Physics Letters B 753 (2016) 363–388

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for exotic decays of a Higgs boson into undetectable particles and one or more photons

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ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 2 December 2015
Accepted 7 December 2015
Available online 11 December 2015
Editor: M. Doser

Keywords:
CMS
Physics
Higgs

ABSTRACT

A search is presented for exotic decays of a Higgs boson into undetectable particles and one or two isolated photons in pp collisions at a center-of-mass energy of 8 TeV. The data correspond to an integrated luminosity of up to 19.4 fb^{-1} collected with the CMS detector at the LHC. Higgs bosons produced in gluon–gluon fusion and in association with a Z boson are investigated, using models in which the Higgs boson decays into a gravitino and a neutralino or a pair of neutralinos, followed by the decay of the neutralino to a gravitino and a photon. The selected events are consistent with the background-only hypothesis, and limits are placed on the product of cross sections and branching fractions. Assuming a standard model Higgs boson production cross section, a 95% confidence level upper limit is set on the branching fraction of a 125 GeV Higgs boson decaying into undetectable particles and one or two isolated photons as a function of the neutralino mass. For this class of models and neutralino masses from 1 to 120 GeV an upper limit in the range of 7 to 13% is obtained. Further results are given as a function of the neutralino lifetime, and also for a range of Higgs boson masses.

1. Introduction

The detailed studies of the properties of the observed Higgs boson [1–3] are key components of the LHC physics program. In the standard model (SM) and for a given mass of the Higgs boson, all properties of the Higgs boson are predicted. Physics beyond the SM (BSM) might lead to deviations from these predictions. Thus far, measurements of the Higgs bosons couplings to fermions and bosons and of the tensor structure of the Higgs boson interaction with electroweak gauge bosons show no significant deviations [4,5] with respect to SM expectations.

Measurements of Higgs boson couplings performed for visible decay modes provide constraints on partial decay widths of the Higgs boson to BSM particles. Assuming that the couplings of the Higgs boson to W and Z bosons are smaller than the SM values, this indirect method provides an upper limit on the branching fraction of the 125 GeV Higgs boson to BSM particles of 57% at a 95% confidence level (CL) [4,6]. An explicit search for BSM Higgs boson decays presents an alternative opportunity for the discovery of BSM physics. The observation of a sizable decay branching fraction of the Higgs boson to undetected (e.g. invisible or largely invisible) final states would be a clear sign of BSM physics and could provide a window on dark matter [7–10].

Several BSM models predict Higgs boson decays to undetectable particles and photons. In certain low-scale supersymmetry (SUSY) models, the Higgs bosons are allowed to decay into a gravitino ($\widetilde{\mathrm{G}}$) and a neutralino ($\widetilde{\chi}_1^0$) or a pair of neutralinos [11,12]. The neutralino then decays into a photon and a gravitino, the lightest supersymmetric particle and dark matter candidate. Fig. 1 shows Feynman diagrams for such decay chains of the Higgs boson (H) produced by gluon–gluon fusion (ggH) or in association with a Z boson decaying to charged leptons (ZH).

As the gravitino in these models has a negligible mass [11,12], the remaining parameter is the neutralino mass. If its mass is in the range $m_\mathrm{H}/2 < m_{\widetilde{\chi}_1^0} < m_\mathrm{H}$, with $m_\mathrm{H} = 125$ GeV the mass of the observed Higgs boson, the branching fraction $\mathcal{B}(\mathrm{H} \to \widetilde{\chi}_1^0\widetilde{\mathrm{G}} \to \gamma\widetilde{\mathrm{G}}\widetilde{\mathrm{G}})$ can be large. For $m_{\widetilde{\chi}_1^0} < m_\mathrm{H}/2$, the decay $\mathrm{H} \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to \gamma\gamma\widetilde{\mathrm{G}}\widetilde{\mathrm{G}}$ is expected to dominate. The same discussion can be applied to heavy neutral Higgs bosons with masses larger than 125 GeV. The lifetime of the neutralino can be finite in some classes of BSM scenarios, leading to the production of one or more photons displaced from the primary interaction.

In the SM, the signature equivalent to the signal arises when the Higgs boson decays as $\mathrm{H} \to \mathrm{Z}\gamma \to \nu\bar{\nu}\gamma$ with a branching frac-

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http://dx.doi.org/10.1016/j.physletb.2015.12.017
0370-2693/

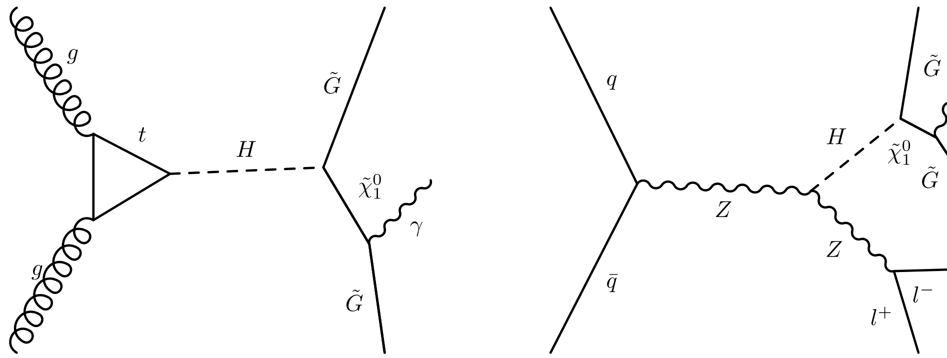

Fig. 1. Feynman diagrams for the $H \to$ undetectable $+ \gamma$ final state produced via ggH (left) and ZH (right).

tion of 3×10^{-4}. The decay $H \to Z\gamma$ has been studied in $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ final states. Upper limits on the product of the cross section and branching fraction of about a factor of ten larger than the SM expectation have been set at the 95% CL [13,14]. With the available data set the search presented is not sensitive to this decay, but it is sensitive to enhancements in the Higgs boson decay rates to undetectable particles and photons arising from BSM physics.

