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Observation of Single Top-Quark production with the CDF II Experiment

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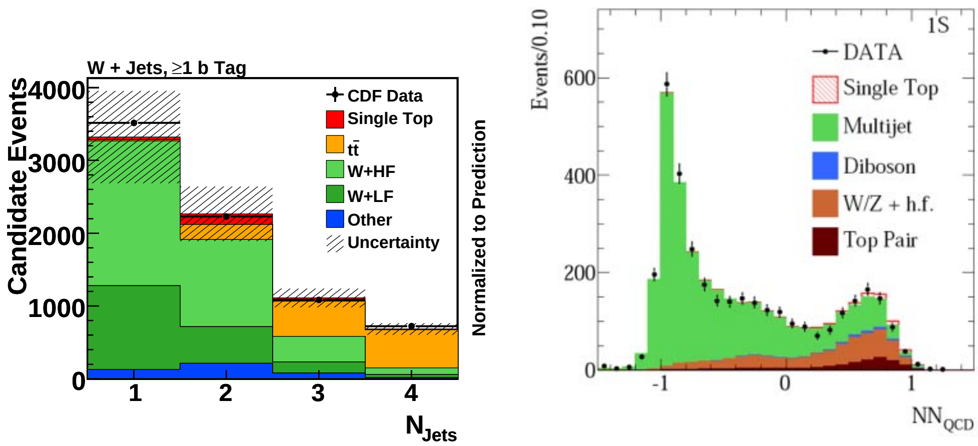
Summary. — We present the observation of electroweak single top-quark production using up to $3.2\,\text{fb}^{-1}$ of data collected by the CDF experiment. Lepton plus jets candidate events are classified by four parallel analysis techniques: one likelihood discriminant, one matrix-element discriminant, one decision-tree discriminant, and one neural-network discriminant. These outputs are combined with a super discriminant based on a neural-network analysis in order to improve the expected sensitivity. In conjunction with one neural-network discriminant using a complementary dataset of MET plus jets events with a veto on identified leptons we observe a signal consistent with the standard model but inconsistent with the background-only model by 5.0 standard deviations, with a median expected sensitivity in excess of 5.9 standard deviations.

PACS 14.65.Ha – Top quarks.
PACS 13.85.Qk – Inclusive production with identified leptons, photons, or other nonhadronic particles.
PACS 12.15.Hh – Determination of Kobayashi-Maskawa matrix elements.
PACS 12.15.Ji – Applications of electroweak models to specific processes.

1. – Motivation

The reasons for studying electroweak single top-quark production are compelling: the production cross section is directly proportional to the square of the CKM matrix element $|V_{tb}|$, and thus a measurement of the rate constrains fourth-generation models and other new phenomena. In the SM, top-quarks are expected to be produced singly through s- or t-channel exchange of a virtual W boson with an expected combined production cross section of $\sigma_{s+t} \sim 2.9\,\text{pb}$ [1,2]. Both the CDF and D0 Collaborations at the Tevatron have reported observation of single top-quark production [3-5], this document describes the analyses done using up to $3.2\,\text{fb}^{-1}$ of data collected with the CDF II detector leading to the observation of single top-quark production.



(a) (b)

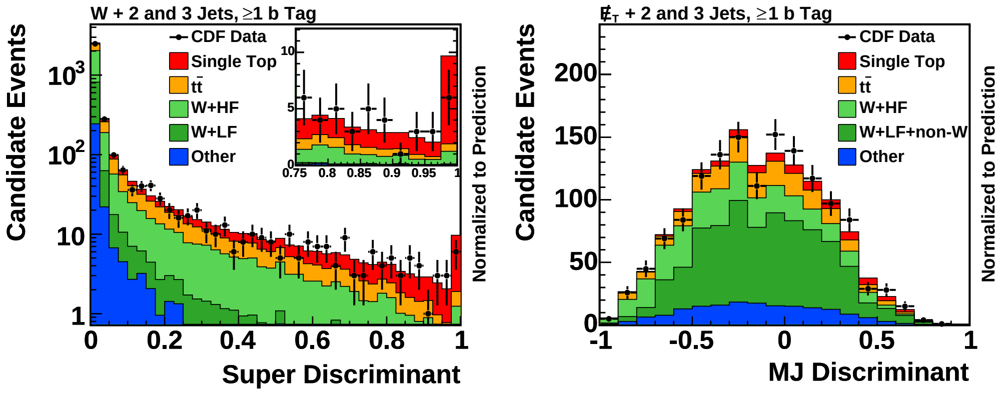
Fig. 1. – (Colour on-line) (a) Expected number of $\ell + \not\!\!E_T$ +jets events as a function of the number of jets for the signal (red) and each background process; the dashed band is the uncertainty on the background predictions. (b) Output of the $\mathrm{NN_{QCD}}$ for the MET plus jets analysis which requires candidate events to pass $\mathrm{NN_{QCD}} > -0.1$. The stacking orderings follow those of the legends.

