PROCEEDINGS OF SCIENCE

Measurements of Higgs boson production and properties in the $\mathrm{b\overline{b}}$ decay channel using the CMS detector

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The latest searches with $\sqrt{s} = 13$ TeV data from 2015 with final states containing Higgs bosons decaying to bottom quarks are presented. Even though the majority of Higgs bosons should decay to bottom quarks, this final state remains very elusive because of overwhelming standard model background. In order to enhance the sensitivity of the standard model searches, additional final state objects are selected when available. We report on the searches with Higgs decaying to a $\mathrm{b\overline{b}}$ pair in the production with an associated top pair and in vector boson fusion. We also report on the production with an associated single top, which is particularly enhanced in models were the relative sign of coupling between top-higgs is flipped with respect to the Standard Model. No excess is observed.

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1. Introduction

The standard model generates the masses of fundamental particles via spontaneous electroweak symmetry breaking. A massive, spin-0 particle (i.e. the Higgs boson) is predicted as a result of the symmetry-breaking mechanism; the mass of the Higgs boson however remains a free parameter. CMS and ATLAS observed a new particle in 2012 in the process of searching for the Higgs boson.[1] The combination of all the Higgs boson measurements performed by ATLAS and CMS at the end of Run 1[2], shows that all the coupling strengths and production cross-sections are compatible with the expectation for a Standard Model Higgs boson of mass 125.09 GeV.

A Higgs boson with this mass has a branching fraction to a bottom quark, anti-bottom quark pair ($\mathrm{b\bar{b}}$) of approximately 58%.[3] However, despite the very large branching fraction an inclusive search for the Higgs boson to $\mathrm{b\bar{b}}$ is not feasible given the large amounts of standard model backgrounds (e.g. top, anti-top pairs and QCD with heavy flavor jets). Moreover, the Run 1 dataset is not large enough to yield evidence of the decay alone.[4] Despite the lack of direct evidence for this decay channel, the compatibility of the Higgs boson at 125 GeV and the expected large branching fraction make the $\mathrm{b\bar{b}}$ channel very attractive for any search containing a Higgs boson in the final state. However, the inclusive search for a Higgs boson decaying into a bottom quark pair is severely affected by the overwhelming QCD background, so typically associated modes of production, with additional objects in the final state, are used to further reject the background

These proceedings will highlight three recent searches containing the 125 GeV Higgs boson decay to $\mathrm{b\bar{b}}$. All of them utilize 2.3-2.7 fb^{-1} of $\sqrt{s} = 13$ TeV CMS data from 2015. They are all searches for 3 different production modes, although the last one is heavily suppressed in the SM due to negative interference with the W diagram, and enhanced only for a flipped sign coupling of the Higgs boson to the top quark.[5, 6, 7]

2. Search for associated production with top quarks

The Higgs boson coupling to the top quark cannot be measured directly in a single final state since Higgs boson decay top quarks is not allowed kinematically. Higgs bosons can however be produced via "$\mathrm{t\bar{t}H}$" in which two top quarks fuse to produce a Higgs boson. In addition there are two top quarks in the final state. The final Run 1 combination of Higgs boson searches from CMS and ATLAS revealed a modest excess in $\mathrm{t\bar{t}H}$ production channel.[2] The sensitivity to the production mode is driven by multi lepton channel (together with the excess). This motivates the detailed analysis of the 2015 to search for a further excess of $\mathrm{t\bar{t}H(b\bar{b})}$.

After the decays of the Higgs boson and the top quarks, the final state will contain the decay products of two, opposite sign W bosons and four b-jets. One or both W bosons are required to decay leptonically–considering only electron or muon final states. This search is a multi-category analysis whose categorization is based on the number of leptons (only electrons or muons), the number of jets and the number of jets from b quarks. There are in total eleven categories total: five di-lepton categories and eight single lepton categories. There is one single lepton category that selects boosted topologies of the Higgs boson (i.e. high transverse momentum).

For each category a boosted decision tree (BDT) is trained on a set of variables specific for that category. For most categories a single dimensional shape analysis of that BDT is performed. In the lepton plus jets categories a two dimensional analysis of the BDT and a Matrix Element Method (MEM) variable is performed. The BDTs in two of the categories with leading significance are shown in Figure 1.