Various background processes lead to the signal signatures and are estimated from simulation or from control samples in data. The dominant background processes are from γ + jets events and diboson events in the ggH and ZH search, respectively. Details of the background estimation techniques are discussed in Section 5. The strength of the ZH channel analysis is an almost background-free selection leading to a larger sensitivity in the model-dependent interpretation. While both the ggH and the ZH channels provide sensitivity to BSM Higgs boson signatures, the ggH channel allows a model-independent interpretation of the results.

This analysis presents a first search for decays of a scalar boson to undetectable particles and one or two isolated photons. The scalar boson is produced in ggH or in ZH. The data used correspond to an integrated luminosity of up to 19.4 ± 0.5 fb^{-1} at a center-of-mass energy of $\sqrt{s} = 8$ TeV in 2012 collected with the CMS detector at the CERN LHC.

The results of the search are presented in terms of the low-scale SUSY breaking model for $m_H = 125$ GeV and $m_{\tilde{\chi}_1^0}$ between 1 GeV and 120 GeV, and for m_H between 125 GeV and 400 GeV for the example case where $m_{\tilde{\chi}_1^0} = m_H - 30$ GeV. The effect of a finite $\tilde{\chi}_1^0$ lifetime ($\tau_{\tilde{\chi}_1^0}$) is studied for the example case where $m_H = 125$ GeV and $m_{\tilde{\chi}_1^0} = 95$ GeV.

2. The CMS experiment

The CMS detector, definitions of angular and spatial coordinates, and its performance can be found in Ref. [15]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. The field volume contains a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the magnet. The first level of the CMS trigger system, composed of specialized hardware processors, is designed to select the most interesting events within 3 μs, using information from the calorimeters and muon detectors. A high-level trigger processor farm is used to reduce the rate to a few hundred events per second before data storage.

A particle-flow algorithm [16,17] is used to reconstruct all observable particles in the event. The algorithm combines all subdetector information to reconstruct individual particles and identify them as charged hadrons, neutral hadrons, photons, and leptons. The missing transverse energy vector $\vec{E}_T^{miss}$ is defined as the negative vector sum of the transverse momenta of all reconstructed particles (charged or neutral) in the event, with $E_T^{miss} = |\vec{E}_T^{miss}|$. Jets are reconstructed using the anti-k_T clustering algorithm [18] with a distance parameter of $R = 0.5$, as implemented in the FastJet package [19,20]. A multivariate selection is applied to separate jets from the primary interaction and those reconstructed due to energy deposits associated with pileup interactions [21]. The discrimination is based on the differences in the jet shapes, on the relative multiplicity of charged and neutral components, and on the different fraction of transverse momentum which is carried by the hardest components. Photon identification requirements and other procedures used in selecting events can be found in Section 4.

3. Data and simulation events

In the search for Higgs bosons produced in ggH, the trigger system requires the presence of one high transverse energy (E_T^γ) photon candidate and significant E_T^{miss}. The presence of a photon candidate with $E_T^\gamma > 30$ GeV is required within the ECAL barrel region ($|\eta^\gamma| < 1.44$). At the trigger level E_T^{miss} is calculated from calorimeter information, and is not corrected for muons. A selection requirement of $E_T^{miss} > 25$ GeV is applied. The efficiency of the trigger is monitored and measured with two control triggers for the photon and the E_T^{miss} trigger requirement. The data recorded with this trigger correspond to an integrated luminosity of 7.4 fb^{-1} and were part of the CMS "data parking" program implemented for the last part of the data taking at $\sqrt{s} = 8$ TeV in 2012. In that program, CMS recorded additional data with relaxed trigger requirements, planning for a delayed offline reconstruction in 2013 after the completion of the LHC Run 1.

For the search for Higgs bosons produced in ZH, collision events were collected using single-electron and single-muon triggers which require the presence of an isolated lepton with p_T in excess of 27 GeV and 24 GeV, respectively. Also a dilepton trigger was used, requiring two leptons with p_T thresholds of 17 GeV and 8 GeV. The luminosity integrated with these triggers at $\sqrt{s} = 8$ TeV is 19.4 fb^{-1}.

Several Monte Carlo (MC) event generators are used to simulate signal and background processes. The simulated samples are used to optimize the event selection, evaluate selection efficiencies and systematic uncertainties, and compute expected event yields. In all cases the MC samples are reweighted to match the trigger efficiency measured in data.

The Vγ, WZ, ZZ, VVV (where V represents W or Z bosons), Drell–Yan (DY) production of $q\bar{q} \to Z/\gamma^*$, and $q\bar{q} \to W^+W^-$ processes are generated with the MadGraph 5.1 event generator [22]