VHbb Analysis with CMS, an introduction

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ABSTRACT

The observation of a new particle with a mass of about 125 GeV, announced in July 2012 by the ATLAS and CMS collaborations, has given hope to the HEP community that the long sought Higgs boson, the last missing ingredient of the Standard Model of Particle Physics, might have been discovered at last. The Compact Muon Solenoid experiment (CMS) is a general-purpose detector installed at the Large Hadron Collider (LHC) at CERN. During 2011 and 2012, the CMS detector has collected over 17 inverse femto-barns of proton-proton collisions (5 fb^{-1} at $\sqrt{s}=7$ TeV and 12 fb^{-1} at $\sqrt{s}=8$ TeV). These data are currently been analyzed to further characterize the recently discovered Higgs boson candidate. For a Higgs mass of about 125 GeV, the dominant decay mode should be into $b\bar{b}$; however, such decay has not yet been observed experimentally due to overwhelming backgrounds. A promising channel to search for $H \rightarrow b\bar{b}$ is the VHbb channel, where the Higgs boson is produced via the 'Higgs-Strahlung' process (a virtual W or Z boson with sufficient energy can then emit a Higgs) and recoils with large momentum transverse to the beam-line, to finally decay into a $b\bar{b}$ pair (b-jets). The presence of a vector boson in the final state highly suppresses the large QCD background and provides an efficient trigger path when the vector boson decays to charged leptons (e, μ). Recent developments in τ lepton reconstruction and vector boson invariant mass determination made it feasible to extend the VHbb analysis to both leptonic (e, μ) and hadronic (jets) decays of the τ lepton. The current VHbb results are summarized and the novel VHbb final states are presented, with particular focus on HZ, with H decaying to b-quarks and Z decaying to tau electron and hadronic tau.

Keywords: Higgs, CMS, LHC, VHbb, Tau

INTRODUCTION

The Higgs Boson is the last missing ingredient of the Standard Model (SM) of particle physics, and is essential for the internal consistency of the whole theory. In 1964, Peter Higgs and others postulated its existence (Higgs, 2008) as the mechanism for which the gauge vector bosons of the weak interaction

($W^{+/-}$ and Z^0) acquire their mass through electroweak symmetry breaking, while the photon stays massless. At energies high enough that electroweak symmetry is unbroken, all elementary particles are massless, but at a critical temperature the symmetry is spontaneously broken and the gauge bosons acquire their masses. Fermions, such as leptons and quarks, also acquire mass by interacting with the Higgs field, but in a slightly different way from gauge bosons.

In other words, elementary particles acquire their mass by interacting with the Higgs field that permeates the entire space. The Higgs boson is an excited quantum of the Higgs field. As the other 19 free parameters of the SM, the mass of the boson is not predicted by the theory and has to be measured experimentally.

On 4 July 2012, both ATLAS and CMS publicly announced the observation of a new particle, showing an excess of events at a mass of about 125-126 GeV in the two-photon and four-lepton channels, with a statistical significance above the background of over 5σ (Chatrchyan et al., 2012; McClatchey, 2012). More recent results show that the new particle's Spin and Parity are indeed consistent with the ones predicted for a Standard Model Higgs boson ($S^P=0^+$), and the mass of the Higgs has been measured as $m_H = 126.2 \pm 0.8$ (CMS Collaboration, 2012).

With a mass of about 126 GeV, the dominant decay mode should be into $H \rightarrow b\bar{b}$. However, because of the large backgrounds, there is no direct evidence for such decay yet, which is crucial to determining the nature of the Higgs boson.

This paper reviews the current state of VHbb analysis with CMS.

VHBB ANALYSIS WITH CMS

The Standard Model predicts a number of possible mechanisms for the production and subsequent decay of the Higgs boson.

The main SM mechanism for Higgs production at the LHC is Gluon Fusion, with a cross section $\sigma \sim 17\ p\bar{b}$ (for m_H=125 GeV) (Ditimatier et al., 2011). However, the detection of a Higgs boson decaying to $b\bar{b}$ in this production channel is almost impossible due to the overwhelming QCD background at the LHC. The next most abundant production mechanism is Vector Boson Fusion (VBF), with a total cross section $\sigma \sim 1.3$ pb (Bolzoni et al., 2010). This process can result in a final state with two b-quarks and a vector boson ($\sigma_{VHbb} \sim 1.02$ pb (Glashow et al., 1978)).

