SINGLE TOP QUARK PHYSICS AT THE TEVATRON

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Recent analyses of single top quark production in proton-anti-proton scattering at a center-of-mass energy of 1.96 TeV are discussed representing up to 9.1 fb^{-1} of Tevatron data. Measurements of the inclusive single top quark production cross section in the s- and t-channels and the extraction of $|V_{tb}|$ are presented. Furthermore, top quark property measurements exploring single top quark production and searches for new physics in single top quark final states are reviewed. The extraction of the top quark width and lifetime and the search for anomalous Wtb couplings are presented in more detail.

1 Introduction

Top quarks were first observed via pair production at the Fermilab Tevatron Collider in 1995 [1]. At the Tevatron, top quarks are either produced in pairs via the strong interaction or singly via the electroweak interaction. In the framework of the standard model (SM), each top quark is expected to decay nearly 100% of the times into a W boson and a b quark W bosons can decay hadronically into $q\bar{q}'$ pairs or leptonically into $e\nu_e$, $\mu\nu_\mu$ and $\tau\nu_\tau$ with the τ in turn decaying into an electron, a muon, or hadrons, and associated neutrinos.

Single top quark production serves as a probe of the Wtb interaction [2], and its production cross section provides a direct measurement of the magnitude of the quark mixing matrix element V_{tb} without assuming three quark generations [3]. However, measuring the yield of single top quarks is difficult because of the small production rate and large backgrounds. At the Tevatron single top quarks are produced predominantly by a t-channel exchange of a virtual W boson which combines with a highly energetic b quark to produce a top quark, or by an s-channel exchange of a far off-shell W boson which decays to produce a top quark and a b antiquark.

2 Cross Section Measurements and Extraction of $|V_{tb}|$

In March 2009, the CDF and D0 Collaborations reported observation of the electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV based on 3.2 fb^{-1} (CDF) [4] and 2.3 fb^{-1} (D0) [5] of data. Both collaborations used events containing an isolated electron or muon and

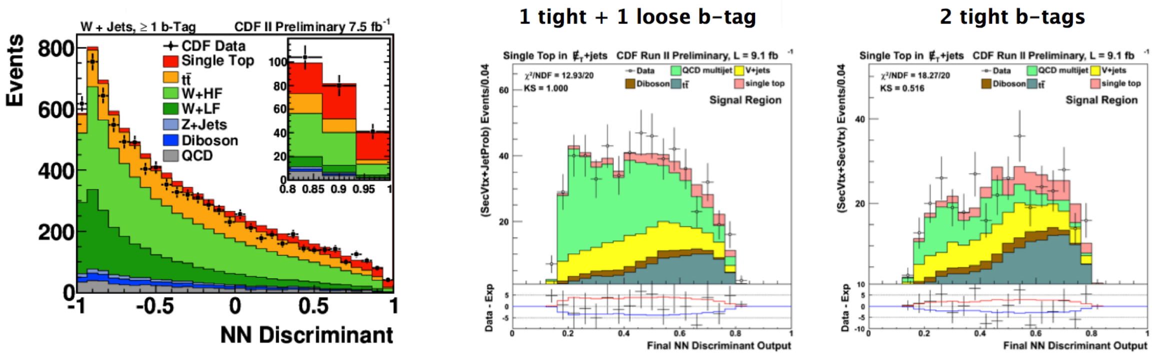

Figure 1: NN output distributions for different b-tagging requirements in the e/μ+jets analysis (left) and in the MET+jets analysis (middle, right). KS/χ^2 tests take into account statistical and systematic uncertainties on signal and background processes.

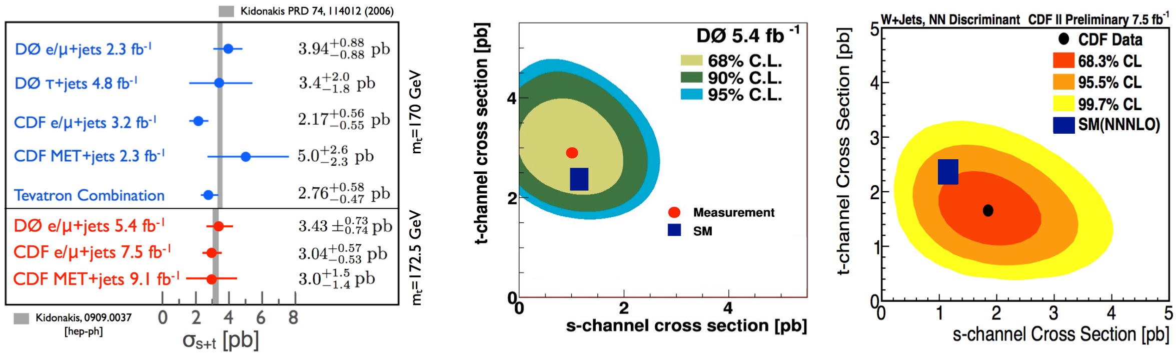

Figure 2: Summary of inclusive single top quark production cross section measurements (left), and Posterior probability density for s-channel vs. t-channel single top quark production in contours of equal probability density for D0 (middle) and CDF (right). The measured cross section and SM prediction are overlaid.

