Single Top Quark Production at the Tevatron

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The Run II of the Tevatron has started in 2001 and the D0 and CDF experiments have collected more than 2 fb^{-1} data since then. We present the results of a search for electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider, using a dataset with integrated luminosity of nearly 1 fb^{-1}.

1 Introduction

First observed in 1995 [1], the top quark is one of a pair of third-generation quarks in the standard model of particle physics. It has charge $+2/3e$ [2] and a mass of 171.4±2.1 GeV [3], about 40 times heavier than its isospin partner, the bottom quark. We present the results of a search for top quarks produced singly via the electroweak interaction from the decay of an off-shell W boson or fusion of a virtual W boson with a b quark [4, 5, 6]. All previously measured top quarks have come from the decay of a highly energetic gluon, which produces top quark - top antiquark ($t\bar{t}$) pairs. The standard model prediction for the cross section for $p\bar{p} \to t\bar{t}$ is 6.7 pb [7, 8], for the s-channel single top quark process $p\bar{p} \to tb$ it is 0.9 ± 0.1 pb, and for the t-channel process it is 2.0 ± 0.3 pb [5]. For brevity, we use the notation "tb" to mean the sum of $t\bar{b}$ and $\bar{t}b$, and "tqb" to mean the sum of $tq\bar{b}$ and $\bar{t}\bar{q}b$. The main tree-level Feynman diagrams for single top quark processes are shown in Fig. 1.

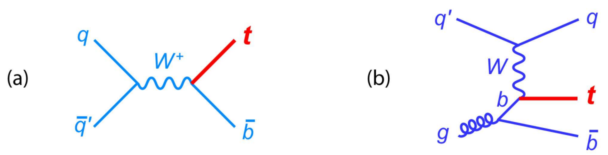

Figure 1: Leading order Feynman diagrams for (a) s-channel single top quark production and (b) t-channel production.

Top quarks are interesting particles to study since their very high mass implies a Yukawa coupling to the Higgs boson with a value near unity, unlike any other known particle. They also decay before they hadronize, allowing the properties of a naked quark such as spin to be transferred into its decay products and thus be measured and compared to standard model predictions. Events with single top quarks can also be used to study the Wtb coupling, and to measure directly the absolute value of the CKM matrix element $|V_{tb}|$ without assuming three generations of quarks. A value not close to one would imply the existence of a fourth quark family.

The rsults presented here are part of a series performed by the CDF and D0 experiments. Both CDF and D0 published papers [9, 10, 11, 12] using Run I and Run II data but none of these searches was sensitive enough to observe single top quark production.

2 Search Strategy and Event Selection

The search focuses on the final state consisting of one high transverse momentum (p_T) isolated electron or muon and missing transverse energy ($\not{E}_T$) together with a b-quark jet from the decay of the top quark ($t \to Wb \to \ell\nu b$), and an additional b antiquark in the case of s-channel production, or an additional light-quark jet and a b-antiquark jet for t-channel production. The b-antiquark jet produced in the t-channel is rarely reconstructed since it is produced in the forward direction with low transverse momentum. The main backgrounds in this analysis share the same lepton+jets final state; they are W-boson production in association with jets (W+jets), top quark pair production ($t\bar{t}$) in the lepton+jets and dilepton final states if a jet or a lepton is not reconstructed, and multijet production, where a jet is misreconstructed as an electron, or a heavy-flavor quark decays to a muon that is misidentified as isolated from the jet.

D0 selects 1,398 lepton+jets data events, which is expected to contain 62 ± 13 single top quark events. The analysis is split into twelve orthogonal channels based on the lepton flavor (e or μ), jet multiplicity (2, 3, or 4), and number of identified b jets (1 or 2), to increase the search sensitivity since the expected signal acceptance and signal to background ratio differ significantly from channel to channel.

CDF selects 644 candidate events for this analysis by requiring a W + 2 jet event topology only, which is expected to contain 38 ± 6 single top quark events. One or both of the two jets should be identified as a b-jet using the secondary vertex tag requirement. CDF further requires the missing transverse energy and the jets not to be collinear for low values of missing transverse energy. This requirement removes a large fraction of the non-W background while retaining most of the signal.

Since we expect the single top quark signal events to constitute only a small fraction of the selected event samples, a counting experiment will not have sufficient sensitivity to verify their presence. Both CDF and D0 use sophisticated analysis techniques (listed below) to discriminate signal from backgrounds. The resulting discriminant distributions are used to set limits or measure the production cross-section.

- Boosted Decision Trees - used by D0
- Matrix Elements - used by D0 and CDF
- Likelihood Discriminants - used by CDF
- Bayesian Neural Networks - used by D0 and CDF

3 Results

In case of CDF, the Likelihood method and Neural Networks set a limit of $\sigma_{s+t} < 2.7$ pb at 95%C.L. and $\sigma_{s+t} < 2.6$ pb at 95%C.L. respectivley. The Matrix Elements method measures a cross section of $\sigma_{s+t} = 2.7^{+1.5}_{-1.3}$ pb with a p-value = 1.0% corresponding to a significance of 2.3σ. Using pseudo experiments, the correlation between these three analyses is detremined to be 60-70% with a 1.2% probabaility that one could get a combination of results given above.

