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# Searches for Higgs bosons decaying to $b\bar{b}$ in CMS

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**Abstract.** Searches for the standard model Higgs boson decaying into b quarks and produced in association with either vector bosons or top quark pairs are performed in proton-proton collisions with the CMS detector at the LHC. A search for neutral Higgs bosons decaying into b quarks and produced in association with at least one additional b quark is also performed. This mode is expected to be particularly sensitive to Higgs bosons in MSSM scenarios with large values of the parameter $\tan\beta$.

## 1 Introduction

In this paper we present searches for the SM Higgs boson decaying into a b-quark pair in the production modes pp → VH, where V is either a Z or a W boson decaying leptonically, and pp → $t\bar{t}$H, where top quarks decay into either lepton plus jets or dileptons. We also present a searches for MSSM neutral Higgs bosons produced in association with at least one b quark, and decaying into a pair of b quarks, pp → b$\phi$+X, $\phi \to b\bar{b}$.

## 2 Standard model searches

### 2.1 VH analysis

A search for the SM Higgs boson decaying to $b\bar{b}$, produced in association with either a Z or a W boson [1] is presented for five channels: W($\ell\nu$)H, Z($\ell^+\ell^-$)H and Z($\nu\nu$)H, where $\ell = e, \mu$. This search is performed using 5.0 (12.1) fb$^{-1}$ of proton-proton collisions at $\sqrt{s}$ = 7 (8) TeV collected in 2011 (2012) by CMS at the LHC.

The initial approach requires the weak vector boson (V) and the di-jet system, with b-tagged jets, to be boosted, which tend to produce V and H back-to-back. Taking such measures reduces significantly the background, that is composed by V+jets, $t\bar{t}$, single top, VV and QCD multijet processes. For each channel, categories of low- and high-boosted regions are defined.

Several triggers consistent with the signal topology of the five processes are used. For each channel, events are selected according to the objects arising from the V decays. In addition, at least two jets passing the CSV [2] b-tagging selection are required, which also reduces V+jets and VV backgrounds. The pair of b-tagged jets with the largest $p_T(bb)$ is used to reconstruct the Higgs candidate.

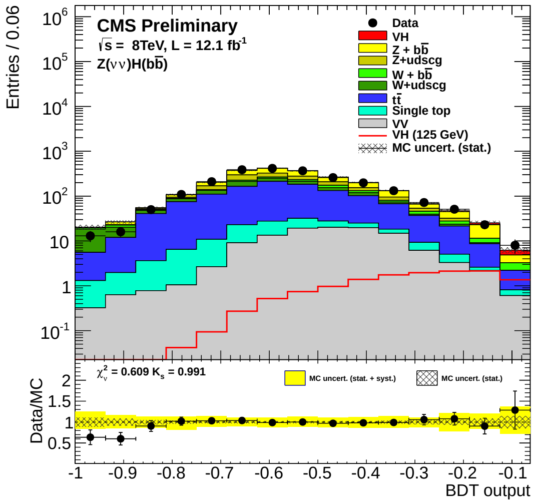


**Figure 1.** Z($\nu\nu$)$H$ channel at 8 TeV. BDT distributions in the high $p_T$(V) category.

The Higgs mass resolution can be improved by 15% by applying a boosted-decision trees (BTD) regression technique, providing an increase in the sensitivity of 10-20%.

At last, a BDT is trained for each mass value using MC samples that pass the event selection. The sensitivity of the analysis is improved by 20% if the fit is performed in the distribution of the BDT discriminator variable, instead of a simple cut-and-count.

The proper normalisation of the V+jets and top-pair processes contributing to the background are obtained in suitable control regions in the data.

A fit of the signal and background to the shape of BDT discriminators yields the results. In the fit, the normalisation and shape of both signal and backgrounds vary within

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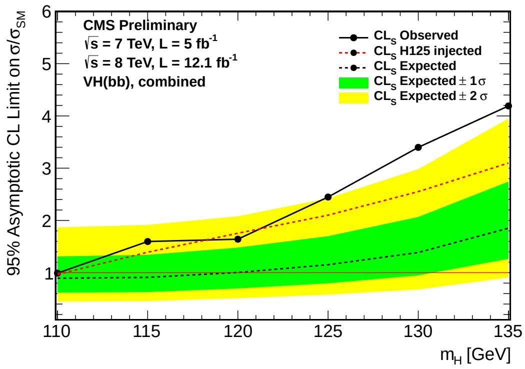



**Figure 2.** Expected and observed upper limits at the 95% CL of the $\sigma(VH)/\sigma_{SM}$. The 1- and 2-$\sigma$ bands of the expected limits are also shown.

the uncertainties. A post-fit BDT distribution for one category is shown in Figure 1 for illustration.

