A search for neutral Higgs bosons produced in association with b-quark(s) and decaying into a pair of b-quarks is performed with the CMS detector at LHC. The Higgs boson signal is expected to emerge as an excess in the mass spectrum of two b-tagged jets. Dedicated triggers with on-line b-tagging in fully hadronic events were developed specifically for this kind of analysis. Limits on the cross section times branching fractions are derived model independently. The result was interpreted in the Minimal Supersymmetric Model (MSSM). Upper limits at $\tan\beta$ are derived as a function of $M_A$, the mass of the Higgs boson $A$. In the analysis presented here data taken in 2011 at 7 TeV are used corresponding to a total luminosity of $L = 2.7 - 4.0fb^{-1}$ for low and medium Higgs boson masses, respectively.

1 Introduction

A search is performed for a Higgs boson produced in association with additional b-quarks. In the Standard Model (SM) the cross section is very low and due to the large background dominated by QCD processes with three b-quark or two b-quark plus c,udsg-quark final states the signal in the current data is not in reach.

In the Minimal Super-symmetric Model (MSSM) $^1$2$, there are 3 neutral Higgs bosons, one CP-odd ($A$) and two CP-even ($h, H$). Their couplings to d-type fermions are enhanced by a factor $\tan\beta$. The Higgs bosons $A$ and $h(H)$ degenerate in the mass. Hence, the cross section of Higgs boson production in association with b quarks increases by a factor $2 \times \tan^2\beta$.

The MSSM Higgs bosons production is dominated at hadron colliders by the sub-process $gg \rightarrow b(\bar{b})\Phi + X$ with only a small contribution from $qq \rightarrow bb\Phi + X$. The branching fraction of the Higgs boson decay to b-quarks are in the range $[70\%, 92\%]$ $^3$, and it remains large even at large masses of the Higgs boson $A$.

The dominant background arises from heavy flavor multi-jet QCD processes. Other background contributions like $Zbb$, $Wbb$, $t\bar{t}$ have low rates.

Data collected with the CMS detector $^4$ in proton-proton collisions at a centre-of-mass energy of 7 TeV at the LHC, corresponding to an integrated luminosity of $2.7 - 4.0fb^{-1}$, were used in this search. Specialized triggers have been developed, using algorithms to tag b-quark jets from displaced vertices of B-meson decays.

2 Trigger and event selection

At LHC multi-jet events are produced copiously via higher order QCD processes. To trigger events with jets originating from the decay of heavy particles thresholds
on transverse momenta ($p_T$) of the jets are imposed in the first level trigger. In the Higgs boson low-mass search, performed in the data taken in the first period, the thresholds were $46 \text{ GeV/c}$ for the leading jet and $38 \text{ GeV/c}$ for the second leading jet. In the second half of 2011, due to the higher luminosity, the threshold for the leading jet was $60 \text{ GeV/c}$, and for the second leading jet $53 \text{ GeV/c}$. This data were used in the search for the medium-mass Higgs boson. On-line b-tagging was performed with TCHE algorithm [5] using the track with 2nd highest significance, and at least two jets must be b-tagged. Tracks were clustered into on-line jets [6] with a cone radius $R = 0.5$.

The jets were reconstructed using the particle-flow algorithm [7–9] and a standard jet energy calibration was applied [10]. Then, jet energies were corrected for the contributions of pile-up (PU) interactions [11]. The combined secondary vertex (CSV) algorithm [12] was applied for the offline identification of b-jets. Secondary vertices (SV) were reconstructed using the Adaptive Vertex Finder [13]. It combines several topological and kinematic variables of the SV and track impact parameters into a ratio of likelihoods. The ratio was required to be larger or equal to 0.89 (tight operation point, CSVt) to tag the jet. Mistagged light flavor jets are suppressed to a level of $\sim 0.2\%$ with a b-jet identification efficiency of about 55% [14].

A variable (EventBta) was created exploiting the SV mass spectra obtained for jets of different flavors. EventBtag combines the SV masses of the three leading jets in one quantity which is small for c- and light-jets and large for b-jets.

The three leading jets have to satisfy the following criteria in the search of the Higgs bosons with low (medium) masses: $p_T(jet_1) \geq 46(60)$, $p_T(jet_2) \geq 38(53)$, $p_T(jet_3) \geq 20 \text{ GeV/c}$; $|\eta(jets)| < 2.2$; at least three b-tagged jets with CSVT are required.

3 Background Modeling

The signature of the process $pp \to bH + X \to 3b + X$ is at least three b-jets which are identified with the b-tagging algorithm. The dominant background is due to multijet QCD processes mainly composed of events with three b-jets and events with two b-jets plus a charm- or udsg(light)-mistagged jet. Contributions from other processes like $t\bar{t}$, Z+jets were estimated to be negligible.

We have used a data sample with two b-tagged jets to estimate the background in data with three b-tagged jets. The double-btag data events were properly weighted assuming the flavor (b,c,udsg) of the not-tagged jet to obtain the shape of QCD background. Then a 2D template spanned by the di-jet mass of first two leading jets, $M_{12}$ and EventBtag was created by filling with the events of the given category. Finally, five templates were used. Their projections in $M_{12}$ and EventBtag are shown in Figure 1. Two additional corrections are applied to remove contamination from non-bb events in the double-btag sample and to account for differences between offline and on-line b-tag efficiencies [15].

Signal templates were obtained for each mass point from samples of Higgs bosons events simulated using PYTHIA [16]. Pileup reweighting and Level-1/Level-2 trigger efficiencies [15] were applied.
Search for Higgs boson in association with b quarks

Figure 1. $M_{12}$ (a) and EventBTag (b) projections for the five background templates used in the search for a low-mass Higgs boson.

