The Compact Muon Solenoid Experiment
Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

20 December 2011 (v2, 06 January 2012)

Searches for the Higgs boson with the CMS Experiment

Andrei Gritsan for the CMS Collaboration

Abstract

We test the nature of Electroweak Symmetry Breaking by searching for the Higgs boson with the CMS detector at the Large Hadron Collider. We report results with both the high-mass final states with weak Bosons (WW , ZZ) and the low-mass final states with photons or taus. Higgs searches performed in sub-channels are further combined to extract the best overall sensitivity in the range of Higgs masses from 110 to 600 GeV.

Presented at *LOMONOSOV11: 15th Lomonosov Conference on Elementary Particle Physics*

SEARCHES FOR THE HIGGS BOSON WITH THE CMS

Andrei V. Gritsan ^a on behalf of the CMS collaboration

*Department of Physics and Astronomy, Johns Hopkins University, Baltimore,
Maryland 21218, USA*

Abstract. We test the nature of Electroweak Symmetry Breaking by searching for the Higgs boson with the CMS detector at the Large Hadron Collider. We report results with both the high-mass final states with weak bosons (WW , ZZ) and the low-mass final states with photons, taus, or beauty quarks. Higgs searches performed in sub-channels are further combined to extract the best overall sensitivity in the range of Higgs masses from 110 to 600 GeV.

1 Introduction

A primary goal of the Large Hadron Collider (LHC) [1] experiments is to study the mechanism of electroweak symmetry breaking where the weak W and Z bosons acquire mass while the photon, γ , remains massless. The standard model (SM) of particle physics postulates the mechanism of electroweak symmetry breaking with the Higgs field as a possible explanation [2]. A consequence of the Higgs field would be existence of the spin-zero Higgs boson (H) with quantum numbers of the vacuum, $J^{PC} = 0^{++}$. Indirect measurements [3] suggest that the mass of a SM Higgs boson would most likely fall in the range below 200 GeV with part of this range already excluded by direct limits from experimental searches at LEP [4] and the Tevatron [5]. However, these constraints are either of limited scope or rely on detailed theoretical assumptions and therefore the aim of the LHC experiments is to explore all accessible masses.

2 Data analysis

The search is performed with a sample of proton-proton collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 4.7 fb^{-1} recorded by the CMS experiment [6] at the LHC during 2011. Several decay channels are studied, the high-mass final states with weak bosons (WW , ZZ) and the low-mass final states with photons, taus, or beauty quarks. Table 1 lists individual analyses used in the combination [7]. Examples of reconstructed variables in four representative analyses are shown in Fig. 1.

The $H \rightarrow \gamma\gamma$ analysis [8] is a search for a narrow peak in the di-photon mass distribution. All selected di-photon candidates are split into four categories based on whether both photons are in the central part of the CMS detector and whether both photons have produced compact electromagnetic showers. This is motivated by the differences in the photon energy resolutions of the

^ae-mail: Gritsan@jhu.edu

barrel/endcap electromagnetic calorimeters and for photons showering or non-showering in the detector volume before the electromagnetic calorimeters. The background under the expected signal peak is extrapolated from sidebands.

The $H \rightarrow b\bar{b}$ search [9] relies on Higgs boson production in association with W or Z bosons (V). We use the following W and Z boson decay modes: $W \rightarrow e\nu/\mu\nu$ and $Z \rightarrow ee/\mu\mu/\nu\nu$. The presence of neutrinos is tagged by requiring a missing transverse energy E_T^{mis} defined as a vector opposite to the vector sum of transverse momenta of all reconstructed objects. The dijet system, with both jets being b -tagged, is required to be boosted in the transverse plane. The main backgrounds V +jets, $Vb\bar{b}$, and $t\bar{t}$ are derived from data control samples. The WZ and ZZ backgrounds with a Z boson decaying to $b\bar{b}$ as well as the single top background are predicted via simulation. A cut is placed on the MVA output and we count the number of events passing the cut in the five channels.