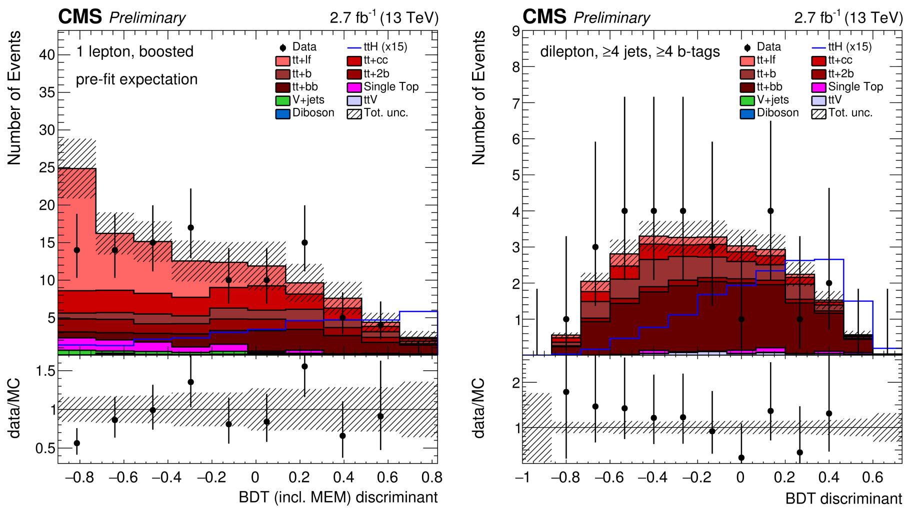

Figure 1: Final discriminant shapes in the different analysis categories in the boosted, lepton+jets channel (left) and four b-tag, dilepton channel before the fit to data.

There is a net deficit of the data with respect to the expected yield from simulation and so the fitted signal strength is -2.0 ± 1.8 times the standard model signal strength. This is a 1.7σ deviation from the standard model expectation. A breakdown of the signal strength in lepton plus jets and di-lepton categories is shown in Figure 2

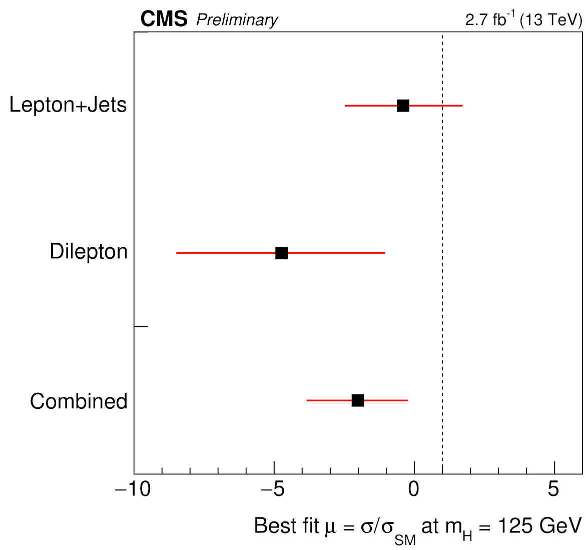

Figure 2: Best-fit values of the signal strength modifiers μ with their $\pm 1\sigma$ confidence intervals.

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3. Search for vector boson fusion production

The search for Higgs bosons produced via vector boson fusion (VBF) and decaying to bottom quark pairs is very challenging at the trigger level. There are four jets in the final state: two from the forward scattered quarks and two others from the Higgs boson decay. In the level 1 trigger, three jets are required. In the high level trigger (HLT), there are two strategies: requiring one or two b-tagged jets at HLT. Both strategies require four jets, but the kinematic requirements of the jets in the two b-tag strategy are somewhat relaxed.

For each trigger, there are separate BDTs trained. The output of the BDTs, which are shown for data and simulation in Figure 3, are used to define analysis categories. The categories with the highest BDT score events are the most sensitive. In each category QCD is the dominant background. In order to overcome discrepancies with in the QCD MC “transfer functions” are produced as a function of $H(b\bar{b})$ invariant mass and for each category. Finally a simultaneous fit of background (mainly QCD) and signal templates in invariant mass are performed over all categories.

