Interplay of Top Quark and Higgs Boson Measurements at the Tevatron and LHC

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Abstract. Given its large mass, the top quark plays an important role in the understanding of the mechanism for electroweak symmetry breaking (EWSB) in the Standard Model (SM). The recently observed new boson, consistent in many ways with the Higgs boson, could be the agent of EWSB. Studies of the production of this new particle in association with top-quark pairs will give important insight into the true nature of this particle. The current status of studies of t $\bar{t}$H production at the LHC and Tevatron are described herein, as well as one of the most important background channels, t $\bar{t}$ + b $\bar{b}$ production. Further, the top quark plays an important role in exotic Higgs models; one such search is also described, looking for t $\rightarrow$ H $\pm$ b.

1. Introduction
In summer 2012, a new boson with a mass of approximately 125 GeV was observed [1, 2] at the Large Hadron Collider (LHC) by the CMS and ATLAS experiments [3, 4]. After several decades of searching for the Standard Model (SM) Higgs boson, this observation is a significant breakthrough. However the effort is far from complete, as hadron collider experiments must now turn their focus to the characterization of the particle to ascertain its consistency with the Standard Model (SM) Higgs boson. Greater than three standard deviation ($\sigma$) significance has been established for direct production in the decay to pairs of either photons, W bosons or Z bosons. The observations in these channels are consistent with the SM Higgs boson within the uncertainties but in order to build a complete understanding of the characteristics of the new boson, the rate of production across all decay channels must be measured. Currently, the least understood aspects of the new boson are the fermionic couplings.

The production of Higgs bosons in association with a pair of top quarks (t $\bar{t}$H) is becoming a particularly important channel in the characterisation of the new boson. It is the only production mode which is directly sensitive to the top-Higgs Yukawa coupling; the cross section is proportional to the coupling squared. Another fermionic coupling, to the b quark, is also accessible through the t $\bar{t}$H channel. At a Higgs boson mass of $\sim$ 125 GeV, the dominant decay mode is to a pair of bottom quarks. In gluon fusion production, the dominant production mechanism at the LHC, this decay channel is not experimentally feasible to probe due to large backgrounds, but associated production mechanisms such as VH [5, 6, 7] and t $\bar{t}$H, despite having a much smaller cross section, give an experimental handle on the Higgs-b coupling. Therefore, t $\bar{t}$H is a unique channel in that it can probe the Higgs coupling to top and bottom in the same process.
The top quark may play a significant role in understanding EWSB. The large mass of the top quark means that it is predicted to have a large coupling to the SM Higgs boson. But in other models, the top quark could play a role in EWSB beyond that of the Higgs mechanism of the SM. Top quark studies also bring about sensitivity to non-SM Higgs bosons for example in the decay of a t quark to a b quark with a charged Higgs boson.

This paper discusses recent experimental results from the LHC and Tevatron which probe the interplay between the top quark and the Higgs boson, either SM or non-SM.

2. Search for SM Higgs boson in association with a top quark pair: $t\bar{t}H$

The SM Higgs boson produced in association with a pair of top quarks has so far been studied at three hadron collider experiments: CDF, CMS and ATLAS [8, 9, 10]. All three analyses select events in the "lepton+jets" channel, but CMS additionally selects "dilepton" events. Figure 1 shows the Feynman diagram for $t\bar{t}H$ production in these two final states which are defined in terms of the decay of the Ws originating from each top quark. Events where one W decays leptonically and the other hadronically are referred to as "lepton+jets" events, whereas in "dilepton" events both W bosons decay leptonically. In the ATLAS results described in this paper, only events with $H \rightarrow b\bar{b}$ are considered as signal and subsequently any limits being set are on the cross section times $H \rightarrow b\bar{b}$ branching ratio. The CMS and CDF analyses, although optimized for $H \rightarrow b\bar{b}$ decays, do not exclude events from other possible Higgs boson decay modes and as such set limits on the $t\bar{t}H$ production cross section.

The lepton+jets final state consists of a high $p_T$ lepton, a large number of jets, some of which are b jets, and a significant amount of missing transverse energy ($E_T^{\text{miss}}$) from the presence of a neutrino. Therefore all three analyses start with a $t\bar{t}$-enriched data sample with all or most of these features. The CMS analysis selects events with an isolated lepton with $p_T \geq 30$ GeV, at least three jets with $p_T \geq 40$ GeV and another jet with $p_T \geq 30$ GeV. At least two jets are required to be tagged as b jets. The dilepton channel events have two leptons: tight ($p_T \geq 20$ GeV) and loose ($p_T \geq 15(10)$ GeV electron(muon)), at least with 2 jets $p_T \geq 30$ GeV and 2 b-tags. In general, $t\bar{t}H$ signal events tend to have a larger number of jets and a larger number of b-tagged jets than background processes, the largest of which is $t\bar{t}$+jets. This feature can be exploited to separate signal and background and so the events are split into 7 jet-tag categories for lepton+jets: $\geq 6$ jets + 2 b-tags, 4 jets + 3 b-tags, 5 jets + 3 b-tags, $\geq 6$ jets + 3 b-tags, 4 jets + $\geq 4$ b-tags, 5 jets + $\geq 4$ b-tags, $\geq 6$ jets + $\geq 4$ b-tags. The most sensitive category is $\geq 6$ jets + $\geq 4$ b-tags with $S/\sqrt{B}$ of 0.31 but categories with lower sensitivity are included to better constrain the background. For dilepton events, two categories are used: 2 jets + 2 b-tags, $\geq 3$ jets + $\geq 3$ b-tags.