In 2008, a new method was proposed (Butterworth et al., 2008) to search for a SM Higgs Boson decaying into $b\bar{b}$, in events where the Higgs is produced in association with a Z or a W. The presence of a vector boson highly suppresses the QCD background and provides an efficient trigger path when the vector boson decays into leptons (Figure 1).

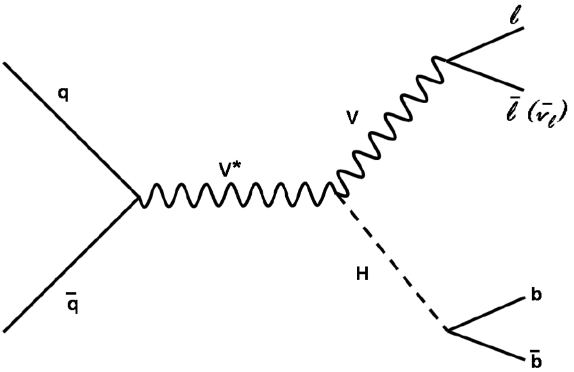

Figure 1. Generic Feynman diagram for a VHbb final state, consisting of two bottom quarks and two leptons (or lepton plus neutrino, or two neutrinos).

Preliminary results from CMS show that, in a region of phase space where the Higgs is boosted, the analysis sensitivity for this production channel (with H→$b\bar{b}$) is significant (CMS Collaboration, 2011).

The VHbb analysis searches for a SM Higgs boson in the pp→VH production mode, where V is a vector boson (either $W^{+/-}$ or Z^0) that decays leptonically, while the Higgs boson decays into $b\bar{b}$.

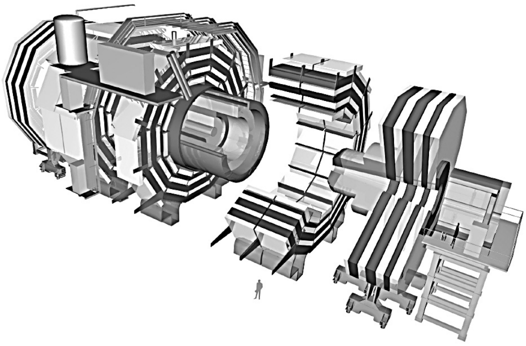

Figure 2. Expanded view of the CMS detector. The LHC beams travel in opposite directions along the central axis of the cylinder, colliding in the middle of the detector (CMS Collaboration, 2011).

The compact muon solenoid experiment

The Compact Muon Solenoid experiment is a general-purpose detector installed at the Large Hadron Collider at CERN. It is composed of concentric shells of different types of detectors, immersed in a strong magnetic field oriented along the beam axis (B ~ 3.8 T). The arrangement is optimized to provide good tracking and particle identification over the full azimuth and over a large pseudo-rapidity window ($|\eta| < 2.5$). Figure 2 shows an expanded view of the CMS detector; a detailed description of the experiment and its sub-detector systems can be found in Chatrchyan et al. (2008).

In 2011-12, CMS collected over 17 inverse femto-barns of proton-proton collisions (about 5 fb^{-1} at $\sqrt{s}$=7 TeV and 12 fb^{-1} at $\sqrt{s}$=8 TeV). Various physics analysis groups are currently investigating this data to finalize the ongoing searches.

Signal and background simulation

The main background arises from single vector bosons associated with jets or di-boson production, from single-top or $t\bar{t}$ events, and from QCD processes involving multiple jets. These processes overwhelm the signal by orders of magnitude; therefore, a careful tuning of the analysis parameters is crucial to acquire a decent sensitivity over the background.

Simulations are produced within the CMSSW software framework (CMS Collaboration), where various event generators (PYTHIA, POWHEG, HERWIG, MADGRAPH) are interfaced to a detailed CMS detector response simulation modeled with GEANT4 (Agostinelli et al., 2003).

