

Search for Standard Model Production of Four Top Quarks

CALEB FANGMEIER

*Department of Physics and Astronomy
University of Nebraska-Lincoln*

Abstract: This talk describes efforts towards a first measurement of the standard model production of four top quarks with results based on up to the full LHC Run 2 dataset collected at CMS at $\sqrt{s} = 13\text{TeV}$. It includes interpretations of this measurement to constrain properties of the Higgs Boson and new physics scenarios including dark matter.

Talk presented at the 2019 Meeting of the Division of Particles and Fields of the American Physical Society (DPF2019), July 29–August 2, 2019, Northeastern University, Boston, C1907293.

1 Introduction

Four top quark production is a rare Standard Model process with a cross section of $\sigma(\text{pp} \rightarrow t\bar{t}t\bar{t}) = 12 \text{ fb}$ calculated at next-to-leading order (NLO) at 13 TeV center of mass energy [1]. The dominant production mode of $t\bar{t}t\bar{t}$ at the LHC is through QCD diagrams such as those shown in figure 1. There are also smaller contributions from Higgs and vector boson mediated diagrams.

The $t\bar{t}t\bar{t}$ cross section can be used to constrain Standard Model parameters such as the top quark Yukawa coupling, as well as properties of several Beyond the Standard Model theories; most notably the Type-II two-Higgs doublet models (2HDM), simplified dark matter, and off-shell mediators such as a top phillic Z' .

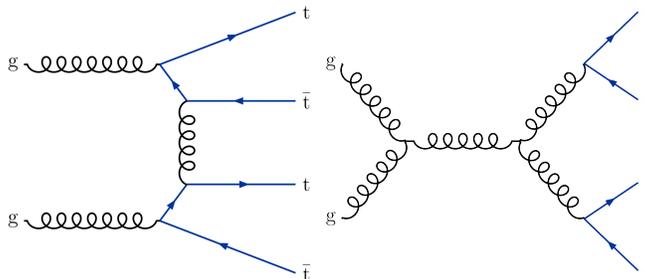


Figure 1: Some representative leading order QCD production diagrams for four top quarks

Four top quark events are notable for their large number of potential final states. Depending on how the W bosons in the event decay, there can be from zero to four prompt leptons and from twelve to four jets, of which four will originate from b quark decays. Covering all final states would be too complicated for a single analysis, so events are classified by the multiplicity and relative charge of final state leptons, with different categories having dedicated analyses. This analysis covers the case where there is a same-sign pair of leptons, including three or more leptons. This report will give a summary of the analysis, but additional details can be found in [2].

2 Event Selection and Background Estimation

The baseline selection is designed to efficiently select $t\bar{t}t\bar{t}$ events with as small as possible contribution of background processes. We first require a high quality (or “tight”) same-sign lepton pair,

30 or three or more tight leptons. Lepton here means electrons, muons, and leptonically decaying τ .
 31 The highest p_T lepton is required to have at least 25 GeV of transverse momentum while all others
 32 have a more relaxed requirement of 20 GeV. The event must also contain at least two jets with p_T
 33 greater than 40 GeV, and at least two jets identified as originating from a bottom quark with p_T
 34 over 25 GeV. Furthermore, we require the scalar sum of transverse jet energy to be greater than
 35 300 GeV, and at least 50 GeV in missing transverse momentum. Finally, if the event contains an
 36 additional lepton satisfying a relaxed ID requirement that forms an opposite-sign same-flavor pair
 37 with one of the tight leptons, and the pair has an invariant mass within 15 GeV of m_Z then the
 38 event is discarded. If there is an additional tight lepton that fulfills these requirements, then the
 39 event is instead placed in a dedicated $t\bar{t}Z$ control region called CRZ. Figure 2 shows the expected
 40 contribution of different processes to the baseline selection differentially in the number of jets and
 41 number of b-tagged jets.

