FERMILAB-CONF-11-638-E

XXXI PHYSICS IN COLLISION, Vancouver, BC Canada, August 28 - September 1, 2011

Top Quark Production at the Tevatron

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The top quark is the most recently discovered of the standard model quarks, and because of its very large mass, studies of the top quark and its interactions are important both as tests of the standard model and searches for new phenomena. In this document, recent results of analyses of top quark production, via both the electroweak and strong interactions, from the CDF and D0 experiments are presented. The results included here utilize a dataset corresponding to up to 6 fb^{-1} of integrated luminosity, slightly more than half of the dataset recorded by each experiment before the Tevatron was shutdown in September 2011.

1. INTRODUCTION

Since its discovery in 1995 at the CDF and DO experiments [1], the study of the production and properties of the top quark has been one of the most active areas of research in high energy particle physics. The top quark has several properties that make it unique among quarks, including a very large mass of approximately 172.5 $\mathrm{GeV/c^2}$, about 40 times larger than the next heaviest quark, the ~ 4 $\mathrm{GeV/c^2}$ bottom quark. Related to this large mass, the top quark also has a very short lifetime. It decays via the electroweak interaction, almost always to Wb, with a lifetime that is shorter than the time required for hadronization. As a result, information about the top momentum and spin is passed to its decay products, allowing the first opportunity to study a "bare" quark.

There are two main top quark production mechanisms studied at the Tevatron, where protons and antiprotons collided with a center of mass energy of 1.96 TeV. Individual top quarks can be produced via the electroweak interaction, usually in association with additional quark jets. This production mode faces difficulties with large non-top backgrounds and a small cross section, and as a result single top production was not observed until 2009 [2], 14 years after the discovery of the top quark. The original top quark discovery took place in events where tops are produced in pairs by the strong interaction. The top pair production mode has the advantages of a larger cross section and more easily controllable backgrounds, resulting in most analyses of top quark properties using top pair events. For both single top and top pair events, a good understanding of the production rate and production mechanisms is essential for studying top quark properties, testing the standard model, and looking for new interactions coupling to top quarks.

2. SINGLE TOP QUARK PRODUCTION

2.1. Single Top Cross Section

The electroweak production of single top quarks at the Tevatron is expected to have a cross section of approximately 3 pb [3], with the precise value dependent on the mass of the top. About one-third of this cross section is due to the exchange of a W boson in the s-channel, while the remainder comes from t-channel W exchange. Single top quarks can also be produced in association with a W boson, but the cross section for this process is negligible at the Tevatron.

With a small cross section compared to top pair production and a large background from the production of W bosons in association with jets, single top quarks are difficult to observe experimentally. Both CDF and D0 use sophisticated multivariate techniques such as neural networks and boosted decision trees in order to extract the single top production signal. By combining results using CDF data corresponding to 3.2 fb^{-1} and D0 data corresponding to 2.3 fb^{-1}, a combined single top cross section of $2.78^{+0.58}_{-0.47}$ pb is measured, which is in good agreement with the theoretical expectation [4]. Because the single top cross section is proportional to the square of the CKM matrix element V_{tb}, this cross section can be used to extract a 95% confidence level limit of $|\mathrm{V}_{tb}| > 0.77$. D0 also has a more recent measurement in 5.4 fb^{-1} which yields a single top cross section of $3.43^{+0.73}_{-0.74}$ pb [5].

Both CDF and D0 also measure cross sections for s-channel and t-channel single top production separately. Such measurements are important tests of the standard model, since many models that predict new production mechanisms for single top quarks, such as flavor changing $t - Z - c$ couplings, can alter the relative proportion of s-channel and t-channel single top production. Using a dataset of 3.2 fb^{-1}, CDF measured cross sections in the two production channels of $\sigma_s = 1.8^{+0.7}_{-0.5}$ pb and $\sigma_t = 0.8^{+0.4}_{-0.4}$ pb [6]. A recent D0 analysis with 5.4 fb^{-1} found $\sigma_s = 0.98 \pm 0.63$ pb