Upper limits at the 95% CL for all channels combined are obtained for the cross section relative to the SM expectation and shown in Figure 2. An excess, with local significance of 2.2$\sigma$, with respect to the background expectation is observed for Higgs boson with a mass of 125 GeV, being consistent with SM Higgs with that mass. The signal strength returned by the fit is $1.3^{+0.7}_{-0.6}$.

In Figure 3 we clearly see the VV contribution well described by the data.

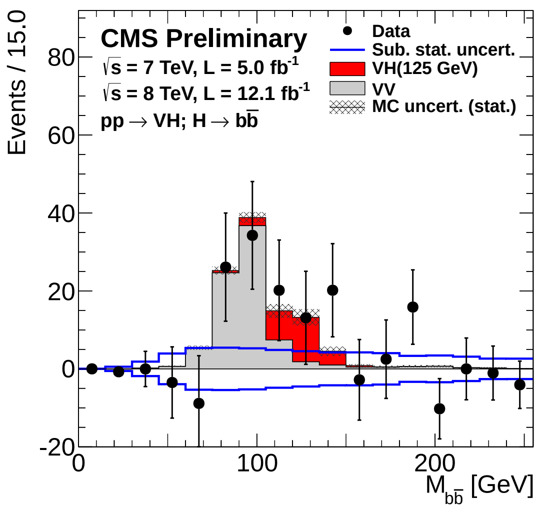



**Figure 3.** Di-jet mass distribution with all backgrounds subtracted, except the VV contribution.

### 2.2 tt̄H analysis

In another analysis [3], the Higgs is produced in association with a top-quark pair, which decays into a single lepton and jets or into di-leptons. This search is performed using 5.0 fb$^{-1}$ of proton-proton collisions at $\sqrt{s}$ = 7 TeV collected in 2011 by CMS at the LHC. The major source of backgrounds is the production of a top pair plus jets. Both signal and background events are modelled with MC simulations.

The event selection is consistent with the presence of a Higgs boson decaying into b quarks and produced in association with a top-quark pair decaying in a single lepton and jets or in two leptons. The triggers for the single-lepton channel requires at least one isolated lepton and at least three jets, whereas in the di-lepton channel at least two leptons are required for the event to be accepted.

Besides two categories defined by the top-pair decay products, events are also categorised in terms of the number of jets and b-tagged jets. A jet is b-tagged when the CSV discriminator is above a certain threshold.

The results are obtained from the simultaneous fit of the signal and backgrounds to the shape of artificial neural network (ANN) discriminators. In the fit, the ANN normalisation and shape, for signal and backgrounds, are allowed to vary within the statistical and systematic uncertainties, which are treated as nuisance parameters in the fit. The ANN distribution for the single lepton + jets, with at least 6 jets and 3 b-tags is shown in Figure 4.

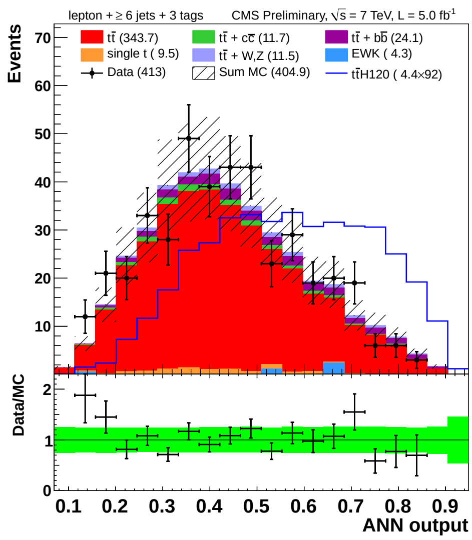



**Figure 4.** tt̄H analysis results. ANN distributions for the category single lepton + jets with at least 6 jets and 3 b-tags.

Figure 5 shows the upper limits at the 95% CL of the cross section relative to the SM expectation. The lepton + jets categories are the most sensitive.