2. – Candidate event selection

The lepton plus jets event selection is based on selecting $\ell + \not\!\!E_T$ +jets events in $3.2\,\mathrm{fb}^{-1}$ of CDF data, where ℓ is an explicitly reconstructed electron or muon with $p_T > 20\,\mathrm{GeV}$ from the W boson decay. The presence of high missing transverse energy, $\not\!\!E_T > 25\,\mathrm{GeV}$, and two or three energetic jets, $E_T > 20\,\mathrm{GeV}$, are also required. At least one of the jets has to be identified as a jet coming from a b-quark.

To add acceptance to the dataset with identified electrons or muons, CDF uses for the first time MET plus jets events containing jets, large missing transverse energy, and no reconstructed electrons or muons. This signature comprises events with $W \to \tau\nu$ decays where the hadronic τ decays are dominant, and with $W \to e\nu$ or $W \to \mu\nu$ decays where the electrons or muons are unidentified. The MET plus jets event selection is based on missing transverse energy, $\not\!\!E_T > 50\,\mathrm{GeV}$, plus two or three jets, $E_T^{J1} > 35\,\mathrm{GeV}$, $E_T^{J2} > 25\,\mathrm{GeV}$, and $E_T^{J3} > 15\,\mathrm{GeV}$, where at least one of the jets is b-tagged, in a dataset corresponding to $2.1\,\mathrm{fb}^{-1}$. Because the event selection vetoes on the presence of a reconstructed electron or muon this measurement is statistically independent of the lepton plus jets analysis. Through its orthogonal event selection, it increases the overall CDF signal acceptance by $\sim 30\%$.

The background has contributions from events in which a W boson is produced in association with one or more heavy flavor jets, events with mistakenly b-tagged light-flavor jets, QCD multijet events, $t\bar{t}$ production, diboson processes, and Z + jet events, as shown in fig. 1(a) for the lepton plus jets event selection. From this figure, it is clear that the signal is hidden under huge and uncertain background processes which make counting experiments impossible.



(a) (b)

Fig. 2. – (Colour on-line) Comparison of the predicted distributions with data of the super discriminant (a) and the MJ discriminant (b). The stacking orderings follow those of the legends.

3. – Multivariate analyses techniques

To overcome these challenges, a variety of multivariate techniques for separating single top-quark events from the backgrounds have been developed as described in the following. One approach [6] employs neural networks (NN) [7] which combine 11 to 18 variables into one more powerful discriminant. Among the most important ones is the output of a jet-flavor separator dedicated neural network [8]. The matrix element (ME) method [9] relies on the evaluation of event probability densities for signal and background processes based on calculations of the differential cross sections. A projective likelihood function (LF) technique [10] is used to combine information from 7 to 10 input variables to optimize the separation of the single top-quark signal from the backgrounds. A separate analysis dedicated to the search for s-channel single top-quark production is additionally performed using this technique [11]. The boosted decision tree (BDT) [12] analysis uses binary cuts iteratively on over 20 input variables to classify events. The MET+Jets analysis uses several powerful variables like the transverse momentum imbalance $\not{p}_{\rm T}$, $\not{E}_{\rm T}$, the angle between the latter, and the jet directions as inputs to a neural network ($\rm NN_{QCD}$) trained to suppress QCD multijet events. The candidate events are required to pass an $\rm NN_{QCD}$ output higher than -0.1 as shown in fig. 1(b), removing 77% of the QCD background events, while keeping 91% of the signal acceptance. The MJ analysis further applies a second neural network to combine information of several input variables to discriminate single top-quark events from the remaining background events.

CDF combines the NN, ME, LF, and BDT analyses using a super-discriminant (SD) technique. The SD method uses a neural network trained with neuro-evolution [13] to separate the signal from the background taking as inputs the discriminant outputs of the four analyses for each event. A simultaneous fit over the two exclusive channels, MJ and SD, see fig. 2, is performed to obtain the final combined results.

The combined s- plus t-channel cross section is measured using a Bayesian binned likelihood technique [14] assuming a flat non-negative prior in the cross sections and integrating over the systematic uncertainties, including jet energy scale, b-tagging efficiencies, background modeling, lepton identification and trigger efficiencies, the amount of initial and final state radiation, PDFs, and factorization and renormalization scales. The significance for the combined measurement is calculated as a p-value [14], which is the probability, assuming the absence of single top-quark production, that the value of the test statistic, $-2\ln Q$, is more signal-like than that observed in data. The p-value is then converted into standard deviations using the integral of one side of a Gaussian.

4. – Results

In the combined search for s- plus t-channel single top-quark production, the excess of signal-like events over the expected background is interpreted as observation of single top-quark production with a p-value of 3.10×10^{-7}, corresponding to a significance of 5.0 standard deviations. The sensitivity is defined to be the median expected significance and is found to be in excess of 5.9 standard deviations. CDF finds, assuming a top-quark mass of $175\,\mathrm{GeV}/c^2$, a value of the combined s- and t-channel cross section of $2.3^{+0.6}_{-0.5}$ pb, and consequential $|V_{tb}| = 0.91 \pm 0.11(\mathrm{stat} + \mathrm{syst}) \pm 0.07$ (theory [1]).