The pile-up scenario (number of simultaneous collisions within the same “trigger”) is tuned to the average pp interaction per bunch crossing during each LHC run. For 2011 data, the average pile-up is about 10, while 2012 data have an average pile-up of ~20-25, due to the higher luminosity (CMS Collaboration, 2013).

Event reconstruction and analysis

A number of triggers are combined to select events that are consistent with the VHbb signal hypothesis in each sub-channel (CMS Collaboration, 2012). Several isolated lepton triggers are applied, together with tight lepton identification and different p_T thresholds for each channel. Missing transverse energy requirements are applied to account for the neutrinos involved in some of the processes.

The analysis strategy begins by identifying the vector boson from its decay products (charged lepton(s) and/or missing transverse energy in case of $Z \rightarrow \nu\nu$) (CMS Collaboration, 2012, CMS VHbb, 2012). The $H \rightarrow b\bar{b}$ decay is reconstructed as two separate jets clustered using the anti-k_T algorithm (Cacciari et al., 2008), with a cone radius of 0.5. The Combined Secondary Vertex algorithm (Weiser, 2006) is used to identify b-jet candidates.

All objects are reconstructed using the particle-flow algorithm (CMS Collaboration, 2009), which best combines the various sub-detectors’ signal into a consistent hypothesis of track, jet, primary or secondary vertex and missing transverse energy.

Event selection/cut optimization

Beside the trigger selection (see Chap. 3 of CMS Collaboration, 2012), a number of kinematic and topological cuts are applied in order to maximize the signal yield with respect to the reducible background in the Higgs mass window: $110 < m_H < 135$ GeV (CMS Collaboration, 2012; CMS VHbb, 2012).

The optimization of the analysis is achieved using Monte Carlo simulations: for a given Higgs mass hypothesis, the expected signal and main backgrounds are simulated and fully reconstructed with CMSSW (CMS Collaboration). The events are then analyzed using the VHbb package and a Figure of Merit (a certain function that quantifies the visibility of the signal over the background) is drawn with respect to the relevant cut-variable.

A set of pre-selection cuts is applied to enforce basic kinematic requirements, as well as track isolation and fit quality requirements. Several other discriminating variables are calculated from event and track observables, such as p_T balance, b-tagging and opening angle between vector and Higgs boson.

In a preliminary stage, the optimization is done by “cut & count” (i.e., cuts are applied in steps, while counting the number of passing candidates). Final results are then produced using a Boosted Decision Tree (BDT), which further improves the optimization and also accounts for existing correlations between cut variables (a multivariate analysis tool is used at this stage) (Hoecker et al., 2007).

For a detailed list of the discriminating variables and applied cuts, see the references CMS Collaboration (2012) and CMS VHbb (2012).

ANALYSIS STATUS

So far, published results only include 2011 data and are limited to five VHbb final states or sub-channels (CMS Collaboration, 2012). Preliminary results on the same sub-channels are publicly available for 2012 data and combined (CMS VHbb, 2012).

Recently, a few additional final states have been included in the VHbb analysis. The study of these novel channels is ongoing.

Published results

Published and preliminary VHbb results are limited to the following five sub-channels: W(μν)H, W(eν)H, Z(μμ)H, Z(ee)H and Z(νν)H, with all the Higgs decaying to $b\bar{b}$.

Due to the small cross section of the VHbb process compared to other SM reactions, a large component of irreducible background will always dominate the signal for about one order of magnitude in the best case. Therefore, the signal is observed as a small excess of events within the Higgs mass window (110-135 GeV) in the di-jet invariant mass plot (m_{jj}).

Cumulative results from all the VHbb sub-channels listed above do not show a significant excess, therefore only upper limits can be drawn. Figure 3 shows the expected and observed 95% Confidence Level upper limit (CL) for a Higgs boson with mass mH. Observed data, background-only and signal + background expectations are plotted. The 1 and 2 σ limits for the background-only hypothesis are also shown (CMS Collaboration, 2012).

Combining 2011 and 2012 data, the excess of observed events at m_{jj}=125 GeV is ~2.2 σ away from the background-only hypothesis. The excess is consistent with the Standard Model prediction for a Higgs boson with that mass (CMS VHbb, 2012).

