Top cross-sections and single top

Reinhard Schwienhorst
(On behalf of the ATLAS, CMS, CDF, D0 Collaborations)

*Department of Physics & Astronomy,
Michigan State University, 567 Wilson Road
East Lansing, Michigan 48823, USA
schwier@pa.msu.edu*

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This paper summarizes top quark cross-section measurements at the Tevatron and the LHC. Top quark pair production cross-sections have been measured in all decay modes by the ATLAS and CMS collaborations at the LHC and by the CDF and D0 collaborations at the Tevatron. Single top quark production has been observed at both the Tevatron and the LHC. The t -channel and associated Wt production modes have been observed at the LHC and evidence for s -channel production has been reported by the Tevatron collaborations.

Keywords: Top quark; LHC; Tevatron.

1. Introduction

The top quark is central to understanding physics in the Standard Model (SM) and beyond. This paper summarizes top-quark related measurements from the Tevatron proton-antiproton collider at Fermilab and from the Large Hadron Collider (LHC), the proton-proton collider at CERN. The top quark couplings to the gluon, to the W boson, and now also to the photon and Z boson are all probed in these measurements. Searches for new physics in the top quark final state look for new particles and new interactions.

The Tevatron operation ended in 2011, with CDF and D0 each collecting 10 fb^{-1} of proton-antiproton data¹ at a center-of-mass (CM) energy of 1.96 TeV. The ATLAS² and CMS³ collaborations at the LHC have reported measurements at CM energies of 7 TeV and 8 TeV, with up to 4.9 fb^{-1} and up to 20 fb^{-1} , respectively.

This paper reports recent measurements of top pair production, of single top production, as well as recent searches for new physics in top quark final states. Giving a complete overview of all activities is not possible here, but I will highlight

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Fig. 1. Feynman diagrams for top pair production (a) via gluon fusion and (b) via quark-antiquark annihilation, and (c) for top quark decay.

relevant measurements and new developments. Section 2 summarizes top quark pair production measurements, Section 4 summarizes single top quark production, Section 5 presents new physics searches in the top quark sector, and Section 6 gives a summary.

2. Top Quark Pair Production

Top quark pair production proceeds mainly via gluon initial states at the LHC, shown in Fig. 1(a), and mainly via quark-antiquark annihilation at the Tevatron, shown in Fig. 1(b).

The production cross-section has been calculated at next-to-next-to leading order (NNLO), including next-to-next-to leading log (NNLL) soft gluon resummation.⁴

The top quark decays to a W boson and a b quark, and the final state topology in top quark pair events is determined by the subsequent decay of the two W bosons, as shown in Fig. 1(c). About a third of top pairs decay to the lepton+jets final state where one W boson decays to an electron or muon and the other to a quark pair. The background to this final state is mainly from W +jets production and QCD multi-jet events where one quark jet is mis-identified as a lepton. This final state topology has reasonable statistics and a manageable background while also allowing for the reconstruction of the two top quarks.

A small fraction of about 6% of top pair events decay to the dilepton (ee , $e\mu$ and $\mu\mu$) final state, which has small backgrounds from Z +jets and diboson production. This topology is attractive for its clean signature, though the individual top quarks can not be reconstructed directly due to the presence of two neutrinos.

About 46% of top pair events decay to an all-hadronic final state which is overwhelmed by a large QCD multi-jet background. Other top pair decays involve τ leptons, and in particular hadronic τ decays are of interest because they provide sensitivity to non-SM top decays. Leptonic τ decays are included in the lepton+jets and dilepton final states, though the lower lepton p_T and the presence of additional neutrinos modifies the event kinematics.

2.1. Lepton+jets final state

The lepton+jets final state (where the lepton is an electron or a muon) has backgrounds that can be controlled and higher event statistics than the dilepton final state. Cross-section measurements both at the Tevatron and the LHC by ATLAS⁵ and CMS⁶ rely on b -quark identification (b -tagging) as well as multivariate analysis techniques to separate the top pair signal from the background sources, mainly W +jets and QCD multi-jet production. The CMS analysis at 7 TeV utilizes the secondary vertex mass to discriminate the top quark pair signal from the backgrounds.⁶ This distribution is shown in Fig. 2 for different jet- and b -tag multiplicities. The measured cross-section is 158.1 ± 11.0 pb for an uncertainty of only 7%.

Differential cross-sections have also been measured in top pair production by ATLAS at 7 TeV⁷ and by CMS at 7 TeV⁸ and 8 TeV.^{9,10} The differential cross-section measured by ATLAS at 7 TeV as a function of the top pair transverse momentum is shown in Fig. 3 (left). The differential cross-section is normalized to the total cross-section, thus canceling many systematic uncertainties.