More details can be found on the CDF public web page [15].

5. – Study of high discriminant output

To achieve confidence in the quality of the signal contribution in the highly signal-enriched region of the discriminants, a further study has been conducted on the NN discriminant in the lepton plus jets channel. By requiring a NN discriminant output above 0.4 in the event sample with 2 jets and 1 b tag, a signal-to-background ratio of about 1 : 3 is achieved, see fig. 3(a). This subsample of signal candidates is expected to be highly enriched with signal candidates and is simultaneously sufficient in size to check the Monte Carlo modeling of the data. We compare the expectations of the signal and background processes to the observed data of this subsample in various highly discriminating variables. The agreement is good, as is shown, for example, for the invariant mass of the charged lepton, the neutrino, and the b-tagged jet $M_{\ell\nu b}$ in fig. 3(c). Since only very signal-like background events are within this subsample, the background shapes are very similar to the signal shapes which can be seen in fig. 3(b). This is because the $M_{\ell\nu b}$ is one of the most important input variables of the NN discriminant, leading to a signal-like sculpted shape for background events in this subsample. As a consequence, the shape of this distribution does not carry information as to whether a signal is present or absent. To overcome the similar shapes of signal and background events in the signal-enriched subsample, a special neural-network discriminant (NN′) is constructed in exactly the same way as the original, but without $M_{\ell\nu b}$ as an input. Since $M_{\ell\nu b}$ is highly correlated with other original neural-network input variables, such as $M_{\mathrm{T}}^{\ell\nu b}$ (with a correlation coefficient of 65%), H_{T} (45%), and M_{jj} (24%), these variables are also omitted for the training of the special NN′ discriminant. Despite the loss of discrimination through the removal of some very important input variables, the NN′ discriminant is still powerful enough to enrich a subsample of events with signal, see fig. 3(d). With the requirement NN′ > 0.4, the signal-to-background ratio is somewhat reduced compared with that of the original NN discriminant. The benefit of this selection is that the predicted distributions of the signal and background are now more different from each other. We predict that background events are dominant at lower values of $M_{\ell\nu b}$ while the single top quark signal is concentrated around the reconstructed top quark mass of $175\,\mathrm{GeV}/c^2$, as shown in fig. 3(e). Because of the more distinct shapes of the signal and background expectations, the observed excess in data over the background is no longer explicable by a higher

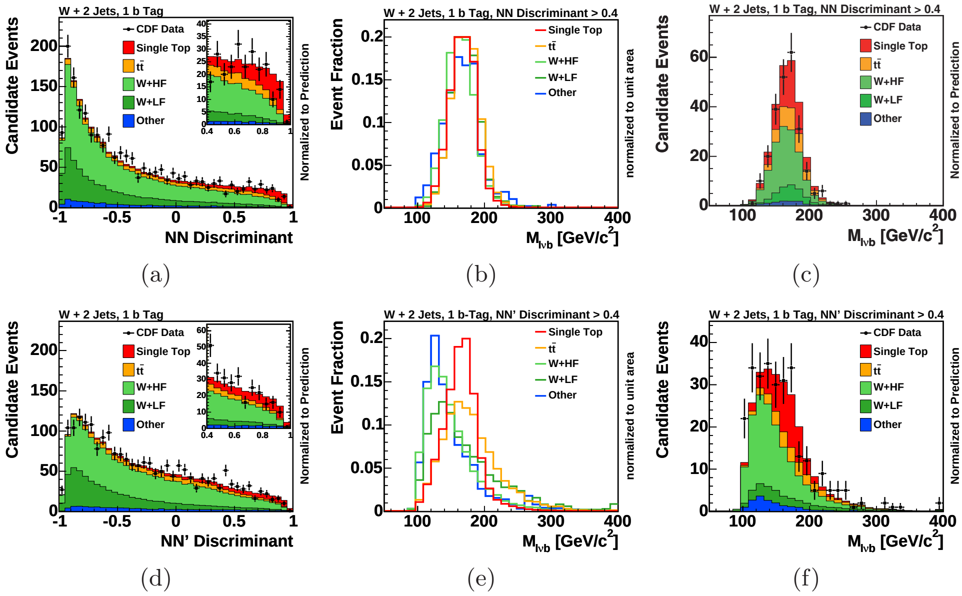


Fig. 3. – (Colour on-line) Comparison of the predictions and the data for $M_{\ell\nu b}$ for events with an output above 0.4 of the original NN (top) and a specially trained NN′ (bottom) discriminant. The stacking orderings follow those of the legends.

number of background events alone; a substantial amount of signal events is needed to describe the observed distribution, see fig. 3(f). The NN′ discriminant is used only for this study; it is not included in the main results of the analysis.

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