missing transverse energy ($\not\!\!E_T$), together with jets where one or two of the jets were required to originate from the fragmentation of b quarks (b-tagging). The data are divided into independent sets depending on lepton flavor, jet multiplicity, number of b-tags and in the case of D0 the run period. CDF and D0 each combine many variables using different multivariate analysis (MVA) methods such as Boosted Decision Trees (BDT), Neural Networks (NN), Bayesian Neural Networks (BNN), Matrix Elements (ME) and Likelihood functions to increase the separation power between signal and background. The discriminant outputs of each MVA are combined to one discriminant taking the correlations into account. The measurements in different final states are summarized (blue) in Fig. 2 (left).

After the observation D0 has updated the measurement of the single top quark production cross section combining BNN, BDT and neuroevolution of augmented topologies (NEAT) MVA methods in final states with an isolated electron or muon, large $\not\!\!E_T$, and two, three, or four jets, with one or two of them containing a bottom hadron (e/μ+jets) using 5.4 fb^{-1} of data [6]. Recently, CDF has updated their measurement (e/μ+jets) using the NN method analyzing final states with an isolated electron or muon, large $\not\!\!E_T$ from the W boson decay and two or three jets, at least one of them is required to be identified as originating from a bottom quark [7]. The resulting NN discriminate distribution is shown in Fig. 1 (left). To increase the acceptance in the combination, CDF has also performed a measurement of the single top quark production cross section selecting events consistent with a W+jets topology but where no electron or muon has been identified, and where the tau lepton in the $t \to Wb \to \tau\nu b$ channel is reconstructed as a jet in the calorimeters (MET+jets). A recent update with 9.1 fb^{-1} of data has been performed utilizing the NN method [8]. NN output distributions in the signal region are presented for two different b-tagging requirements in Fig. 1 (middle, right).

The three measurements since the observation are summarized (red) in Fig. 2 (left). All measurements agree with each other and the Standard Model (SM) prediction [9]. The results are translated into a direct measurement of the amplitude of the CKM matrix element V_{tb} without making assumptions on the number of quark generations and the matrix unitarity. D0 obtains $|V_{tb}| = 0.92^{+0.10}_{-0.11}$ [6], CDF derives $|V_{tb}| = 0.92 \pm 0.10$ [7], while the Tevatron combination represents the most accurate result of $|V_{tb}| = 0.88 \pm 0.07$ [10].

It is important to measure s-channel and t-channel production separately in a model-independent way, because the SM relation between the two production channels could be changed due to the existence of new physics. D0 has observed t-channel production for the first time separately considering s-channel production as background using 5.4 fb^{-1} of integrated luminosity [11]. Selecting events containing an isolated electron or muon, missing transverse energy and one or two jets originating from the fragmentation of b quarks, the cross section was measured as $\sigma(p\bar{p} \rightarrow tqb + X) = 2.90 \pm 0.59$ (stat + syst) pb for a top quark mass of 172.5 GeV, corresponding to a significance of 5.5 standard deviations.

Both collaborations have also used the measurements of the single top quark production cross section [6,7] to construct a two-dimensional (2D) posterior probability density as a function of the cross sections for the s-channel and t-channel processes. As Fig. 2 shows (middle, right) both measurements agree with the SM predictions.

3 Top Quark Properties

It is an interesting fact that the Tevatron single top quark data set allows sensitive measurements of fundamental top quark properties, such as of the top quark polarization [12] and the top quark width and lifetime [13]. The determination of the latter property has been updated using 5.4 fb^{-1} of integrated luminosity [14]. The total width Γ_t is extracted by combining the partial decay width $\Gamma(t \rightarrow Wb)$ and the branching fraction $\mathcal{B}(t \rightarrow Wb)$. Following the idea proposed in [16], $\Gamma(t \rightarrow Wb)$ is obtained from the measured t-channel single top quark production cross section [11] assuming that the coupling leading to t-channel single top quark production is identical to the coupling leading to top quark decay. $\mathcal{B}(t \rightarrow Wb)$ has been measured in top quark pair production [15]. For a top quark mass of 172.5 GeV, the resulting total width is $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV. This translates to a lifetime of $\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ s.

