Evidence For Single Top Quark Production Using The Matrix Element Analysis Technique in 1 fb^{-1} of Tevatron RunII Data

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We present the first evidence for electroweak single top quark production using nearly 1 fb^{-1} of Tevatron Run II data at $\sqrt{s} = 1.96$ TeV. We select single-top-like data events in the lepton+jets decay channel and isolate them from backgrounds using the matrix element analysis method. This technique employs leading order matrix elements to compute an event probability for both signal and background hypotheses. Using the expected signal acceptance, background, and observed data we measure the single top quark cross section:

$$\sigma\left(p\bar{p} \rightarrow tb + tqb + X\right) = 4.6^{+1.8}_{-1.5}\ \text{pb}$$

The probability for the background to have fluctuated up to give at least the cross section measured in this analysis is 0.21%, which corresponds to a Gaussian equivalent significance of 2.9σ.

1 Introduction

The top quark is the heaviest of the known fermions and is currently only produced at Fermilab's Tevatron proton-antiproton collider with a center-of-mass energy of 1.96 TeV. While most top quarks are produced via the well measured QCD pair production mode ($p\bar{p} \rightarrow t\bar{t}$), they can also be created via an electroweak interaction known as single top. At the Tevatron, single top quarks are produced in two modes: the s-channel process ($p\bar{p} \rightarrow tb$) which has an estimated cross section of 0.88 ± 0.11 pb and the t-channel process ($p\bar{p} \rightarrow tqb$) with a cross section of 1.98 ± 0.25 pb[1]. Feynman diagrams for the two production channels are shown in Figure 1.

Measuring single top quark production is interesting because one can directly determine the magnitude of the CKM matrix element V_{tb} since $\sigma_{tb+tqb} \propto |V_{tb}|^2$. Single top quark production is also sensitive to new physics. The existence of a new charged gauge boson ($W^{'}$) would enhance

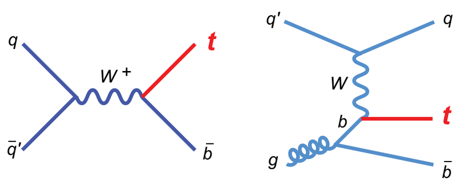

Figure 1: Representative Feynman diagrams for s-channel (left) and t-channel (right) single top production.

the effective s-channel cross section, while flavor changing neutral currents in the top sector would enhance the effective t-channel cross section.

2 Event Selection and Background Modeling

We measure single top quark production in the lepton+jets decay channel. These events are selected in data by requiring the following selection cuts.

- One high p_T isolated lepton (electron or muon). The electron is required to be measured in the central calorimeter ($|\eta^{\text{det}}| < 1.1$) with $p_T > 15$ GeV. The muon must have $p_T > 18$ GeV and $|\eta^{\text{det}}| < 2.0$. Events with electrons veto events with muons and visa versa.
- Missing transverse energy > 15 GeV.
- Between two and three reconstructed jets. The leading jet (highest p_T) must have $p_T > 25$ GeV and $|\eta^{\text{det}}| < 2.5$. The second jet is required to have $p_T > 20$ GeV and the third jet must have $p_T > 15$ GeV. Both the second and third jets much have $|\eta^{\text{det}}| < 3.4$.
- At least one jet must be b-tagged by the neural network b-tagger. This analysis selects events with one or two b-tagged jets.

After applying this event selection there are three main backgrounds present in the data: W+jets, $t\bar{t}$, and QCD multijet production. The W+jets and $t\bar{t}$ backgrounds are modeled using ALPGEN [2] with the MLM jet-parton matching scheme. The shape for QCD multijet events is derived from data events that pass all selection criteria except lepton-jet isolation. The $t\bar{t}$ background is normalized to the NLLO Tevatron cross section, while W+jets and QCD multijet events are normalized to the data before b-tagging.

Both s-channel and t-channel single top quark events are modeled using the SINGLETOP [3] Monte Carlo generator. A table showing the expected number of single and background events can be found on the DØ single top public webpage [4].

3 Matrix Element Analysis Technique

The matrix element analysis technique attempts to assign events as signal or background-like based on the normalized proton-antiproton differential cross section as shown in Equation 1

$$P(\vec{x}) = \frac{1}{\sigma}\frac{d\sigma}{d\vec{x}} = \frac{1}{\sigma}\sum_{i,j}\int d\vec{y}\left[f_i(q_1,Q^2)dq_1 \times f_j(q_2,Q^2)dq_2 \times \frac{d\sigma_{hs,ij}}{d\vec{y}} \times W(\vec{x},\vec{y})\right]; \qquad (1)$$

where $f_i(q_1, Q^2)$ is the parton distribution function for parton flavor i, $\frac{d\sigma_{hs,ij}}{d\vec{y}}$ is the parton-parton hard scatter differential cross section ($\propto |\mathcal{M}|^2$), σ is the normalization factor, $\int dy dq_1 dq_2$ represents the integration over the parton phase space, and $W(\vec{x}, \vec{y})$ is the detector resolution function that maps the parton state ($\vec{y}$) to the detector state ($\vec{x}$).

The probability density in Equation 1 is evaluated separately for events with two and three jets. Events with two jets are evaluated using two single top matrix elements and three background W+jets matrix elements as shown in Figure 2.