Figure 2. (a) Results of the 'background-only' fit in the triple-btag sample in the projection on the di-jet mass, (b) Results of the fit in the di-jet mass projection including a signal template for a Higgs boson with a mass of $200\text{GeV}/c^2$ in the triple-btag data for the medium-mass scenario.

4 Results

The signal and background yields were obtained from a binned unconstrained least-squares fit of '2D' templates to the triple-btag data distributions in the $M_{12}$ and EventBTag space [15]. The statistical uncertainties of the templates are taken into account.

The fit to the data distribution was performed using only background templates. The result for the low-mass scenario of the Higgs bosons search is shown in Figure 2 (a).

The data distribution is well described by the fit, with a $\chi^2/N_{\text{dof}} \sim 1$. The data points are within the uncertainty of the fit, indicated by the cyan area. The same 'background-only-fit' for the medium-mass scenario also perfectly describes the data distribution. In both cases events with at least three b jets constitute the
largest contribution to the background. For the low-mass Higgs bosons search it amounts to about 74%, in good agreement with the MC background estimation of 72%.

The fits were repeated including signal templates for several Higgs boson masses between 90 to 350 GeV/c^2. As an example, the result of the fit assuming a Higgs boson with a mass of 200 GeV/c^2 is shown in Figure 2(b). The values of the signal fractions obtained in the fits using all Higgs boson mass hypotheses are used to derive signal cross sections multiplied with the branching fraction of the Higgs boson in a pair of b-quarks as shown in Figure 3(a).

Upper limits on the cross section multiplied by the branching fraction, \( \sigma(pp \to b\Phi) \times BR(\Phi \to b\bar{b}) \), were calculated in the [90, 350] GeV/c^2 range for \( M_A \). The modified frequentist CLs method [17] is applied using the RooStats package [18]. As test statistics for the CLs method the profile likelihood ratio distribution was used. Systematic uncertainties were taken into account as nuisance parameters of the likelihood fit to the data. Normalizations of the templates were unconstrained in the fit. The observed and the median expected 95% C.L. limits as functions of the Higgs boson mass are shown in Figure 3(b). The observed limit is well within the expected 2σ band.

The model independent limits on \( \sigma(pp \to b\Phi) \times BR(\Phi \to b\bar{b}) \) were translated into \( \tan\beta \) limits within the \( m_h^{\text{max}} \) scenario [19], where the parameter \( \mu \) is set to \(+200\) and \(-200\)GeV/c^2.

The expected cross section and branching fraction, in the MSSM framework, are calculated by BBH@NNLO [20] and FEYNHIGGS [21]-[24], respectively. The observed and expected median 95% C.L. upper limits on \( \tan\beta \) as a function of \( M_A \) using \( \mu = +200\)GeV/c^2 are shown in Figure 3(b). The upper limits on \( \tan\beta \)
Search for Higgs boson in association with b quarks

for $\mu = -200$ GeV/$c^2$ case were compared with the recent results from D0 [25] and CDF [26] experiments at the Tevatron collider. The limits obtained in the current analysis are significantly lower than the Tevatron results.

References

1. H. P. Nilles, Phys.Rept. 110 (1984) 1.
2. H. E. Haber and G. L. Kane, Phys.Rept. 117 (1985) 75.
3. S. Heinemeyer, Int.J.Mod.Phys. A21 (2006) 2659.
4. CMS, S. Chatrchyan et al., JINST 3 (2008) S08004.
5. CMS, B-tag POG, Track counting b tagging algorithm.
   https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideBTagTrackCounting
6. M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804 (2008) 063.
7. CMS, S. Chatrchyan et al., CMS PAS CMS-PAS-PFT-09-001 (2009).
8. CMS, S. Chatrchyan et al., CMS PAS CMS-PAS-PFT-10-001 (2010).
9. CMS, S. Chatrchyan et al., CMS PAS CMS-PAS-PFT-10-002 (2010).
10. CMS, S. Chatrchyan, et al., JINST 6 (2011) P11002. hep-ph/1107.4277
11. CMS, S. Chatrchyan, et al., CMS CR CMS-CR-2012-191, CERN-CMS-CR-2012-191 (2012).
12. CMS, S. Chatrchyan, et al., CMS Note CMS-NOTE-2006-014 (2006).
13. CMS, S. Chatrchyan, et al., CMS Note CMS-NOTE-2008-033 (2008).
14. CMS, S. Chatrchyan, et al., CMS PAS CMS-PAS-BTV-11-004 (2011).
15. CMS, S. Chatrchyan, et al., CMS PAS CMS-PAS-HIG-12-026 (2012).
16. T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605 (2006) 026.
17. A. L. Read, J.Phys. G28 (2002) 2693.
18. L. Moneta, K. Belasco, K. S. Cranmer, S. Kreiss, A. Lazzaro et al., PoS ACAT2010 (2010) 057.
19. M. S. Carena, S. Heinemeyer, C. Wagner and G. Weiglein, Eur.Phys.J. C45 (2006) 797.
20. R.V. Harlander and W.B. Kilgore, Phys. Rev. D68 (2003) 013001
21. S. Heinemeyer, W. Hollik, and G. Weiglein, Comput.Phys.Commun. 124 (2000) 76.
22. S. Heinemeyer, W. Hollik, and G. Weiglein, Eur. Phys. J. C9 (1999) 343.
23. G. Degrassi et al., Eur. Phys. J. C28 (2003) 133.
24. M. Frank et al., JHEP 2 (2007) 47.
25. D0, V. Abazov et al., Phys.Lett. B710 (2012) 569.
26. CDF, T. Aaltonen et al., Phys.Rev. D85 (2012) 032005.