Determination of κ_t from $t\bar{t}$, $t\bar{t}t\bar{t}$, and others

Emanuele Usai on behalf of the ATLAS and CMS Collaborations[a],[*]

[a]*Department of Physics, Brown University,*
182 Hope Street, Providence, RI, USA

E-mail: emanuele.usai@cern.ch

In this document I report the determination of the Yukawa coupling of the top quark in $t\bar{t}$ and $t\bar{t}t\bar{t}$ final states in ATLAS and CMS. I will also briefly describe the determination of κ_t and its CP structure from $t\bar{t}H$ final states.

The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021
7-12 June 2021
Online

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[*]Speaker

1. Introduction

In the standard model (SM) the Yukawa couplings are proportional to the mass of the fermions. Being the heaviest particle in the SM, the top quark has the largest Yukawa coupling to the Higgs boson (κ_t), therefore it provides an insight on SM physics in the Higgs sector. It is also particularly sensitive to some extensions of the standard model. Such extensions would alter the top quark-Higgs interaction and therefore modify the value of κ_t in measurable ways. The κ_t parameter can be probed directly, that is in events containing both the top quark and the Higgs boson in the final state, e.g. in $t\bar{t}H$ and tH events. κ_t can also be measured indirectly in final states with only the Higgs boson or top quarks. Examples of these measurements are analyses probing the $t\bar{t}$ and $t\bar{t}t\bar{t}$ final states. In the case of $t\bar{t}$, the coupling to the Higgs boson is exposed through loop diagrams, while in the case of four-top-quark production, one of the contributing tree-level diagrams includes the Higgs boson. Therefore, deviations of κ_t from unity are indicative of new physics.

The different final states used to probe κ_t yield different kind of information. For example, the measurement of κ_t from $t\bar{t}H$ events is not sensitive to its sign. However, due to the interference between the W boson and top quark couplings, the tH final state is sensitive to the sign of κ_t. More generally, the CP properties of the Higgs boson can be probed in both $t\bar{t}H$ and tH modes.

2. κ_t from $t\bar{t}$

The CMS experiment [1] measured the top quark Yukawa coupling using kinematic distributions of $t\bar{t}$ events in the final state with two leptons [2]. This analysis includes data collected by the CMS experiment at 13 TeV during the entire Run 2 (137fb^{-1}).

As briefly mentioned in Sec.1, Feynman diagrams containing the Higgs boson contribute to $t\bar{t}$ production at order α_s times the Yukawa coupling. This yields small effects on the total cross section, but has a noticeable impact on the differential distributions of kinematic variables. This shape effect is enhanced in the case of an anomalously large coupling.

In this analysis, events with two leptons are selected: ee, eμ and $\mu\mu$. In single-flavor channels, $\mu\mu$ and ee, selection criteria on the invariant mass of the dilepton pair and on missing transverse momentum are added to reduce the background from Drell-Yan events.

In principle, the invariant mass of the $t\bar{t}$ system and the difference in the top quark rapidity are particularly sensitive to variations of the Yukawa coupling. These differences can be exploited to derive multiplicative correction factors to reweight the full detector simulation to a specific value of the Yukawa coupling. The strategy of the analysis consists in performing a profile likelihood scan on the value of κ_t, the Yukawa coupling normalized to the SM value, to extract the best fit value of the coupling.

In terms of event reconstruction, the dilepton $t\bar{t}$ system can usually be reconstructed in good approximation, but is very sensitive to the missing transverse momentum and its uncertainties, particularly the off-shell component. Therefore the analysis uses proxy substitute variables that do not include the missing transverse momentum. These variables are used to derive and apply the correction factors to the simulation in place of the original $t\bar{t}$ system variables. The proxy variables maintain the sensitivity to variations of the Yukawa coupling. A profile likelihood scan for κ_t is

performed showing the best fit value to be $\kappa_t = 1.16^{+0.07}_{-0.08}(\text{stat})^{+0.17}_{-0.27}(\text{syst})$. Additionally, the coupling is constrained to be smaller than 1.62 at 95% confidence level (CL).

3. κ_t from $t\bar{t}t\bar{t}$

The production of four top quarks ($t\bar{t}t\bar{t}$) is a rare process in the SM, the computed cross section at next-to-leading order (NLO) in quantum chromodynamics (QCD) plus electroweak (EWK) is 12fb [3]. This is approximately one order of magnitude smaller than the cross section of Higgs boson production in association with top quarks ($t\bar{t}H$). About 20% of the production diagrams for $t\bar{t}t\bar{t}$ contain the Higgs boson, hence the top quark-Higgs boson coupling has a substantial influence on the value of the cross section of $t\bar{t}t\bar{t}$. The process has not been observed yet, but the ATLAS experiment [4] has shown evidence of $t\bar{t}t\bar{t}$ production at the LHC [5].

The CMS Collaboration conducted a search for four-top-quark production in final states with two same-sign or multiple leptons with the full Run 2 data set [6]. The $t\bar{t}t\bar{t}$ process produces a challenging signature in the detector: the final state considered in the CMS analysis is characterized by two leptons, 4 b-flavor jets (b jets) and 4 light-flavor jets (light jets), or three leptons, 4 b jets and 2 light jets, or four leptons, 4 b jets and no light jets. The branching fraction of $t\bar{t}t\bar{t}$ for two, three and four leptons in the final state is 0.28, 0.09, and 0.04, respectively.

