



Higgs boson production in association with top quarks in CMS

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Abstract

In this paper searches for Higgs bosons produced in association with top quarks are presented. The searches are performed using the data collected during the first LHC run at a center-of-mass energy of 7 and 8 TeV and results are presented for different Higgs boson decay final states, including $b\bar{b}$, $\tau\tau$, $WW^{(*)}/ZZ^{(*)}$ and $\gamma\gamma$, as well as their combination. The paper highlights experimental and theoretical challenges, in particular in view of the upcoming, higher energy LHC run.

Keywords: LHC, Higgs, Top

1. Introduction

After the recent discovery of a Higgs boson at the LHC [1, 2] the study of the properties of the new particle is most crucial to either confirm the standard model (SM) or find hints for new physics effects. In the SM the coupling strength between the Higgs boson and a fermion is proportional to the fermion mass. Since the top-quark is by far the heaviest fermion, a measurement of the top-quark Yukawa coupling will be a stringent test of this prediction. Knowledge of the precise value of the top-quark coupling to the Higgs field can shed light on electroweak symmetry breaking as well as the potential existence of new top-quark partners.

Indirect constraints on the top-quark Yukawa coupling can be obtained from loop contributions in either the production of Higgs bosons through gluon fusion or its decay to a pair of photons. However, these couplings can be affected by contribution from beyond-Standard-Model particles. Only a direct measurement of the top-quark Yukawa coupling can disentangle potential new physics contributions. A direct measurement can be achieved by studying observables that probe the top-quark Yukawa interaction with the Higgs boson already at the tree-level. The production cross section of the Higgs boson in association with a single top quark (referred to as tH) or a top-quark pair (referred to as $t\bar{t}H$)

provide examples of such a processes.

The production process of $pp \rightarrow t\bar{t}H$ is proportional to the square of the Yukawa coupling and has a predicted cross section of about 130 fb at $\sqrt{s} = 8$ TeV [3]. Single top quark plus Higgs boson production on the other hand is much suppressed in the SM with a cross section of approximately 18 fb at $\sqrt{s} = 8$ TeV. The process of $pp \rightarrow tHq$ proceeds mainly through t -channel diagrams, with the Higgs boson being emitted either from a top-quark leg or a W -boson propagator. Since the coupling of the Higgs boson to the W boson and the top quark have opposite sign, these diagrams suffer from destructive interference.

At CMS [4] searches are performed for both $t\bar{t}H$ and tH production exploiting a large fraction of the Higgs boson decay channels. The searches are performed using the data sets corresponding to integrated luminosities of up to 5.1 fb^{-1} and 19.7 fb^{-1} collected during the years 2011 and 2012 at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively, and are described in more detail in the following.

2. Higgs boson production in association with top-quark pairs

As the top quark decays nearly exclusively to a W boson and a b quark, the experimental signatures for top-

quark pair production are determined by the decay of the W boson. When both W bosons decay hadronically, the resulting final state with six jets (two of which are b -quark jets) is referred to as the all-hadronic final state. If one of the W bosons decays leptonically, the final state with a charged lepton, a neutrino, and four jets (two of which are b -quark jets) is called lepton+jets. Finally, when both W bosons decay leptonically, the resulting di-lepton final state has two charged leptons, two neutrinos, and two b -quark jets. All three of these top-quark pair signatures are used in the search for $t\bar{t}H$ at CMS.

The Higgs boson decay to a pair of b -quarks represents the dominant decay mode with a branching ratio of about 58%. The next largest contribution comes from Higgs boson decays to di-bosons ($WW^{(*)}/ZZ^{(*)}$) with a branching ratio of about 24%. Other decays with significantly smaller branching ratio are still accessible experimentally due to their unique signature in the detector, in particular $H \rightarrow \gamma\gamma$ and $H \rightarrow \tau\tau$. In order to study all of these decays, the search for $t\bar{t}H$ is performed in three broad categories: Higgs boson to photons, Higgs boson to leptons and Higgs boson to hadrons [5].

Higgs boson to photons. The Higgs boson decay mode $H \rightarrow \gamma\gamma$ has a distinct signature with low systematic uncertainties. The photons provide the trigger for the event, which allows to include all top-quark decay channels in the analysis. The excellent resolution of the CMS calorimeter detector allows for a precise reconstruction of the invariant mass of the two photons ($m_{\gamma\gamma}$) which can then be exploited to separate the $t\bar{t}H$ signal from background events. The leading photon is required to have $p_T > m_{\gamma\gamma}/2$ and the second photon must have $p_T > 25$ GeV. Events are further categorized in leptonic and hadronic channels. The hadronic channels requires at least four jets of which at least one is b -tagged [6] and no leptons in the event. The leptonic channel requires at least two jets of which at least one is b -tagged and at least one charged electron or muon with $p_T > 20$ GeV.

The main background in this channels comes from γ +jets and $t\bar{t}+\gamma$ production. Furthermore, there is a non-negligible contamination from other Higgs boson production mechanism in the signal region. The latter contribution is estimated from simulation, while the background model for the former is extracted from data in the fit to the invariant mass distribution. The di-photon mass spectrum observed in data agrees well with the background estimates. Due to the low event rate, the analysis is limited by the statistical uncertainty.

Higgs boson to leptons. In the Higgs boson to leptons search, the leptons arise as secondary decay products

from $H \rightarrow WW^{(*)}/ZZ^{(*)}$ and $H \rightarrow \tau\tau$ decays, as well as from the W boson produced in the top-quark decay. Events with two same-sign leptons or more than three leptons are selected in order to optimize the signal-to-background ratio. The events are required to pass the di-lepton or tri-lepton triggers. The leading lepton has to fulfill the requirement of $p_T > 20$ GeV, the second lepton has to have $p_T > 10$ GeV. In addition, the presence of two b -quark jets is required. The search uses multivariate analysis techniques [7] to discriminate signal from background events. The largest backgrounds in the analysis are due to events with non-prompt leptons from b - or c -quark decays or di-boson production associated with multiple hadronic jets. The backgrounds are estimated using data-driven techniques using suitable control regions. The signal is extracted by fitting the output discriminant of a boosted-decision-tree (BDT), that has been trained separately for same-sign di-lepton and higher multiplicity lepton events.

While the data in the tri-lepton and di-lepton ee and $e\mu$ channels are in good agreement with background prediction, an excess of signal-like events is observed in the $\mu\mu$ final state. In the four lepton category only one event is observed in data compared to an overall prediction of about three events.

Higgs boson to hadrons. The two main decay modes that contribute to the Higgs boson to hadron search are $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$, with both τ -leptons decaying hadronically. Despite the large branching ratio the reconstruction of hadronic Higgs boson decays is experimentally very challenging due to the large irreducible background from $t\bar{t}$ +jets events and the large combinatorial self background (in particular for $H \rightarrow b\bar{b}$). In order to be able to trigger these events, either one or two leptons from the decay of the top-quark pairs are required. The analysis is performed in different categories determined by the number of jets and the number of b -quark jets in the event. BDTs are employed to identify the jets coming from b -quark or τ -lepton decays and to separate $t\bar{t}H$ events from background events. For the latter, variables involving the kinematics of the reconstructed objects, the event shapes and the b -tagging information are used. Signal events are extracted by fitting the output distribution of the BDT in the different categories. The distribution observed in data agree well with the background prediction and are used to set limits on the $t\bar{t}H$ production cross section in combination with the other channels.

Combination. The results in the different analysis channels are combined using a binned likelihood method.

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