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

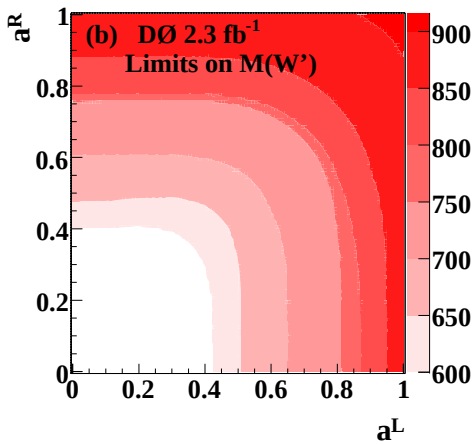

Figure 1: W' mass limits from D0.

and $\sigma_t = 2.90 \pm 0.59$ pb [7]. This D0 result provided the first observation of single top production via the t-channel exchange of a W boson.

2.2. Exotic Single Top Production

Many proposed extensions to the standard model result in new mechanisms for producing top quarks. In particular, one new mechanism that is common to many new models is the production of a top quark and a bottom quark from the decay of a heavier version of the W boson, called a W'. Searches for W' production can be performed by looking for resonant production of a top quark with a b. D0 has recently performed a search for W' bosons decaying to tb, allowing for arbitrary combinations of left-handed and right-handed W' couplings to fermions [8]. This analysis improved the 95% confidence level limit on the mass of a W' with purely right-handed couplings to $M_{W'} > 885$ GeV/c^2, an increase of 85 GeV/c^2 over the previous limit set by CDF [9]. Mass limits from D0 for arbitrary left-handed and right-handed couplings are shown in Figure 1.

3. TOP QUARK PAIR PRODUCTION

3.1. Cross Section Measurements

Top pair production via the strong interaction has a predicted cross section of approximately 7.5 pb [10] at the Tevatron. This larger cross section compared to single top production, along with the fact that the signal is more easily distinguished from the backgrounds because of the presence of two top quarks rather than one, makes $t\bar{t}$ production an ideal place to study top properties. However, first the production rate of top pairs must be well understood.

Because tops decay predominantly to Wb, the $t\bar{t}$ final states are categorized by the decay of the two W bosons in the event. The dilepton decay channel, with both W's decaying to leptons[1], provides a very clean channel with little background, but the branching ratio for this channel is also small and as a result the total number of candidate events is smaller than in other channels. The lepton+jets channel, with one W decaying leptonically and the other decaying to a pair of quarks, provides a good combination of both relatively small background contamination and a reasonably large branching ratio. Because events in this channel are fully constrained kinematically, so that the top quarks can be completely reconstructed, this channel is often used in top quark property measurements. The all-hadronic channel, where both W bosons decay to quark pairs, has the largest branching ratio, but also faces extremely large backgrounds from QCD multijet production.

The most precise measurements of the top quark pair production cross section at the Tevatron use the lepton+jets channel. Top decays almost always include a b quark, and since hadrons containing b's have a long lifetime, jets originating from b quarks can be identified by the presence of displaced secondary vertices from long-lived particles. Cross section measurements in the lepton+jets channel can be made both with and without requiring the presence of such b-tagged jets. In the case where no tagged jets are present, kinematic features are used to separate the $t\bar{t}$ signal from the backgrounds, while for the case where a b-tag is required, backgrounds are small enough that a simple counting experiment can be used to measure a cross section. CDF has performed measurements using both methods with 4.3 fb^{-1} and then combined the results, yielding a cross section of 7.70 ± 0.52 pb [11]. A recent D0 analysis in 5.4 fb^{-1} combined aspects of both the b-tagged and non-b-tagged approach to find a cross section of $7.78^{+0.77}_{-0.64}$ pb [12].

The dilepton channel has a limited sample size due to its small branching ratio, but because of its low background contamination, it provides a sample that is almost exclusively made up of top quark pairs. D0 performed a measurement in this channel with 5.1 fb^{-1} that also takes advantage of b-tagging information in order to further separate signal from background. A neural network was used to determine the probability that the jets in each event originated from b quarks, and then a likelihood fit to the resulting discriminant was performed to extract the $t\bar{t}$ cross section. This procedure yielded a cross sec-

[1] Throughout, "lepton" refers only to electrons or muons. Tau leptons are more difficult to identify experimentally and are generally treated separately.

tion of $7.36^{+0.90}_{-0.79}$ pb [13], with the precision beginning to approach that of the lepton+jets channel. CDF also measured the cross section in the dilepton channel with a requirement that one of the jets be tagged as coming from a b, yielding 7.25 ± 0.92 pb [14] in 5.1 fb^{-1}.