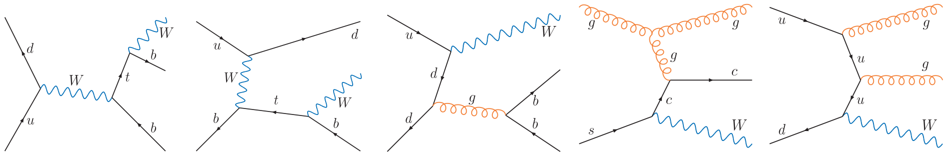

Figure 2: Leading order Feynman diagrams used for events with two jets. From left to right: $p\bar{p} \rightarrow tb$ (signal), $p\bar{p} \rightarrow tq$ (signal), $p\bar{p} \rightarrow Wbb$ (background), $p\bar{p} \rightarrow Wcg$ (background), and $p\bar{p} \rightarrow Wgg$ (background).

Events with three jets are evaluated using two single top matrix elements and one background W+jets matrix element as shown in Figure 3.

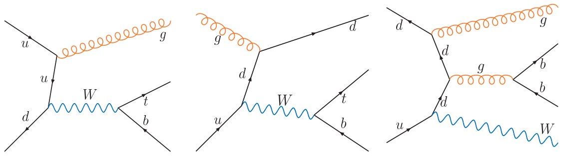

Figure 3: Leading order Feynman diagrams used for events with two jets. From left to right: $p\bar{p} \rightarrow tbg$ (signal), $p\bar{p} \rightarrow tqb$ (signal), and $p\bar{p} \rightarrow Wbbg$ (background).

The signal and background probabilities are combined using the *a-posteriori* Bayesian probability density for the signal process (either s-channel or t-channel) given the event $\vec{x}$ as shown in Equation 2

$$D(\vec{x}) = \frac{P_{\text{Signal}}(\vec{x})}{P_{\text{Signal}}(\vec{x}) + P_{\text{Background}}(\vec{x})}. \tag{2}$$

The discriminant variable defined in Equation 2 is evaluated for all data, signal Monte Carlo, and background events. Figure 4 shows the expected distributions of s-channel, t-channel, and Wbb Monte Carlo events in a two-dimensional plane defined by the t-channel and s-channel discriminant.

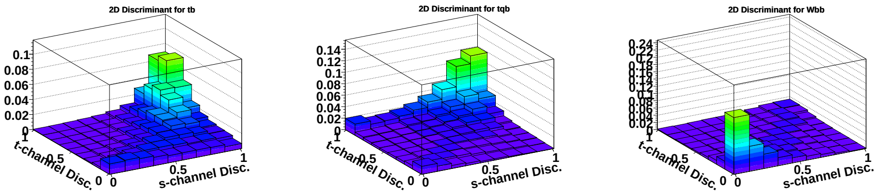

Figure 4: Expected performance of s-channel (left), t-channel (middle), and Wbb (right) Monte Carlo events shown in a two-dimensional plane defined by the t-channel and s-channel discriminant.

4 Results with 0.9 fb^{-1}

Applying the matrix element discriminant to signal, background, and data event resulted in an excess of data events in the signal region. From this excess, we measure the single top cross section as

$$\sigma\left(p\bar{p} \rightarrow tb + tqb + X\right) = 4.6^{+1.8}_{-1.5}\ \text{pb}.$$

The full matrix element discriminant including a zoom of the signal region is shown in Figure 5.

The significance of the observed result is determined using ensemble tests. In this test, pseudo datasets with zero signal content are created and the number of datasets that yield a

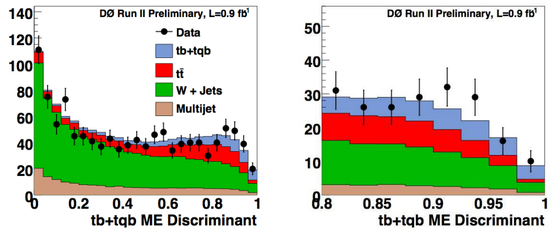

Figure 5: The matrix element discriminant applied to the data, signal, and background events. The left plot shows the full discriminant range, while the right plot is a zoomed into the signal region. The excess of data above the background hypothesis is clearly seen in this plot.

cross section greater than or above the measured cross section is determined. Using nearly 100,000 ensemble datasets, this fraction was measured to be 0.21% corresponding to a 2.9σ signal significance. The agreement of this result with the standard Model was measured using pseudo datasets with the signal fraction set to the standard model value. In this test, 21% of the datasets resulted in a cross section greater than or equal to the measured value. Information regarding the systematics errors in this analysis as well as the Bayesian statistical technique used in the cross section measurement can be found in our recently published article in Physical Review Letters [5].

5 Summary

We presented evidence for electroweak single top quark production at the Tevatron. An analysis of nearly 1 fb^{-1} of Run II data using the matrix element method to select single top quark-like events measures the combined $s + t$-channel production cross section to be

$$\sigma\left(p\bar{p} \to tb + tqb + X\right) = 4.6^{+1.8}_{-1.5} \text{ pb},$$

where the probability of a background fluctuation is 0.21%, which corresponds to a Gaussian equivalent signal significance of 2.9σ.

6 Acknowledgments

I would like to thank the organizers of this conference for the excellent scientific program as well as the excellent skiing. I would also like to thank the European Union for the grant covering the cost of the hotel.

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