Artificial Neural Networks (ANNs) are trained in each category to better separate signal and
The input variables vary from category to category but in general can be described by four main classes of variables: basic single object kinematics (e.g. jet $p_T$), kinematics of pairs of jets (e.g. invariant mass of pairs of untagged jets), event shape variables (e.g. sphericity) and b-tag related variables (e.g. average b-tag discriminant value which is the most discriminating variable in the majority of jet-tag categories). Ten input variables are used in each lepton+jets jet-tag category and five or six in the dilepton categories. The ANN output gives better discriminating power than any one of the single input variables. The ANN output distribution is shown in Fig. 2 for the $\geq 6$ jets $+ \geq 4$ b-tags comparing data and MC simulated background. The signal MC distribution is also shown, normalized to the area of the background for visual purposes. A maximum likelihood fit of the ANN output distributions from the nine jet-tag categories considered in the analysis. Both background and signal processes are modelled with Monte Carlo simulation. Currently no significant excess in the data is observed and so 95% confidence level (C.L.) upper limits are set as a function of $m_H$ on the possible presence of a SM-like signal, as shown in Fig. 2. The median expected limit for a Higgs boson mass of 125GeV is $4.6 \sigma_{SM}$ while the observed limit is $3.8 \sigma_{SM}$.

The CDF collaboration have previously performed an analysis which is very similar to the CMS lepton+jets search, fitting an ANN output distribution to separate signal from background. The 6 jet-tag categories used were 4, 5 and $\geq 6$ jets with 2 or $\geq 3$ b-tags. The data used corresponded to 9.45 fb$^{-1}$ of 1.96 TeV $p\bar{p}$ collisions collected with the CDF detector. Again a 95% C.L. upper limit was set as a function of $m_H$ on the possible presence of a SM-like signal: the median expected limit for a Higgs boson mass of 125GeV is $12.6 \sigma_{SM}$ while the observed limit is $20.5 \sigma_{SM}$.

The ATLAS search also exploits the difference between signal and background in terms of the number of jets and the number of tags in events, by dividing into jet-tag categories. Events were selected with an isolated electron (muon) with $p_T \geq 25(20)$ GeV, at least four jets with $p_T \geq 25$ GeV. Additional cuts on the $E_T^{miss}$ and the transverse mass of the leptonic W ($M_T$) are included to reduce the QCD multijet background contribution. The nine jet-tag categories used are divided into signal enriched: 5 jets (3, $\geq 4$ b-tags) and $\geq 6$ jets (3, $\geq 4$ b-tags), and background enriched categories: 4 jets (0, 1, $\geq 2$ b-tags), 5 jets + 2 b-tags and $\geq 6$ jets + 2 b-tags. A discriminating variable is employed in each jet-tag category to further separate signal and background. For the first variable, a kinematic fit is used first to reconstruct the $t\bar{t}$ system from selected objects (jets, lepton and $E_T^{miss}$). The remaining two jets are then combined to
reconstruct the invariant mass of the $b\bar{b}$ system ($m_{b\bar{b}}$). This variable is used in a fit in the categories with $\geq 6$ jets and shows a peak near the Higgs boson mass in signal MC. In all other categories, the scalar sum of jet $p_T$ ($H_T^{had}$) is used in the fit. Signal to background shape comparisons of the distributions of both these variables are shown in Fig. 3. The simultaneous fit to background-like and signal-like topologies acts to improve the background prediction and reduce background related uncertainties.

The signal and largest background process (t\bar{t}+jets) are modelled using MC, but data are used in the construction of the W+jets and QCD multijet backgrounds. Observed and expected 95% C.L. upper limits were set on the Higgs boson production cross section times the branching ratio to a pair of b quarks ($\sigma(t\bar{t}H) \times BR(H \rightarrow b\bar{b})$) as a function of $m_H$, as shown in Fig. 3. The median expected limit for a Higgs boson mass of 125GeV is 10.5 $\sigma_{SM}$ while the observed limit is 13.1 $\sigma_{SM}$.

