GeV for $M(W') < m(\nu_R)$ and $M(W') > 890$ GeV for $M(W') > m(\nu_R)$. If both left-handed
and right-handed couplings are present, the limit is $M(W') > 916$ GeV.

**IV. CONCLUSIONS**

The D0 experiment at the Tevatron has presented updates on the measurement of single top quark production. Besides a more precise combined single top quark production cross section measurement, the $t$-channel mode was isolated for the first time. All of the measurements are consistent with the SM expectation. Several new physics scenarios have been explored in the single top quark final state and limits have been set on on flavor-changing neutral currents and on new heavy boson $W'$ production.

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