2.2. Dilepton final state

The dilepton final state (di-electron, di-muon and electron-muon) is clean with small backgrounds and small uncertainties, hence it provides high-precision measurements

Fig. 2. Secondary vertex mass distribution in electron+jet events in the measurement of the top pair production cross-section at 7 TeV by the CMS Collaboration.⁶

Fig. 3. (Left) ATLAS differential cross-section normalized to the total cross-section versus the transverse momentum of the $t\bar{t}$ system at 7 TeV.⁷ (Right) CMS differential cross-section normalized to the total cross-section versus the transverse momentum of the $t\bar{t}$ system at 8 TeV,¹⁰ where data points are shifted horizontally to be directly comparable to the theory prediction.

of the production cross-section. The CMS measurement at 7 TeV has an uncertainty of 4.2%, currently the single most precise measurement.¹¹

The differential cross-section has also been measured in the dilepton final state. Figure 3 (right) shows the relative differential cross-section of the transverse momentum of the top quark pair.

2.3. Pair production summary

The Tevatron measurements are summarized in Fig. 4. The combined Tevatron top pair cross-section is measured to be $7.60 \pm 0.41 \text{ pb}$, an uncertainty of only 5.4%.¹²

The measurements by ATLAS and CMS are shown as a function of the collider energy in Figs. 5 and 6, respectively. Note that the CMS summary figures do not yet include the latest CMS dilepton result.¹¹ The measured cross-sections are consistent with each other and with the theory predictions.^{13, 14} The LHC top pair cross-section combination from Fall 2012¹⁵ is also shown in Fig. 6.

3. Associated Production

Top quark pair production in association with one or more quarks or with a W or Z boson provides a measurement of the top quark strong and weak interactions and is an important background in new physics searches and Higgs boson measurements in $t\bar{t}H$.

The jet multiplicity in top pair events has been measured by both ATLAS¹⁸ and CMS.^{19, 20} Figure 7 shows the jet multiplicity in lepton+jets top pair events. At low jet multiplicities, the measurement agrees within the large uncertainty band with the theoretical predictions, while at high jet multiplicities the agreement is poor.

Fig. 4. Tevatron top quark pair production cross-section measurements and their combination.¹²

Fig. 5. ATLAS top quark pair production cross-section measurements as a function of collider energy.¹⁶

The production of top quark pairs in association with Z bosons has a small cross-section and is difficult to measure. ATLAS had a first search for $t\bar{t}Z$ production at 7 TeV.²² CMS found evidence for top pair production in association with a boson in two analyses²¹ using 7 TeV data: A search for $t\bar{t}Z$ and a search for $t\bar{t}V$, where V

Fig. 6. CMS top quark pair production cross-section measurements as a function of collider energy.¹⁷

Fig. 7. Multiplicity of jets with $p_T > 25$ GeV in top quark pair events measured by ATLAS at 7 TeV.¹⁸

Fig. 8. Event yields in the tri-lepton channels in the CMS $t\bar{t}V$ analysis at 7 TeV.²¹

can be a W boson or a Z boson. Figure 8 shows the two cross-section measurements and their uncertainties.

4. Single Top Production

Single top quark production proceeds via the t -channel exchange of a W boson between a heavy quark line and a light quark line, shown in Fig. 9(a) or via the

Fig. 9. Feynman diagrams for single top quark production in the (a) t -channel, (b) s -channel, (c) in association with a W boson.

Fig. 10. D0 s -channel discriminant signal region.²³

Fig. 11. Summary of Tevatron s -channel single top cross-section measurements.

s -channel production and decay of a virtual W boson, shown in Fig. 9(b) or as the production of a top quark in association with a W boson, shown in Fig. 9(c). At the Tevatron, the t -channel cross-section is largest, followed by the s -channel, while the Wt cross-section is too small to be observed. At the LHC, t -channel production benefits from the qb initial state, with a large cross-section. The s -channel has a smaller cross-section and has not been seen yet. The associated production has a gb initial state and can be observed.

4.1. s -channel production

Evidence for single top quark production in the s -channel was reported recently by the D0²³ and CDF²⁴ collaborations at the Tevatron. Both collaborations measure a cross-section that is consistent with the SM expectation, and both report an observed significance of 3.8 standard deviations. This is a challenging analysis that relies on multivariate analysis techniques in order to separate the signal from the large backgrounds. The s -channel signal region is shown in Fig. 10. A comparison of the CDF and D0 measurements is shown in Fig. 11. CDF also has a measurement using missing transverse energy plus jets events²⁵ and a combination of the two results.²⁶ A Tevatron combination of the CDF and D0 results is in progress.