Top events where one of the W bosons decays to a tau lepton are generally difficult to identify. If the tau decays to an electron or muon, the event can be found in the dilepton or lepton+jets samples, but taus can also decay hadronically, in which case it is difficult to distinguish them from quark jets. In such cases, the tau can be identified as a narrow jet containing a small number of charged tracks, but there is a very large background from QCD multijet production. Sophisticated multivariate techniques are needed to extract the signal from the background. A recent CDF result in this channel used 2.2 fb^{-1} to find a cross section of 8.8 ± 4.3 pb [15], which is in good agreement with the theoretical prediction and with the results measured in other decay channels. D0 performed a measurement in the same channel using 1 fb^{-1}, finding a cross section of $6.9^{+1.5}_{-1.4}$ pb [16].

Because the CDF and D0 results agree well across different decay channels, the cross section measurements from the various channels can be combined in order to improve precision. Both CDF and D0 have produced combined top pair cross section measurements[2]. CDF measured a combined cross section of 7.50 ± 0.48 pb [17]. D0 found a cross section of $7.56^{+0.63}_{-0.56}$ pb [13] when combining measurements in the dilepton and lepton+jets channels. Both experiments measure cross sections that are in good agreement with each other and with the standard model prediction.

3.2. Other Aspects of Top Pair Production

Beyond inclusive cross section measurements, there are many other aspects of $t\bar{t}$ production that are studied at the Tevatron. Some of these analyses are meant to test specific predictions of the standard model, for example by comparing differential cross sections to theoretical expectations. Others are explicit searches for new particles and interactions that can produce top pairs.

3.2.1. Cross Section vs. Top p_T

The D0 experiment has studied the differential cross section for top pair production as a function of the transverse momentum, p_T, of the top quark [18]. This variable is of particular interest because in many models containing new particles that interact with tops, these new particles are very massive. As a result, the top quarks produced by these interactions would have large p_T. D0 measured the differential cross section in the lepton+jets channel, unfolding to correct for acceptance and detector affects, and then compared the result to various calculations of the standard model prediction, finding good agreement.

3.2.2. Boosted Top Quarks

A recent analysis at CDF searched for highly boosted top quarks with p_T above 400 GeV/c [19]. Although the standard model cross section for such highly boosted tops is small at the Tevatron (approximately 5 fb), this search is important both because new interactions could produce very energetic top pairs and also for comparison with LHC data, where these boosted tops will be much more common. At such high energies, the top quark decay products are collimated into a single jet, and the analysis relied on the ability to distinguish these energetic top jets from energetic light quark jets. This analysis placed a 95% confidence level upper limit of 38 fb on the cross section for the production of top pairs with at least one top having p_T above 400 GeV/c.

3.2.3. Resonance Searches

Many models for physics beyond the standard model predict that top quark pairs can be produced via a resonance of some new heavy particle that decays to $t\bar{t}$. For example, new physics models that contain additional gauge symmetries often predict a new heavy version of the Z boson, called Z', that decays to top pairs. As long as such resonances are not too wide, they can appear as bumps in the $t\bar{t}$ invariant mass distribution at the mass of the new particle.

Searches have been performed at both CDF and D0 for resonant $t\bar{t}$ production by searching for bumps in the top pair mass distribution. At D0, using 3.6 fb^{-1}, a 95% confidence level limit on the mass of a new Z' of $M_{Z'} > 820$ GeV/c^2 was set [20]. A more recent analysis at CDF using 4.8 fb^{-1} set a limit of $M_{Z'} > 900$ GeV/c^2 [21].

3.2.4. New Particles Decaying to Top

Top quark pairs can also be created through the pair production of some heavy particle that then decays to top. One particular search channel where this type of interaction could be observed is the production of top pairs along with additional missing transverse energy due to an invisible particle. This final state could be created, for example, by the pair production of exotic fourth generation quarks T', with each T' then decaying to a top quark and a dark matter particle.

[2] The combinations include some results not listed here, and some of the most recent measurements discussed here are not included in the combinations.