In this final state the main background processes are $t\bar{t}H$, $t\bar{t}Z$, $t\bar{t}W$, and events with a mis-identified lepton. The analysis uses a boosted decision tree (BDT) to distinguish the four-top-quark signal from the dominant $t\bar{t}$ background. This leads to a substantial improvement over the traditional cut and count approach. The analysis phase space is subdivided in fourteen signal regions and two separated control regions enriched in events with W and Z bosons. The events are categorized using a combination of selection criteria on the number of leptons, jet multiplicity, and b jet multiplicity.

The analysis measures the four-top-quark cross section to be $\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}$fb. The BDT analysis reaches 2.6 standard deviations significance (2.7 expected from simulation) over the no $t\bar{t}t\bar{t}$ hypothesis. A search for $t\bar{t}t\bar{t}$ from the ATLAS Collaboration using single lepton, dilepton and multi lepton final states and using the full Run 2 data set reached a 4.7 standard deviations significance (2.6 expected from simulated events) over the null hypothesis [5]. The best estimate for the cross section is $\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}$fb.

In the CMS analysis, the dependence of the four-top-quark cross section on κ_t is obtained from Cao et al. [7] at leading order and scaled to the measured cross section value of 12.6 fb. As mentioned previously, $t\bar{t}H$ is a relevant background for this analysis and it is affected by the variation of κ_t. As a consequence of this, the measured cross section does have a mild dependence on the assumed value of κ_t. The parametrization of the cross section as a function of κ_t allows to extract an upper limit on the value of the Yukawa coupling. In the most conservative scenario, that is taking into account he effect of κ_t variation in the $t\bar{t}H$ background, the ratio of the Yukawa coupling to the SM value is found to be $\kappa_t < 1.7$ at 95% CL. When assuming on-shell Yukawa coupling to be the same as the SM, that is with no rescaling of the $t\bar{t}H$ process, the ratio of the off-shell Yukawa coupling to the SM value is found to be smaller than 1.8 at 95% CL. While this result is more stringent than other measurements, it does not make any assumption of the width of the Higgs boson.

4. κ_t **from** $t\bar{t}H$

The ATLAS Collaboration performed a measurement of the CP properties of Higgs boson interactions using $t\bar{t}H$ and tH production modes and the decay of the Higgs boson to a pair of photons [8]. The analysis uses two separate BDTs, one to discriminate $t\bar{t}H$ and tH signal from backgrounds and another to distinguish CP-odd from CP-even Higgs-top quark couplings. Constraints on κ_t are extracted from a bidimensional fit to $\kappa_t \cos\alpha$ and $\kappa_t \sin\alpha$, the CP-even and CP-odd components of κ_t, respectively, where α is defined as the mixing angle between the two components. Limits on the value of the mixing angle α are extracted: $|\alpha| > 43$ is excluded at 95% CL with no assumptions on κ_t. Additionally, $\alpha = 90, 180$ are excluded at 3.9 and 2.5σ. CMS performed a measurement in a similar final state and excludes a pure CP-odd structure of the top quark Yukawa coupling at 3.2σ [9], that is to be compared to the $\alpha = 90$ case from the correspondent ATLAS analysis.

CMS measured κ_t from $t\bar{t}H$ events in final states with electrons, muons, and hadronically decaying τ leptons using the full Run2 data set [10]. This analysis uses different BDTs and Deep Neural Networks (DNNs) to enhance background rejection. In order to extract a limit on κ_t, the production rates of $t\bar{t}H$ and tH are parametrized in function of the Yukawa coupling. In particular, in the case of tH events, varying κ_t affects the interference of the production diagrams for this process. This effect alters the kinematics of the events and is taken into account in the yields and in the shape of the distribution of BDT and DNN discriminators. The effect of the modified kinematics is taken into account in the acceptance of the selection criteria as well. The compatibility of the data with the various kt hypotheses is shown in the distribution of the log likelihood in function of kt and kv, the coupling to vector bosons, which can affect kinematics as well. The analysis measures $-0.9 < \kappa_t < -0.7$ and $0.7 < \kappa_t < 1.1$ at 95% confidence level, compatible with SM.

Finally, both ATLAS and CMS provide an estimate of κ_t from combined measurements of the Higgs boson in multiple final states and production modes. In this context, ATLAS measures $\kappa_t = 0.96 \pm 0.08$ [11]. In this combined measurement using it can be noted that the ZH production mode contributes to the determination of κ_t as well. The CMS experiment, using a partial Run2 data set combination measures $\kappa_t = 1.01 \pm 0.11$ [12].

5. **Conclusions**

It has been shown how κ_t and the CP structure are measured across different final states with and without the Higgs boson in the final state. Each measurement provides a different and complementary information. The κ_t parameter is extracted from $t\bar{t}$ events by CMS using the full Run 2 data set. The value is $\kappa_t = 1.16^{+0.07}_{-0.08}(\text{stat})^{+0.17}_{-0.27}(\text{syst})$. The Yukawa coupling of the top quark is measured to be $|\kappa_t| < 1.7$ in $t\bar{t}t\bar{t}$ events using the full Run2 data set from the CMS Experiment. The measurement is independent of the total width of the Higgs boson. The CP structure of the top quark-Higgs boson coupling CP is measured in $t\bar{t}H$ and tH events with $H \rightarrow \gamma\gamma$ by ATLAS and CMS and a pure CP-odd coupling is excluded at 3.9σ and 3.2σ, respectively. Finally, κ_t is measured in $t\bar{t}H$ and tH events with $H \rightarrow WW, ZZ, \tau_h\tau_h$ by CMS $-0.9 < \kappa_t < -0.7$ and $0.7 < \kappa_t < 1.1$ at 95% confidence level.

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