3. Measurement of $\sigma(t\bar{t}+b\bar{b})/\sigma(t\bar{t}+jj)$

One of the main challenges in the search for t\bar{t}H is the t\bar{t} + b\bar{b} background which has the same signature as t\bar{t}H. It has a very small cross section which makes it difficult to measure experimentally; while theoretical predictions, although available at NLO, suffer from larger scale uncertainties due to the presence of two very different energy scales ($m_t$ and the jet $p_T$ threshold). A more accessible quantity is the ratio of the t\bar{t} + b\bar{b} cross section to the total t\bar{t} + jj cross section. CMS carried out the first measurement [11] of this ratio is 5 fb$^{-1}$ of 7 TeV ATLAS data in the dilepton channel. Events were selected with 2 isolated leptons ($ee$, $e\mu$, $\mu\mu$) with $p_T \geq 20$ GeV. These lepton pairs were required to have an invariant mass ($m_\ell\ell$) outside a 12 GeV window around the Z boson mass to reduce the large background from $Z \rightarrow ll^+$ decays present in the dilepton channel. Events were required to have $E_T^{miss} \geq 30$ GeV in the $ee/\mu\mu$ channels to suppress any remaining QCD multijet background. Finally, only events with $\geq 4$ jets and $\geq 2$ (4) b-tags were used for the t\bar{t} + jj (t\bar{t} + b\bar{b}) sample. The difference in the b-jet multiplicity spectrum between $t\bar{t} + b\bar{b}$ and $t\bar{t} + jj$ was exploited to extract $t\bar{t} + b\bar{b}$ signal by performing a fit of this distribution to data. Correcting to the visible phase space, a value for the ratio of the cross sections was measured to be $\sigma(t\bar{t}+b\bar{b})/\sigma(t\bar{t}+jj) = 3.6 \pm 1.1$ (stat.) $\pm 0.9$ (sys.). The result cannot be directly compared to current NLO QCD calculations since the $p_T$ thresholds differ. The result is somewhat larger than predictions from MADGRAPH and POWHEG, which are 1.2% and 1.3% respectively.
4. Direct Searches for Charged Higgs

Events containing top quarks can also be used to search for evidence of Higgs physics beyond the SM, such as MSSM charged Higgs production through $t \rightarrow H^\pm b$. In the SM, $t\bar{t}$ events are dominated by the Wb final states. The presence of a light charged Higgs, with mass smaller than that of the top quark, would result in a different distribution of final states than is expected in the SM. For low Higgs mass and high $\tan\beta$, the dominant decay mode of a charged Higgs is $H^\pm \rightarrow \tau \nu$. The CMS and ATLAS collaborations have completed searches [12, 13] for charged Higgs bosons in the $H^\pm \rightarrow \tau \nu$ decay in a variety of final states, each defined by (a) the decay of the $\tau$ from the Higgs (hadronic: $\tau_h$ or leptonic: $e/\mu$), and (b) the decay of the W from the other top decay (hadronic: "jets" or leptonic: "$e/\mu$").

The three channels used in the CMS analysis are $\tau_h$+jets, $\tau_h$+e/\mu, and e+\mu. In the $\tau_h$+jets, the transverse mass of the $\tau_h$ and $E^\text{miss}_{T}$ ($m_T$) is constructed. This quantity is expected to be larger in signal where the $\tau$ and neutrino originate from a $H^\pm$ as opposed to from a W, as in background. A binned maximum-likelihood fit to this distribution is used to extract the signal. In the $\tau_h$+e/\mu and e+\mu channels, a counting experiment is performed in order to extract the final limits. In the analysis performed by ATLAS, the $\tau_h$+jets and $\tau_h$+e/\mu channels and a third channel, e/\mu+jets are used. A different discriminating variable is used in each channel to extract the signal: $m_T$ in $\tau_h$+jets events, $E^\text{miss}_{T}$ in $\tau_h$+e/\mu events and $m_T^H$ (the transverse mass of the leptonically decaying $H^\pm$, or W in the case of the background).

Both collaborations set 95% C.L. upper limits on the $BR(t \rightarrow H^\pm b)$ as a function of the mass of $H^\pm$ using 2.3(4.6) fb$^{-1}$ of CMS (ATLAS) data, as shown in Fig. 4. An upper limit of 2-3% for a mass range of 80-160 GeV was set by CMS and of 1-5% over a mass range of 90-160 GeV by ATLAS. The analyses from both collaborations also exclude a large region of $m_{H^\pm}$ - $\tan\beta$ parameter space.

5. Conclusion

The current status of searches for the SM Higgs boson in association with top quarks has been presented, including analyses from the LHC and Tevatron. These are the first searches in this production mode. The first measurement from CMS of the $t\bar{t} + bb$ cross section ratio was also described, a large and important background to tH searches. Finally, two searches for MSSM charged light Higgs in the $H^\pm \rightarrow \tau \nu$ decay channel were described. These analyses were carried out by the CMS and ATLAS collaborations and set limits on $BR(t \rightarrow H^\pm b)$. 

Figure 4. The upper limit on the branching fraction for $t$ to a charged Higgs and a b quark for CMS (left) and ATLAS (right).
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