The three methods used by D0, Decision Trees, Matrix Elements, Bayesian Neural Networks measure a production cross section of $\sigma_{s+t} = 4.9 \pm 1.4$ pb, $\sigma_{s+t} = 4.6^{+1.8}_{-1.5}$ pb, $\sigma_{s+t} = 5.0 \pm 1.9$ pb respectively, with respective p-values corresponding to a significanse of 3.4σ, 2.9σ and 2.3σ. It should be noted here that CDF and D0 use slightly different methods to measure p-values and thus the two values are not directly comparable. The correlation between these three analysis methods is measured using the ensemble of pseudo-datasets. The Boosted Decision Tree analysis is 39% correlated with the matrix element analysis and 57% correlated with the Bayesian Neural Networks analysis.

D0 uses the Best Linear Unbiased Estimate (BLUE) method [13] to obtain the combined measurement.

$$\sigma\left(p\bar{p} \to tb + X,\ tqb + X\right) \quad = 4.7 \pm 1.3 \text{ pb} \quad (\text{DT} + \text{ME} + \text{BNN combined}),$$

The p-value for the combination corresponds to a significanse of 3.5σ, thus providing the first evidence for single top production. Fig. 2 summarizes the measurements from the individual analyses as well as the combination.

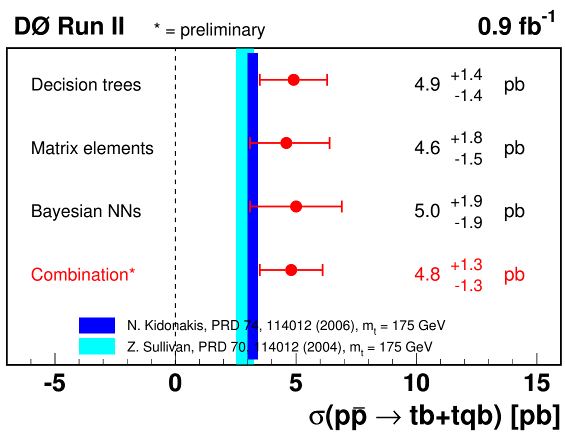

Figure 2: The single top cross section measurements using real data, from the individual analyses and the combination.

D0 also sets a lower limit of $|V_{tb}| > 0.68$ on the absolute value of the CKM matrix element $|V_{tb}|$ based on the single top quark analysis. These result by D0 has already been published [14] .

4 Bibliography

For more information on results from both experiments please visit the following public web pages:

D0: `http://www-d0.fnal.gov/Run2Physics/top/public/fall06/singletop/`
CDF: `http://www-cdf.fnal.gov/physics/new/top/top.html`

4.1 Link to slides

`http://indico.cern.ch/contributionDisplay.py?contribId=109&sessionId=9&confId=9499`

References

[1] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **74**, 2626 (1995); S. Abachi *et al.* (D0 Collaboration), Phys. Rev. Lett. **74**, 2632 (1995).

[2] V.M. Abazov *et al.* (D0 Collaboration), submitted to Phys. Rev. Lett., hep-ex/0608044.

[3] The Tevatron Electroweak Working Group for the CDF and D0 Collaborations, hep-ex/0608032.

[4] S.S.D. Willenbrock and D.A. Dicus, Phys. Rev. D **34**, 155 (1986); S. Dawson and S.S.D. Willenbrock, Nucl. Phys. **B 284**, 449 (1987); C.-P. Yuan, Phys. Rev. D **41**, 42 (1990); S. Cortese and R. Petronzio, Phys. Lett. **B 253**, 494 (1991); R.K. Ellis and S.J. Parke, Phys. Rev. D **46**, 3785 (1992); D.O. Carlson and C.-P. Yuan, Phys. Lett. **B 306**, 386 (1993); G. Bordes and B. van Eijk, Nucl. Phys. **B 435**, 23 (1995); T. Stelzer and S. Willenbrock, Phys. Lett. **B357**, 125 (1995); M.C. Smith and S. Willenbrock, Phys. Rev. D **54**, 6696 (1996); A.P. Heinson, A.S. Belyaev, and E.E. Boos, Phys. Rev. D **56**, 3114 (1997); T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D **56**, 5919 (1997); T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D **58**, 094021 (1997); B.W. Harris *et al.*, Phys. Rev. D **66**, 054024 (2002); Q.-H. Cao *et al.*, Phys. Rev. D **72**, 094027 (2005); N. Kidonakis, hep-ph/0609287.

[5] Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).

[6] Q.-H. Cao, R. Schwienhorst, and C.-P. Yuan, Phys. Rev. D **71**, 054023 (2005).

[7] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).

[8] M. Cacciari *et al.*, J. High Energy Phys. **0404**, 068 (2004).

[9] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **65**, 091102 (2002); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **69**, 053003 (2004).

[10] B. Abbott *et al.* (D0 Collaboration), Phys. Rev. D **63**, 031101 (2001); V.M. Abazov *et al.* (D0 Collaboration), Phys. Lett. **B 517**, 282 (2001).

[11] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 012005 (2005).

[12] V.M. Abazov *et al.* (D0 Collaboration), Phys. Lett. **B 622**, 265 (2005); V.M. Abazov *et al.* (D0 Collaboration), submitted to Phys. Rev. D, hep-ex/0604020.

[13] L. Lyons, D. Gibaut, and P. Clifford, Nucl. Instrum. Methods **A 270**, 110 (1988); R. J. Barlow, *Statistics: A Guide To The Use Of Statistical Methods In The Physical Sciences*, The Manchester Physics Series, John Wiley and Sons, New York (1989); G. Cowan, *Statistical Data Analysis*, Oxford (1998).

[14] D0 Collaboration, Search for single top production PLB 622, 265 (2005)