The $H \rightarrow \tau\tau$ search [10] is performed using the di-tau final state signatures $e\mu$, $e\tau_h$, $\mu\tau_h$, where τ_h stands for a τ decaying hadronically. Each of these three categories is further divided into exclusive sub-categories according to the associated jet activity: events with two VBF-like jets, events with at least one high E_T jet, and events with no or exactly one low E_T jet. We search for a broad excess in the di-tau mass $m_{\tau\tau}$ distribution. The main irreducible background is $Z \rightarrow \tau\tau$ derived from data by using $Z \rightarrow \mu\mu$ events using simulated taus. The reducible backgrounds (W + jets, QCD, $Z \rightarrow ee$) are evaluated using data driven techniques.

In the $H \rightarrow WW^{(*)} \rightarrow 2\ell 2\nu$ search [11], we look for an excess of events with two leptons of opposite sign, missing transverse energy, and 0/1/2 jets. All events are split into five categories. For events with 0 jets, the main background is WW production. For events with 1 jet, WW and $t\bar{t}$ are the main backgrounds. Both 0- and 1-jet categories are further split into same-flavour and opposite-flavor dilepton sub-channels. The 2-jet category is optimized to take advantage of the VBF production signature. The main background for

Table 1: Summary information on the analyses included in the combination ($\ell = e, \mu$).

Channel	m_H range (GeV)	Lumi (fb $^{-1}$)	sub- channels	m_H reso- lution
$H \rightarrow \gamma\gamma$	110 – 150	4.7	4	1–3%
$H \rightarrow \tau\tau$	110 – 145	4.6	9	20%
$H \rightarrow b\bar{b}$	110 – 135	4.7	5	10%
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	110 – 600	4.6	5	20%
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$	110 – 600	4.7	3	1–2%
$H \rightarrow ZZ \rightarrow 2\ell 2\tau$	190 – 600	4.7	8	10–15%
$H \rightarrow ZZ \rightarrow 2\ell 2\nu$	250 – 600	4.6	2	7%
$H \rightarrow ZZ^{(*)} \rightarrow 2q2\ell$	130 – 164 & 200 – 600	4.6	6	3%

this channel is $t\bar{t}$. We search for an excess of events in the MVA output distributions. All backgrounds, except for very small contributions from WZ , ZZ , and $W\gamma$ are evaluated directly from data using various control samples.

In the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ search [12], we look for a four-lepton mass peak. The $4e$, 4μ , $2e2\mu$ sub-channels are tracked individually. The dominant irreducible background is electroweak ZZ diboson production (with both Z s decaying to either $2e$, 2μ , or 2τ) and taken from simulation. The smaller backgrounds with jets faking leptons (e.g. $Z + \text{jets}$, $Zb\bar{b}$, $t\bar{t}$) are evaluated all together from data.

In the $H \rightarrow ZZ \rightarrow 2\ell 2\tau$ search [13], one Z boson is required to decay to a dilepton pair (e^+e^- or $\mu^+\mu^-$) forming an on-shell Z boson. The other Z boson is required to decay to $\tau\tau$, with the following four final state signatures used in the analysis: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$. We search for a broad excess in the visible mass distribution. The dominant background is electroweak ZZ diboson production and taken from simulation. The main sub-leading backgrounds with jets faking τ -leptons come from $Z + \text{jets}$ (including ZW) and $t\bar{t}$.

In the $H \rightarrow ZZ \rightarrow 2\ell 2\nu$ search [14], we select events with $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ and a large missing transverse energy E_T^{mis} . We then build the transverse invariant mass m_T from the dilepton pair momenta and E_T^{mis} , assuming that E_T^{mis} arises from a $Z \rightarrow \nu\nu$ decay. We search for a correspondingly broad excess of events in the m_T distribution. The ZZ and WZ backgrounds are taken from simulation, while all other backgrounds, $Z + \text{jets}$ and a cumulative sum of the rest, are evaluated from control samples in data.