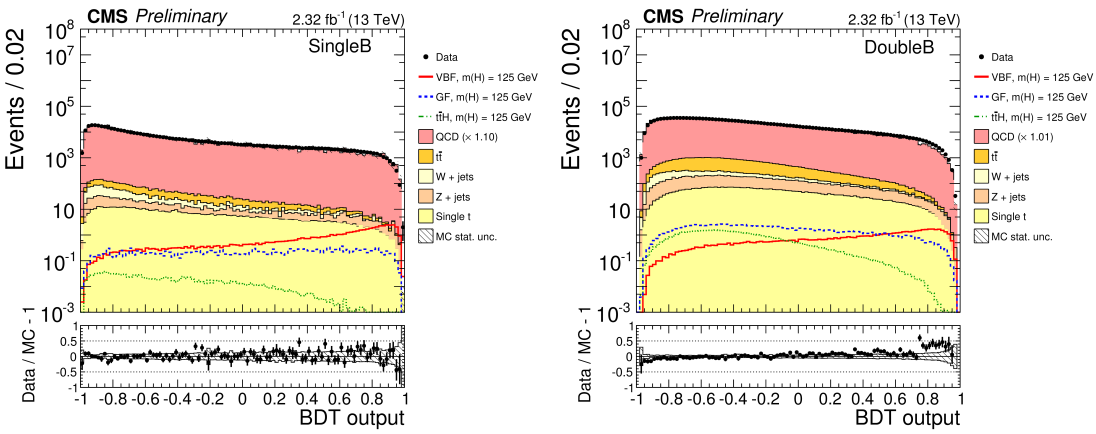

Figure 3: Distribution of the BDT output for the events in the SingleB (left) and DoubleB (right) sets. Data are shown by the points, while the simulated backgrounds are stacked. The LO QCD cross sections are scaled such that the total number of background events equals the number of events in data. The panels at the bottom show the fractional difference between the data and the background simulation, with the shaded band representing the statistical uncertainties of the MC samples.

The negative logarithmic likelihood of data compatibility as a function the Higgs boson signal strength for this analysis is shown in Figure 4 in green. At the maximum likelihood the signal strength is $\mu_{2015} = -3.7^{+2.4}_{-2.5}$ since there is a deficit of data compared to expected yield at the mass of the Higgs boson. A combination of this analysis with Run 1 results in the same channel are also shown. The signal strength in the combined analysis at maximum likelihood is $\mu_{Run1+2015} = 1.3^{+1.2}_{-1.1}$.

4. Search for Higgs boson plus single top

The Feynman diagrams in Figure 5 all contain single top and a Higgs boson in the final state. With standard model couplings there is destructive interference such that the production cross sec-

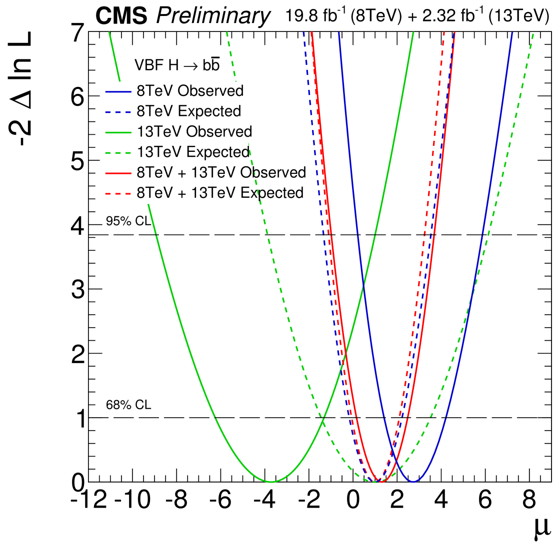

Figure 4: Observed and SM-expected likelihood profile of the signal strength $\mu = \sigma/\sigma_{SM}$ with $m_{\mathrm{H}} = 125$ GeV, using Run 1 8TeV data, Run 2 13TeV data, and for the combination of 8 TeV and 13 TeV 2015 data.