## 3 MSSM searches

We searched for MSSM neutral Higgs bosons produced in association with b quarks, and decaying into a pair of b quarks. This search is performed using 2.7-4.8 fb$^{-1}$ of proton-proton collisions at $\sqrt{s}$ = 7 TeV collected in 2011 by CMS at the LHC.

Two quasi-orthogonal analyses searched for a signal in final states defined either purely by jets (all-hadronic) [4] or requiring an additional non-isolated muon (semileptonic) [5]. Both analyses strategy is to search, in events

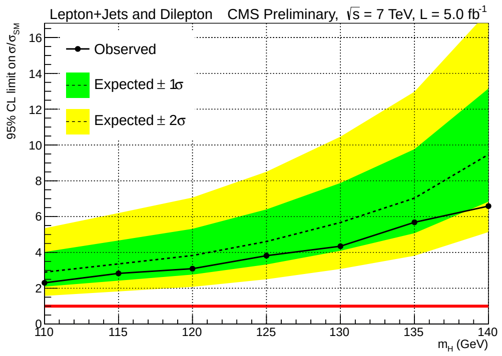


**Figure 5.** Expected and observed upper limits at the 95% CL of the $\sigma(t\bar{t}H)/\sigma_{SM}$. The 1- and 2-$\sigma$ bands of the expected limits are also shown.

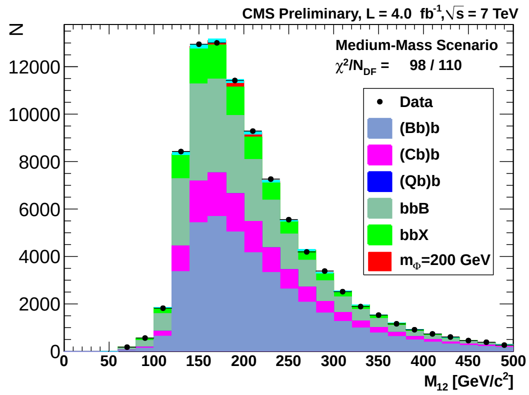


**Figure 6.** Results of the all-hadronic analysis from the fit of a signal with mass 200 GeV and background templates. The plot shows the projection of $M_{12}$ in the medium-mass scenario.

with at least three b-tagged jets, for a peak in the invariant mass distribution of the two leading jets[1], $M_{12}$, on top of the heavy-flavour multijet background that is modelled using data samples. Events common to both samples are excluded and the results combined.

### 3.1 All-hadronic analysis

Different triggers have been used requiring at least two or three jets with three sets of $p_T$ thresholds. Crucial is the requirement of at least two online b-tagged jets.

Two scenarios are defined, the low- and medium-mass scenarios. Events are required to have at least three reconstructed jets with two sets of $p_T$ cuts, depending on the scenario. The two leading jets must have a minimum separation with each other. At least the three leading jets must be b-tagged, which is done using the CSV b-tagging algorithm. The secondary-vertex mass is used to build a variable, EvtBTag, reflecting the b-jet content of the event.

The dominant heavy flavour QCD multijet background is not fully reducible nor well described by MC simulations. Therefore, to model the background, two-dimensional (2D) templates on $M_{12}$ and EvtBTag of the different flavour compositions of the background are constructed from a double-b-tag data sample. Signal templates are built using MC simulations.

A 2D fit of a linear combination of the background-only templates shows good agreement between data and the background estimation. According to the fit the three b-jets production is dominant contribution to the background. The signal yield is extracted by fitting a linear combination of signal and background templates. No significant deviation from background is observed. Figure 6 shows projection of the $M_{12}$ distributions after the fit including a signal with mass of 200 GeV.

### 3.2 Semileptonic analysis

For the semileptonic analysis different triggers were used as the luminosity increased. Events are accepted by the trigger if they contain at least one or two jets with $p_T$ thresholds softer than the all-hadronic search, but requiring in addition the presence of a muon. At least one or two jets must be online b-tagged.