4 Searches for New Physics

Analyses of single top quark final states at the Tevatron also provide sensitive searches for new physics. So far searches for anomalous Wtb couplings [17,18], for a fourth-generation b quark coupling to the top quark [13], for single top quark production via flavor-changing neutral currents [19,20], for $W' \rightarrow tb$ resonances [21] and for charged Higgs bosons decaying to top and bottom quarks [22] have been performed.

D0 has performed a new search for physics beyond the SM in the form of anomalous Wtb right-handed vector couplings or left- or right-handed tensor couplings, described by an effective Lagrangian including operators up to dimension five [23]. It has been demonstrated that combining the anomalous Wtb couplings search in the single top quark final state [18] with the W boson helicity measurement in top quark decays [24], leads to significant improvements in sensitivity [25]. Fig. 3 shows resulting posterior density distributions for different anomalous couplings. Consistency with the SM is found and 95% C.L. limits on anomalous Wtb couplings are set.

5 Summary

The analysis of single top quark final states provides a very rich physics program at the Tevatron. The inclusive s+t-channel (separate t-channel) production cross section has been measured with

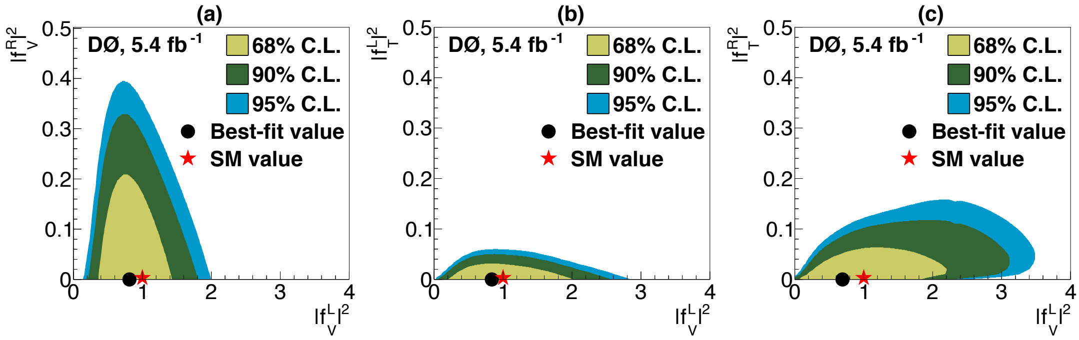

Figure 3: Posterior density distribution for the combination of W boson helicity and single top quark measurements for (a) right-vector vs. left-vector form factors, (b) left-tensor vs. left-vector form factors and (c) right-tensor vs. left-vector form factors. All systematic uncertainties are included.

an uncertainty of 18% (20%). The CKM matrix element $|V_{tb}|$ has been extracted with an uncertainty of 8%. Separate evidence of s-channel production is still one of the most important aims of the single top quark program at the Tevatron. Top quark properties such as the top quark decay width have been measured and many sensitive searches for new physics have been performed. All measurements agree with the SM predictions. Final results with the full data set of ≈ 10 fb^{-1} and a new Tevatron combination of the single top quark cross section and $|V_{tb}|$ are expected soon.

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. A.P. Heinson, A.S. Belyaev, and E.E. Boos, Phys. Rev. D **56**, 3114 (1997).
3. G.V. Jikia and S.R. Slabospitsky, Phys. Lett. B **295**, 136 (1992).
4. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 092002 (2009); T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **82**, 112005 (2010).
5. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **103**, 092001 (2009).
6. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **84**, 112001 (2011).
7. CDF Collaboration, conference note 10793.
8. CDF Collaboration, conference note 10979.
9. N. Kidonakis, arXiv:0909.0037 [hep-ph]; N. Kidonakis, Phys. Rev. D **74**, 114012 (2006).
10. T. E. W. Group [CDF and D0 Collaborations], arXiv:0908.2171 [hep-ex].
11. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **705** 313 (2011).
12. CDF Collaboration, conference note 9920.
13. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **106**, 022001 (2011).
14. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **85**, 091104 (2012).
15. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **107**, 121802 (2011).
16. D. O. Carlson and C. P. Yuan, hep-ph/9509208.
17. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 041801 (2009).
18. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **708**, 21 (2012).
19. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102**, 151801 (2009).
20. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **693**, 81 (2010).
21. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **699**, 145 (2011).
22. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **102**, 191802 (2009).
23. G. L. Kane, G. A. Ladinsky and C. P. Yuan, Phys. Rev. D **45**, 124 (1992).
24. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **83**, 032009 (2011).
25. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **713**, 165 (2012).