tions are $\sigma_{\mathrm{tHq,SM}} = 71$fb and $\sigma_{\mathrm{tHW,SM}} = 16$fb in 13 TeV proton-proton collisions. However, since only one of each set of diagrams contains a Higgs boson coupling directly to the top quark (via coupling of κ_t), if the sign of the coupling strength is opposite in sign, then the interference is constructive–yielding much larger cross sections. This is the so-called "Inverted Top Coupling" (ITC) model and the cross sections are $\sigma_{\mathrm{tHq,ITC}} = 739$fb and $\sigma_{\mathrm{tHW,SM}} = 147$fb in 13 TeV proton-proton collisions.

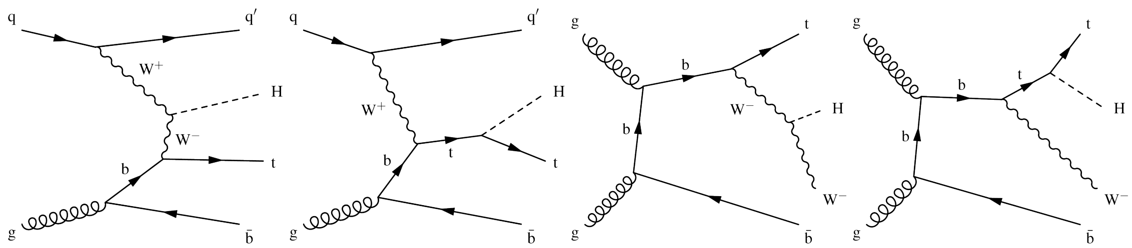

Figure 5: Representative Feynman diagrams for the associated production of a single top quark and a Higgs boson in the t channel (left plots) and in the tW channel (right plots).

Since the final state contains several b-jets, the combinatorics of matching the proper pair of jets to the Higgs boson and the top is complex. In order to select them in an optimal manner, a BDT is trained using the correct matching (from simulation level information) as the target and randomly assigning b-jets to the Higgs boson and the top quark at reconstruction level in signal simulation as the background for the training. In the analysis the b-jet assignment scheme that has the highest BDT score is used for the analysis. This methodology is validated in the well-simulated, high efficiency, and high yield environment of standard model $t\bar{t}$ events.

As in the previous analyses, a shape analysis is performed on BDT outputs. In this analysis, there are separate BDTs trained for events with three and four b-tags. The output for simulation and data are shown in Figure 6.

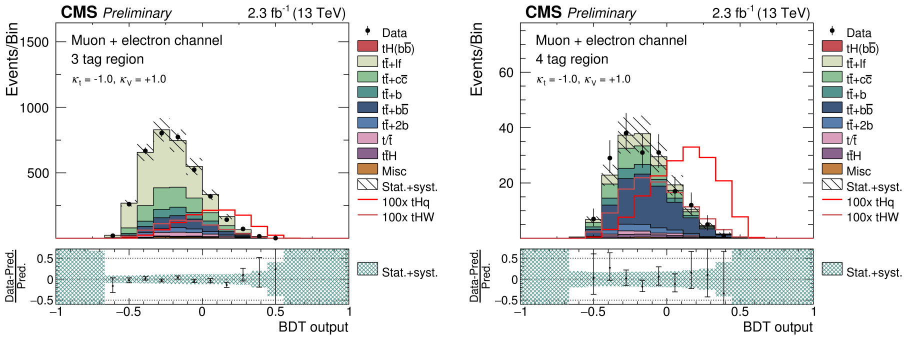

Figure 6: Postfit distributions of the classification BDT response in the 3 tag (left) and 4 tag (right) regions for the ITC coupling scenarios. The uncertainty bands contain both systematic and statistical contributions. The signal distributions correspond to the expected contributions scaled by the factors given in the legends.

No excesses are found in this search and so exclusion limits at the 95% confidence level are set. Figure 7 summarizes these limits as a function of κ_t for $\kappa_V = +1$. For the standard model scenario of $\kappa_t = +1$, the limits are in excess of 100 times the production cross section. However, for the ITC where $\kappa_t = -1$, the limits are approximately 6 times the production cross section.