In the $H \rightarrow ZZ^{(*)} \rightarrow 2q2\ell$ search [15], we select events with two leptons and with two jets including two, one, or no b -tags. Motivation for b -tagging is driven by the high rate of b -jets in $Z \rightarrow q\bar{q}$ decays in comparison to general QCD jets produced in association with a Z boson. The two jets are required to form an invariant mass consistent with the Z boson mass. For the search in the mass range 200–600 GeV, the mass of the dilepton pair is also required to be consistent with the Z boson mass. For the search in the mass range 130–164 GeV, the requirement on the mass of the dilepton pair is relaxed. In the high mass range, events are further selected using a cut on a multivariate angular likelihood constructed from the kinematic variables of the two leptons and two jets. In this search we look for a peak in the dilepton-dijet invariant mass distribution, with the dijet mass constrained to the mass of the Z boson. The background dilepton-dijet mass distribution is derived using sideband regions in data.

3 Results

Figure 2 shows the CL_s value for the SM Higgs boson as a function of its mass. The observed values are shown by the solid line. The dashed line indicates the median expected value of CL_s . We exclude the SM Higgs boson at 95%

C.L. in the mass range 127–600 GeV. To quantify the consistency of the observed excesses with the background-only hypothesis, Fig. 3 shows a scan of the observed combined local p -value in the low mass range. One can see that the p -value curve dips downward over a large range of masses, driven by the broad excesses in the channels with poor mass resolution, with two narrower features corresponding to the $ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels. The second dip is mostly driven by the $\gamma\gamma$ excess around di-photon mass $m_{\gamma\gamma} \sim 124$ GeV. The local significance of the minimum p -value is 2.6σ . The global significance of the excess, taking into account the look-elsewhere effect for the entire search mass range 110–600 GeV, has been approximately evaluated directly from the data as 0.6σ . For a restricted range of interest, the global p -value can be evaluated by generating pseudo-data. If this is done, by way of illustration, for the mass range 110–145 GeV, we obtain a global significance of 1.9σ .

Acknowledgments

We would like to thank our CMS colleagues for making these results happen and wish to congratulate LHC colleagues for the excellent machine performance.

References

- [1] L. Evans and P. Bryant (eds.), JINST 3, S08001 (2008).
- [2] F. Englert and R. Brout, Phys. Rev. Lett. 13, 321 (1964); P. Higgs, Phys. Rev. Lett. 13, 508 (1964); G. S. Guralnik, C. R. Hagen, T. W. B. Kibble, Phys. Rev. Lett. 13, 585 (1964).
- [3] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the Tevatron Electroweak Working Group, and the SLD electroweak and heavy flavour groups, CERN-PH-EP-2010-09 (2010).
- [4] ALEPH, DELPHI, L3, OPAL Collaborations, Phys. Lett. B565, 61 (2003).
- [5] CDF, D0, and the TEVNPHWG Working Group, arXiv:1103.3233.
- [6] CMS Collaboration, JINST 0803, S08004 (2008).
- [7] CMS Collaboration, preprint CMS-HIG-11-032.
- [8] CMS Collaboration, preprint CMS-HIG-11-030.
- [9] CMS Collaboration, preprint CMS-HIG-11-031.
- [10] CMS Collaboration, preprint CMS-HIG-11-029.
- [11] CMS Collaboration, preprint CMS-HIG-11-024.
- [12] CMS Collaboration, preprint CMS-HIG-11-025.
- [13] CMS Collaboration, preprint CMS-HIG-11-028.
- [14] CMS Collaboration, preprint CMS-HIG-11-026.
- [15] CMS Collaboration, preprint CMS-HIG-11-027.

Figure 1: Top-left: diphoton mass in the $H \rightarrow \gamma\gamma$ analysis. Top-right: dilepton mass of the two selected leptons in the 0-jet in the $H \rightarrow WW^{(*)}$ analysis. Bottom-left: four-lepton mass in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ analysis. Bottom-right: Higgs candidate mass in the $H \rightarrow ZZ^{(*)} \rightarrow 2q2\ell$ analysis with both quarks tagged as b .

Figure 2: The observed (solid) and expected (dashed) 95% C.L. upper limits on the ratio of the production cross section to the SM expectation for the Higgs boson as a function of its mass for eight analyses and the combination.

Figure 3: The observed local p-value as a function of the SM Higgs boson mass.