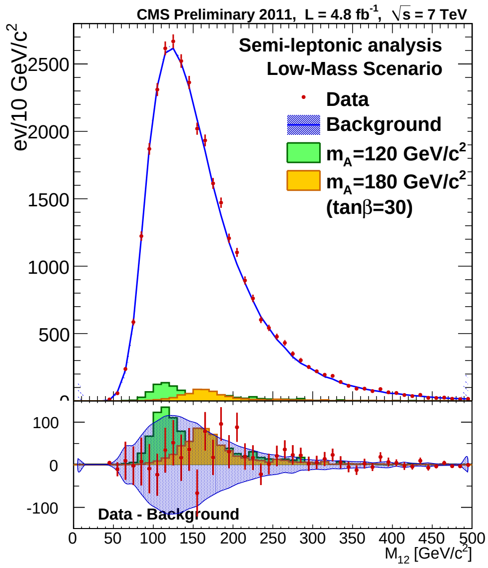


**Figure 7.** Results of the semileptonic analysis. $M_{12}$ distributions of data and predicted background in the signal region, for the low-mass scenario.

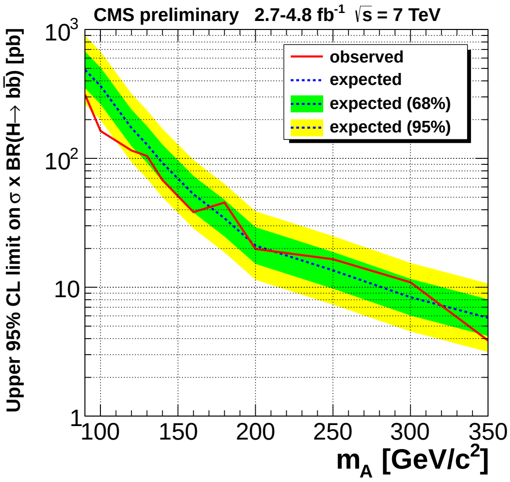
The event selection requires at least three jets with $p_T$ cuts softer than in the all-hadronic case, with a minimum separation with each other and b-tagged using the CSV b-tagging algorithm. Moreover, a muon must be contained in one of the two leading jets.

Two methods using data sample are employed to estimate the background contribution. For each method, two discriminating variables with a likelihood ratio, using various kinematic inputs, are obtained, each for one mass scenario, namely the low- and medium-mass scenarios. In both scenarios, the control (signal) region is defined by an upper (lower) threshold of the likelihood discriminant.

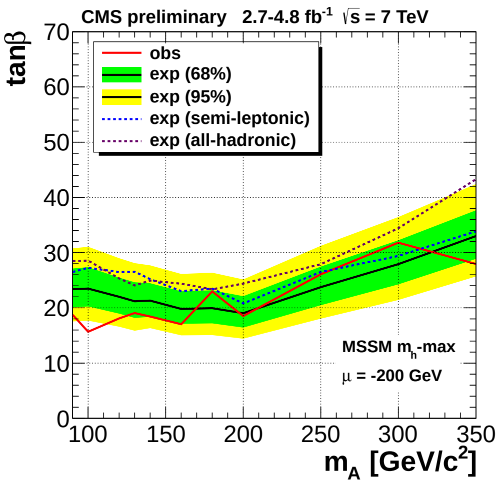
[1] Jets are ranked in decreasing value of their transverse momenta.

The signal contribution is extracted with a binned likelihood fit to the invariant mass distribution of the two leading jets. No significant deviation from background is observed, as illustrated in Figure 7.

### 3.3 Combined results




(a)




(b)

**Figure 8.** Observed and expected upper limits at 95% CL for (a) the cross section times branching fraction and (b) $\tan\beta$ as a function of the Higgs mass for the combined results. 1- and 2-$\sigma$ bands for the expected limits are also shown.

A very small overlap is found between the two samples. To combine the results the overlapping events (< 2.7%) are removed from the all-hadronic samples.

In this search no significant excess is observed, both analyses are combined and the 95% CL upper limits on the cross section times the branching fraction are obtained. The results are shown in Figure 8a.

The results are translated into 95% CL upper limits of $\tan\beta$ in the $m_h^{max}$ scenario with $\mu = -200$ GeV, displayed in Figure 8b. The expected cross section and branching fractions are calculated by hbb@nnlo [6] and Feynhiggs [7–10], respectively.

## 4 Summary

We presented searches for a Higgs boson decaying in b quarks. In the VH analysis an excess with a local significance of 2.2$\sigma$, consistent with a 125 GeV SM Higgs, is observed. So far, no evidence of a signal corresponding to a SM Higgs is found in the $t\bar{t}H$ analysis. In searches for MSSM Higgs bosons produced in association with b quarks, no evidence of a signal is found.

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