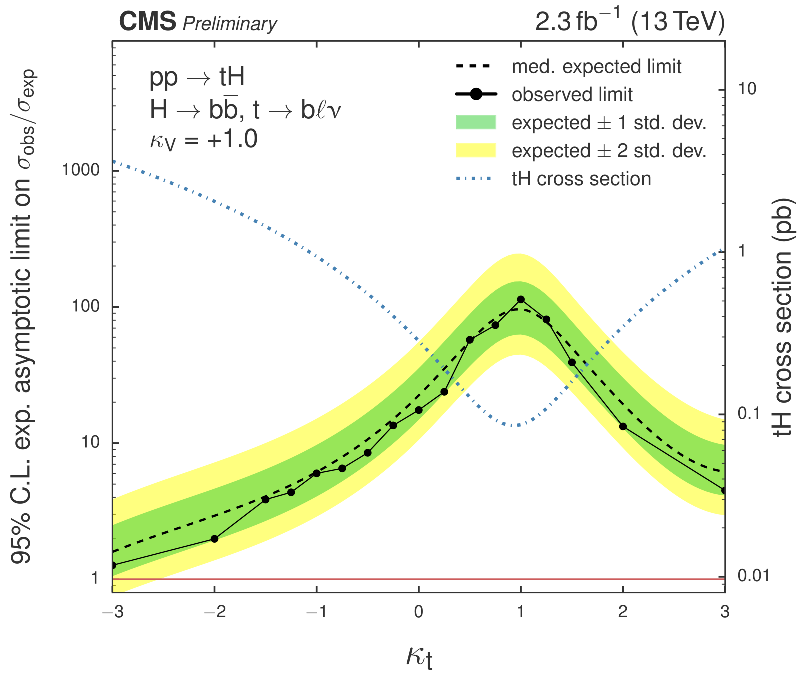

Figure 7: Upper limits on tH scenarios as a function of κ_t for $\kappa_V = +1$. In addition, the tH cross section is given (right y axis).

5. Outlook

CMS has a full and robust program of Higgs boson searches that utilize the $\mathrm{b\bar{b}}$ final state. These analyses (and several others) anticipate adding more data from 2016 in the near future.

References

[1] S. Chatrchyan, "Observation of a new boson at a mass of 125 gev with the cms experiment at the lhc," *Physics Letters B*, vol. 716, no. 1, pp. 30 – 61, 2012.

[2] G. Aad, "Measurements of the higgs boson production and decay rates and constraints on its couplings from a combined atlas and cms analysis of the lhc pp collision data at $\sqrt{s} = 7$ tev and 8 tev," *Journal of High Energy Physics*, vol. 2016, no. 8, p. 45, 2016.

[3] S. Heinemeyer, "Handbook of LHC Higgs Cross Sections: 3. Higgs Properties: Report of the LHC Higgs Cross Section Working Group," Tech. Rep. arXiv:1307.1347. CERN-2013-004, Geneva, 2013. Comments: 404 pages, 139 figures, to be submitted to CERN Report. Working Group web page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections.

[4] V. Khachatryan, "Search for the standard model higgs boson produced through vector boson fusion and decaying to $b\bar{b}$," *Phys. Rev. D*, vol. 92, p. 032008, Aug 2015.

[5] "Search for $\mathrm{t\bar{t}H}$ production in the $\mathrm{H \to b\bar{b}}$ decay channel with $\sqrt{s} = 13$ TeV pp collisions at the CMS experiment," Tech. Rep. CMS-PAS-HIG-16-004, CERN, Geneva, 2016.

[6] "Search for the standard model Higgs boson produced through vector boson fusion and decaying to $\mathrm{b\bar{b}}$ with proton-proton collisions at $\sqrt{s} = 13$ TeV," Tech. Rep. CMS-PAS-HIG-16-003, CERN, Geneva, 2016.

[7] "Search for H to $\mathrm{b\bar{b}}$ in association with a single top quark as a test of Higgs boson couplings at 13 TeV," Tech. Rep. CMS-PAS-HIG-16-019, CERN, Geneva, 2016.