4.2. Wt associated production

The production cross-section of a single top quark in association with a W boson has been measured both at 7 TeV and at 8 TeV by both ATLAS²⁷ and CMS.^{28,29} The final state in Wt events is categorized by lepton multiplicity, similar to top pair production. The difference to top pair production is that Wt production results in exactly one high- p_T b -quark jet. Hence top pair events comprise the largest background in Wt dilepton events, with smaller contributions for Z +jets, dibosons, and events with fake leptons. Multivariate techniques are required to separate the signal from these backgrounds, and systematic uncertainties are large. Nevertheless, the cross-section has now been measured with a relative uncertainty of 25%. The 7 TeV ATLAS analysis measures a cross-section of 16.8 ± 2.9 (stat) ± 4.9 (syst) pb.²⁷ The multivariate discriminant for the CMS 8 TeV analysis is shown in Fig. 12, CMS cross-section measurement is 23.4 ± 5.5 pb.²⁹ Both are consistent with the SM expectation.

4.3. t -channel production

Single top quark production through the t -channel is sensitive to the parton distribution function (PDF) of the light quarks in the proton. The t -channel final state is comprised of a lepton, neutrino and b quark from the top quark decay, a high- p_T forward jet, and possibly a third jet. The main backgrounds to this signature are from W +jets and top pair production. The ratio of top to antitop quark production in the t -channel is a particularly sensitive variable because many of the experimental uncertainties cancel. ATLAS has measured this ratio in t -channel events at 7 TeV using a neural network to separate the t -channel events from the background.³⁰ The measured ratio is $1.81^{+0.23}_{-0.22}$ and is compared to several different PDFs in Fig. 13.

Fig. 12. CMS Wt discriminant in the 8 TeV analysis.²⁹

Fig. 13. Ratio of top to anti-top quark production in t -channel single top measured by ATLAS at 7 TeV.³⁰

CMS has measured the same ratio using 8 TeV data to be 1.76 ± 0.27 , again consistent with expectations.³¹ The precision of these measurements is not yet sufficient to constrain PDFs, but future measurements should be able to improve on this situation. Along with the ratio, ATLAS and CMS have also measured the total t -channel cross section, with an uncertainty of 14% from ATLAS at 8 TeV³⁰ and an uncertainty of 9% from CMS at 7 TeV.³²

5. New Physics Searches

Searches for new physics in the top quark sector are particularly sensitive to models that have an enhanced coupling to the third generation of fermions. New heavy bosons Z' and W' appear in many models of new physics, and searches for these heavy resonances are a priority at hadron colliders.

The reconstructed mass of the top quark pair system in the ATLAS 7 TeV analysis is shown in Fig. 14.³³ The transverse momentum of the top quark produced in the decay of a heavy Z' boson is sufficient to collimate quark jets from the top quark decay such that they can no longer be resolved individually. Recent searches for Z' bosons employ algorithms to identify such boosted top quark jets.^{33,34} The Z' mass at which such algorithms perform better than resolved algorithms that reconstruct each of the top quark decay jets individually is around 1 TeV as can be seen by the vertical dashed line in Fig. 15. The mass range probed by these searches extends up to masses of 2 TeV. The mass range below 0.75 TeV is also probed at the Tevatron where a CDF search currently provides the best sensitivity.³⁵

A new charged heavy boson W' can decay to a top quark together with a b quark, leading to a single top final state. The W' boson may have SM-like left-handed couplings or it may have right-handed couplings to the top quark and the b quark. The ATLAS³⁶ and CMS³⁷ analyses probe these couplings separately, with CMS also providing two-dimensional limits as a function of the two couplings.

Fig. 14. Reconstructed invariant mass of the top quark pair system for the 7 TeV ATLAS analysis.³³

Fig. 15. Upper limit on $Z' \rightarrow t\bar{t}$ from CMS at 8 TeV.³⁴

6. Summary

The top quark pair production cross-section has been measured in many final states and with high precision by the CDF and D0 collaborations at the Tevatron proton-antiproton collider and by the ATLAS and CMS collaborations at the 7 TeV and 8 TeV LHC proton-proton collider. The single top quark cross-sections have been measured in the t -channel and now also in the s -channel at the Tevatron, and in the t -channel and the Wt associated production at the LHC. Many of these measurements are now at the level of precision of the theory predictions, and higher-precision results are yet to come with 8 TeV data. Searches for new physics in top quark final states have reached a sensitivity to high-mass resonances of over 2 TeV. This reach will be extended significantly at the 14 TeV LHC.

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