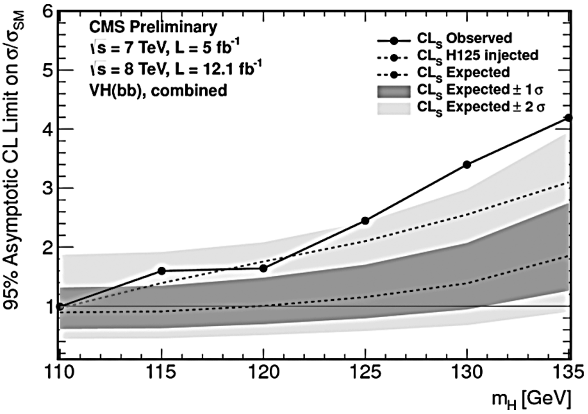

Figure 3. Expected and observed 95% Confidence Level upper limits for the VHbb production of a Higgs boson with mass m_H. This plot shows the combined results of 2011 and 2012 data from all five VHbb sub-channels mentioned in the text (see CMS VHbb, 2012).

Ongoing efforts

The VHbb analysis has been extended to include channels with τ lepton(s) from the vector boson.

Tau leptons are short lived particles with a mean lifetime of $t_\tau = 2.9\times10^{-13}$ sec. ($c\cdot t_\tau = 87.11$ μm); therefore they are not directly observed with the CMS tracker, but their decay product(s) can be used to reconstruct the secondary vertex of the τ decay. Taus decay leptonically into muons ($\tau\rightarrow\mu+\bar{\nu}_\tau+\nu_\mu$) or electrons ($\tau\rightarrow e+\bar{\nu}_\tau+\nu_e$) about 35% of the time, and hadronically ($\tau\rightarrow \text{hadrons}+\bar{\nu}_\tau$) the remaining 65% [Beringer, J. et al. 2012].

The novel VHbb sub-channels are chosen to be orthogonal to the existing ones (i.e., they do not produce the same final state particles). They are the following: $W(\tau_h\nu)H$, $Z(\tau(e)\tau(\mu))H$, $Z(\tau(\mu)\tau_h)H$ and $Z(\tau(e)\tau_h)H$, with all the Higgs decaying to $b\bar{b}$.

The study of these channels is made possible thanks to improved algorithms for the reconstruction of hadronic τ decays, such as the Hadron Plus Stript (HPS) algorithm (Bachtis et al., 2010; CMS Collaboration, 2010), and through the use of a likelihood method to determine the mass of the vector boson decaying into τ(s) (Conway et al., 2011). This method combines the information on the visible products and missing transverse energy with knowledge about the kinematics of either hadronic or leptonic τ decays, and it can reconstruct the invariant mass of the vector boson when the reaction involves one or more neutrinos that escape undetected.

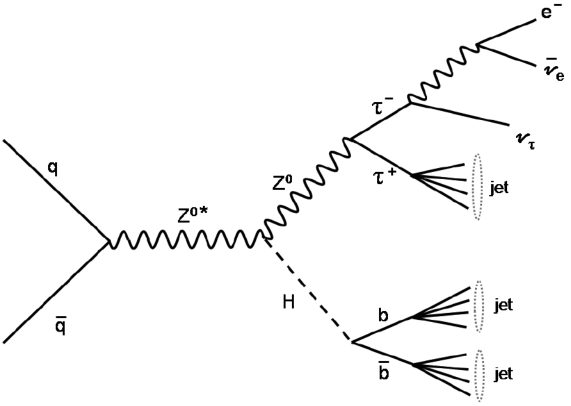

Figure 4. Intuitive diagram of the production and decay of a novel VHbb channel, with hadronic tau and tau electron in the final state: $Z \rightarrow \tau(e)\tau_h$, $H \rightarrow b\bar{b}$.

Figure 4 shows the pseudo-Feynman diagram of one of these novel sub-channels included in the VHbb analysis: $Z(\tau(e)\tau_h)$ $H(b\bar{b})$.

This channel is particularly challenging due to the weak signature of the Z^0 boson (with only one charged lepton in the final state), the missing transverse energy carried away by the neutrinos from tau decays and the large irreducible background from more copious SM processes.