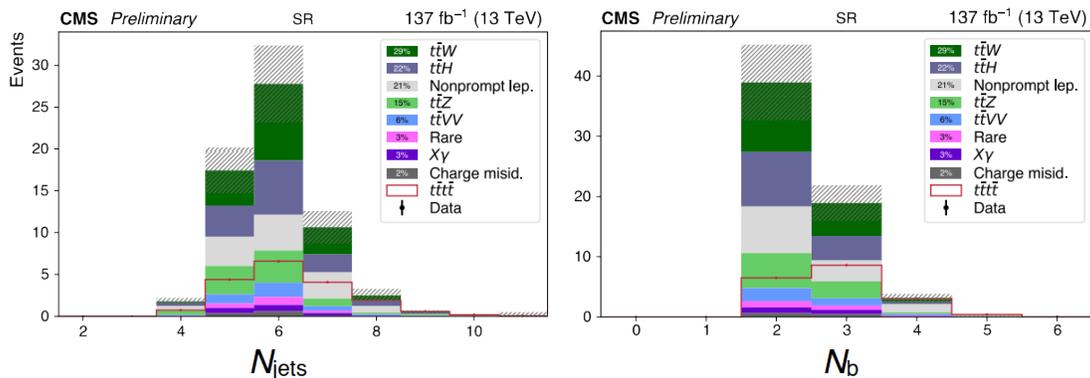


Figure 2: Content of events within the baseline selection

42 The backgrounds for this analysis come in two types: processes with genuine prompt same-sign
 43 lepton pairs, and events with “fake” same-sign lepton pairs. Of the former, the most important
 44 processes are $t\bar{t}W$, $t\bar{t}H$, and $t\bar{t}Z$. The contributions from these processes are estimated by simulat-
 45 ing events at NLO. In the case of $t\bar{t}Z$, there is a dedicated control region that is used to normalize
 46 its contribution.

47 The contribution of the nonprompt lepton background is estimated using the “tight-to-loose”
 48 ratio method [3]. This is a common technique employed in many analyses which deal with back-
 49 grounds resulting from nonprompt leptons. The method first measures the proportion of lower
 50 quality or “loose” leptons that also pass the stricter tight requirements in a sideband that is en-
 51 riched in nonprompt leptons. This proportion can then be used to calculate a weight that is applied
 52 to events that would pass the baseline selection except for having one tight and one loose-not-tight
 53 lepton instead of the two tight leptons normally required. These weighted events make up the
 54 nonprompt background estimation. The charge misidentified background estimate works similarly
 55 except that the charge misidentification probability is measured in simulation, and the resulting
 56 transfer factor is applied to opposite-sign events.

57 3 Results

58 A boosted decision tree (BDT) classifier is utilized to separate $t\bar{t}t\bar{t}$ events from background events.
 59 The BDT consists of 500 trees with a depth of 4. It uses 19 event level variables which take into
 60 account object multiplicities, reconstruction quality, energies, and angular relations. The results of

61 applying this BDT to events in the signal region are shown in figure 3.

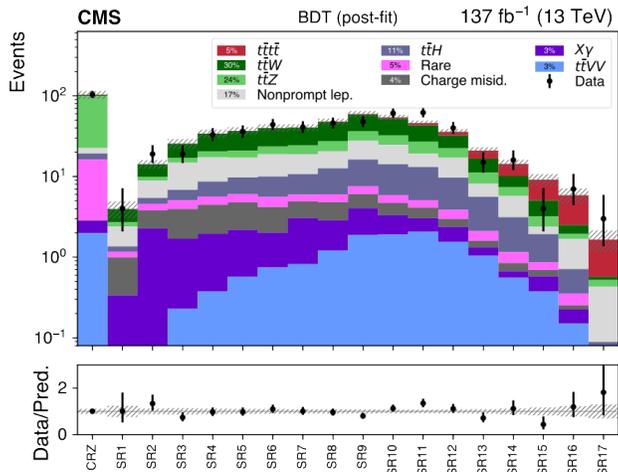


Figure 3: Observed yields of the binned BDT discriminant compared to the post-fit predictions for signal and background processes. The hatched area shows the total uncertainty on the background and signal prediction.