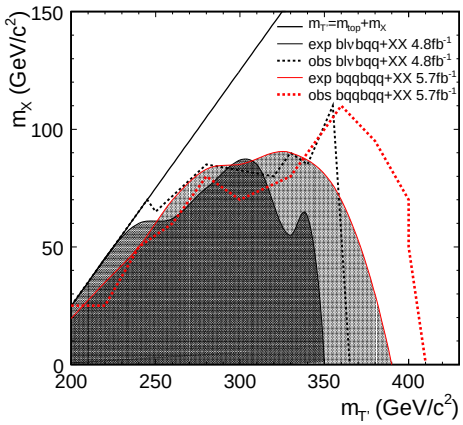

Figure 2: Limits on T' and dark matter particle masses from CDF.

CDF performed two searches for this process, one in the lepton+jets decay channel and one in the all-hadronic channel [22]. Although the searches were optimized for this particular process, they were also sensitive to other processes with the same final state - for example, supersymmetric stop pair production, with the stop quarks decaying to tops and neutralinos. After selecting top quark pair events, these analyses looked for evidence of large additional missing transverse energy. No such evidence was found, and limits were placed on the masses of the T' and the dark matter particle, as shown in Figure 2.

3.2.5. Searches for Heavy Top Quarks

If a fourth generation of standard-model-like quarks exists, then it is possible that the fourth generation top-like quark, t', could decay to a final state similar to top, $t' \to Wq$ where q is a down-type quark (d, s, or b). In this case, pair-produced t' would have the same final states as standard model $t\bar{t}$ production and such events could be found in the $t\bar{t}$ signal sample. Both CDF and D0 performed analyses which search the $t\bar{t}$ sample in the lepton+jets final state for such events by looking at both the reconstructed top quark mass and total transverse energy in each event.

At D0, using 5.3 fb^{-1}, a 95% confidence level limit on the mass of the t' was set, limiting $M_{t'} > 285$ GeV/c^2 [23]. This is smaller than the expected limit of 320 GeV/c^2 due to a small excess in events where the lepton was a muon. CDF used 5.6 fb^{-1} to set a limit of $M_{t'} > 340$ GeV/c^2 [24]. In the CDF analysis, when the additional assumption was made that the down-type quark q is always specifically a b quark, b-tagging could be utilized and the limit was strengthened to $M_{t'} > 358$ GeV/c^2.

3.2.6. Forward-Backward Asymmetry

One aspect of $t\bar{t}$ production that has been of particular interest is the forward-backward asymmetry. This analysis is particularly suited to a $p\bar{p}$ collider like the Tevatron, rather than the LHC which has a symmetric pp initial state. The standard model predicts that in $t\bar{t}$ production, there will be a slight excess in the number of top quarks that follow the proton direction compared to antitops, resulting in an asymmetry of approximately 5% [25]. Many extensions to the standard model predict an enhancement of the asymmetry. Both CDF and D0 measure this asymmetry, with corrections applied to account for acceptance and detector effects. CDF performed measurements in both the dilepton and lepton+jets decay channels, which when combined yield an asymmetry of $20 \pm 7\%$ [26]. A recent D0 measurement found an asymmetry of $19.6 \pm 6.5\%$ [27]. The asymmetries from both experiments are approximately three standard deviations away from zero and up to two standard deviations away from theoretical calculations of the standard model asymmetry, leading to much interest in the possibility that this asymmetry could be caused by a new top pair production mechanism, for example [28].

4. CONCLUSION

Studies of the interactions of the top quark remain an important part of the research program at the Tevatron. Although the data-taking run has now ended, the analyses presented here only use up to a little more than half of the recorded data. Both the CDF and D0 experiments have much data yet to be analyzed, and analyses focused on top production play an integral role in testing the standard model and understanding the sample composition for detailed studies of top quark properties. Precise cross section measurements will continue to test the predictions of QCD and establish the top quark backgrounds in searches for new physics. Analyses of production properties that are more difficult to study at the LHC, such as the top pair forward-backward asymmetry, also continue to move forward at the Tevatron, furthering our understanding of the most recently discovered quark.

Acknowledgments

I would like to thank the members of the CDF and DO collaborations for their dedication to the study of top quark production, especially the top group conveners and the authors of the analyses included here. I also want to thank the organizers of the 2011 Physics

in Collision symposium and everyone who contributed to the conference.

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