CONCLUSION

So far, there are no significant excesses of events in the VHbb signal region; therefore, there is no direct evidence of the decay $H \rightarrow b\bar{b}$.

Combined VHbb results from 2011 and 2012 data are still to be finalized, but they are ~2.2 standard deviations away from the SM background and are consistent with a SM Higgs boson of mass 125-126 GeV.

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REFERENCES

Agostinelli, S., et al. 2003. Geant 4: A Simulation Toolkit. Nucl. Inst. Meth. A50: 250. DOI: 10.1016/S0168-9002(03)01368-8

Bachtis, M. et al. 2010. Study of the di-tau spectrum using muon-tau and electron-tau final states with CMS detector at √s=7TeV. CMS AN-2010/387.

Beringer, J. et al. 2012. Particle Data Group Collaboration. 2012. Review of Particle Physics. Phys. Rev. D 86: 010001. DOI: 10.1103/PhysRevD.86.010001

Bolzoni, P., et al. 2010. Higgs production via vector-boson fusion at NNLO in QCD. Phys. Rev. Lett. 105: 011801.

Butterworth, J.M., et al. 2008. Jet substructure as a new Higgs search channel at the LHC. Phys. Rev. Lett. 100: 242001. DOI: 10.1063/1.3051904

Cacciari, M., G.P. Salam, and G. Soyez. 2008. The anti-k_T jet clustering algorithm. JHEP04. DOI: 10.1088/1126-6708/2008/04/063

Chatrchyan, S., et al. 2008. The CMS experiment at the CERN LHC. JINST 3 S08004. doi:10.1088/1748-0221/3/08/S08004

Chatrchyan, S., et al. 2012. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Phys. Lett. B 716: 1-29.DOI: 10.1016/j.physletb.2012.08.020

CMS Collaboration. The CMS Offline SW Guide. https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuide.

CMS Collaboration. 2009. Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{miss}. CMS Physics Analysis Summary CMS-PAS-PFT-09-001.

CMS Collaboration. 2010. Search For Neutral MSSM Higgs Boson Production via Decays to Tau Pairs in pp Collisions at √s=7TeV. CMS-PAS-HIG-10-002. DOI: 10.1016/j.physletb.2012.05.028

CMS Collaboration. 2011. Search for SM Higgs boson decaying to Bottom Quarks and Produced in Association with a W or a Z Boson. HIG-11-012.

CMS Collaboration. 2012. Search for the standard model Higgs boson decaying to bottom quarks in pp collisions at √s=7TeV. CERN-PH-EP/2012-040. DOI: 10.1016/j.physletb.2012.02.085

CMS Collaboration. 2012. Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs. CMS-HIG-12-041.DOI: 10.1103/PhysRevLett.110.081803

CMS Collaboration. 2013. Public CMS LuminosityInformation._https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults.

CMS VHbb. 2012. Search for the standard model Higgs boson produced in association with W or Z bosons, and decaying to bottom_quarks._https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12044TWiki, preliminary. DOI: 10.1103/PhysRevD.89.012003

Conway, J., E. K. Friis, and C. Veelken, 2011. Likelihood based Mass Reconstruction in Events containing Tau Leptons. CMS AN AN-11-165.

Ditimatier, S., C. Mariotti, G. Passarino, and R. Tanaka. 2011. Handbook of LHC Higgs cross sections: 1. Inclusive Observables. CERN Report CERN-2011-002.

Glashow, S., L. D. V. Nanopoulos, and A. Yildiz. 1978. Associated production of Higgs bosons and Z particles. Phys. Rev. D 18: 1724. DOI: 10.1103/PhysRevD.18.1724

Higgs, P.W. 1964. Broken symmetry and the mass of gauge vector mesons. Phys. Rev. Lett. 13: 508. DOI: 10.1103/PhysRevLett.13.321

Hoecker, A., et al., 2007. TMVA - toolkit for multivariate data analysis. arXiv: 0703039.

McClatchey, R. 2012. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Phys. Lett. B 716: 30–61. DOI: 10.1016/j.physletb.2012.08.021

Weiser, C. 2006. A Combined Secondary Vertex Based B-Tagging Algorithm in CMS. CERN-CMS-NOTE-2006-014.