62 A binned likelihood is constructed from 17 bins of the BDT discriminant with an additional
 63 bin containing CRZ. A profile maximum-likelihood fit is then performed with experimental and
 64 theoretical uncertainties incorporated as nuisance parameters. The fit results in a measured $t\bar{t}\bar{t}\bar{t}$
 65 cross section of $12.6_{-5.8}^{+5.8}$ fb with a 68% confidence interval. A cross check was performed using an
 66 event binning based on the number of jets, b jets, and leptons instead of the BDT discriminant.
 67 This yielded a cross section of $9.4_{-5.6}^{+6.2}$ fb, consistent with the BDT-based measurement.

68 4 Interpretations

69 The result of the analysis can be used to constrain Standard Model parameters, as well as BSM
 70 processes that can affect the $t\bar{t}\bar{t}\bar{t}$ production rate. The existence of off-shell Higgs mediated Feynman
 71 diagrams for $t\bar{t}\bar{t}\bar{t}$ production means that the cross section is sensitive to the top quark Yukawa
 72 coupling [4, 5]. Figure 4 shows the predicted cross section as a function of the ratio of the top
 73 Yukawa coupling to its Standard Model value. We observe a limit of $|y_t/y_t^{\text{SM}}| < 1.7$ at the 95%
 74 confidence level.

75 New particles with $m > 2m_t$ that couple to the top quark can also be constrained by a measure-
 76 ment of $\sigma(t\bar{t}\bar{t}\bar{t})$. In particular, we considered the Type-II Two Higgs Doublet Model (2HDM) [6,
 77 7, 8]. A general 2HDM predicts four new “Higgs” particles, but in the “alignment condition” the
 78 lightest CP-even particle becomes the Standard Model Higgs. Of the remaining new particles, we
 79 consider a heavy scalar and heavy pseudoscalar which couple to top quarks similarly to the SM
 80 higgs. Figure 5 shows the cross section times branching ratio of the scalar (H) and pseudoscalar
 81 (A) particles as a function of their respective masses as well as the observed limit for our analysis.
 82 We exclude a new scalar (pseudoscalar) with mass below 470 (550) GeV at the 95% confidence
 83 level.

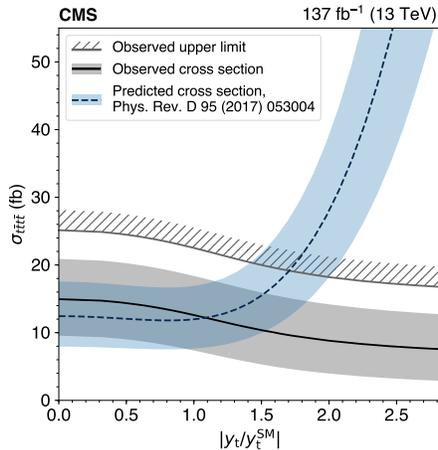


Figure 4: The observed $\sigma(t\bar{t}t\bar{t})$ and 95% CL upper limit as a function of $|y_t/y_t^{\text{SM}}|$. The dashed line shows the predicted cross section calculated at LO and scaled to the NLO result of Ref. [1]. The observed limit on $t\bar{t}t\bar{t}$ varies as a function of $|y_t/y_t^{\text{SM}}|$ because the $t\bar{t}H$ ($H \rightarrow WW$) background grows with increasing y_t .

5 Conclusion

The measurement of the $t\bar{t}t\bar{t}$ cross section is an important tool in better understanding interesting aspects of the Standard Model, as well as an important source of constraint on several BSM theories. Additional interpretations have been considered and are detailed in the paper[2]. This cross section measurement is found to be consistent with the Standard Model prediction. However, the additional data and increased center-of-mass energy promised by the HL-LHC makes for an exciting future of precision measurements of $t\bar{t}t\bar{t}$ and other rare Standard Model processes[9].

Acknowledgements

I would like to recognize my co-analyzers: Nick Amin, Claudio Campagnari, Frank Golf, and Giovanni Zevi Della Porta. Their ingenuity and willingness to help this beginner was and continues to be greatly appreciated.

References

- [1] Rikkert Frederix, Davide Pagani, and Marco Zaro. “Large NLO corrections in $t\bar{t}W^\pm$ and $t\bar{t}t\bar{t}$ hadroproduction from supposedly subleading EW contributions”. In: *JHEP* 02 (2018), p. 031. DOI: 10.1007/JHEP02(2018)031. arXiv: 1711.02116 [hep-ph].
- [2] CMS Collaboration. *Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV*. 2019. eprint: arXiv:1908.06463.
- [3] V. Khachatryan et al. “Search for new physics in same-sign dilepton events in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *Eur. Phys. J. C* 76 (2016), p. 439. DOI: 10.1140/epjc/s10052-016-4261-z. arXiv: 1605.03171 [hep-ex].

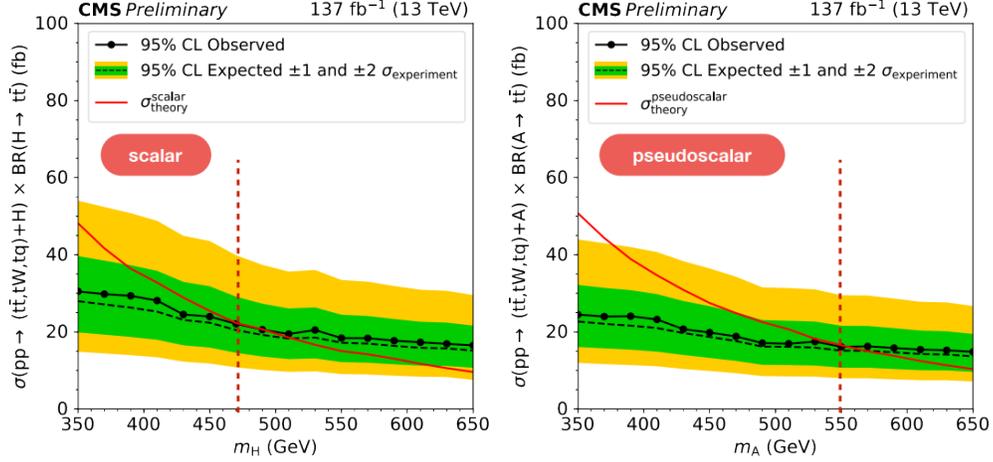


Figure 5: The observed and expected 95% CL upper limits on cross section times branching ratio to $t\bar{t}$ of the production of new scalar (left) and pseudoscalar (right) heavy Higgs as a function of mass. The theoretical value for the 2HDM in the alignment limit is plotted on the solid line.

- 104 [4] Qing-Hong Cao, Shao-Long Chen, and Yandong Liu. “Probing Higgs width and top quark
 105 Yukawa coupling from $t\bar{t}H$ and $t\bar{t}\bar{t}$ productions”. In: *Phys. Rev. D* 95 (2017), p. 053004. DOI:
 106 10.1103/PhysRevD.95.053004. arXiv: 1602.01934 [hep-ph].
- 107 [5] Qing-Hong Cao et al. “Limiting top-Higgs interaction and Higgs-boson width from multi-top
 108 productions”. 2019.
- 109 [6] D. Dicus, A. Stange, and S. Willenbrock. “Higgs decay to top quarks at hadron colliders”.
 110 In: *Phys. Lett. B* 333 (1994), p. 126. DOI: 10.1016/0370-2693(94)91017-0. arXiv: hep-
 111 ph/9404359 [hep-ph].
- 112 [7] Nathaniel Craig et al. “The hunt for the rest of the Higgs bosons”. In: *JHEP* 06 (2015), p. 137.
 113 DOI: 10.1007/JHEP06(2015)137. arXiv: 1504.04630 [hep-ph].
- 114 [8] Nathaniel Craig et al. “Heavy Higgs bosons at low $\tan\beta$: from the LHC to 100 TeV”. In: *JHEP*
 115 01 (2017), p. 018. DOI: 10.1007/JHEP01(2017)018. arXiv: 1605.08744 [hep-ph].
- 116 [9] P. Azzi et al. *Standard Model Physics at the HL-LHC and HE-LHC*. 2019. arXiv: 1902.04070
 117 [hep-ph].