CMS Draft Analysis Note

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2013/12/02
Head Id: 218969
Archive Id: 218950:218969
Archive Date: 2013/12/02
Archive Tag: trunk

Search for an Invisible decays of a Higgs Boson : Combination of ZH and VBF searches

The CMS Collaboration

Abstract

In this note we describe the combination of searches for an invisibly decaying Higgs boson in the ZH and VBF channels.

1 Introduction

The motivation to search for an invisibly decaying Higgs boson is well documented elsewhere [1–3]. In this note we describe the statistical combination of the results of three searches for an invisibly decaying Higgs boson in the following Higgs boson production channels: vector boson fusion (VBF) production [1], ZH production where the Z decays to leptons (Z→ll+H→inv) [2], and ZH production where the Z decays to $b\bar{b}$ quark pairs (Z→ $b\bar{b}$+H→inv) [3]. No evidence for a signal is observed in any of the three searches. Each of the three searches has presented limits on the production cross-section times branching fraction. In this note we first present the combination of the ZH searches, then the combination of all three searches. Finally, we present an interpretation of the combined limit on $\mathcal{B}(H \to inv)$in terms of a "Higgs portal" model of dark matter (DM).

2 Combination Procedure

We set 95% C.L. upper limits on the Higgs boson production cross section times invisible branching fraction using a CL_s method [4–6], following the standard CMS Higgs combination technique [7]. We also present these limits normalized to the SM Higgs boson production cross sections [8, 9].

The nuisance parameters which are considered correlated between analyses can be seen in Table 1. The most important correlations are unsurprisingly those associated with the signal uncertainty in the ZH searches, due to PDFs and QCD scale variation. Further correlated nuisance parameters arise from, in decreasing order of importance, uncertainties on the jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale and resolution, the total integrated luminosity, and the lepton momentum scale.

Table 1: List of nuisances correlated between analyses and the analyses they affect

Nuisance	Analyses which it affects
b quark tagging efficiency	Z→ll+H→inv
Jet energy scale	VBF, Z→ll+H→inv
Jet energy resolution	VBF, Z→ll+H→inv
Unclustered energy scale	VBF, Z→ $b\bar{b}$+H→inv, Z→ll+H→inv
Muon identification efficiency	VBF, Z→ll+H→inv
Electron identification efficiency	VBF, Z→ll+H→inv
Luminosity	VBF, Z→ $b\bar{b}$+H→inv, Z→ll+H→inv
PDF uncertainties	VBF, Z→ll+H→inv
QCD scale	VBF, Z→ll+H→inv

3 Datacards

The three channels all have signal Monte Carlo at different Higgs mass points (see Table 2). For the VBF channel the analysis is the same at all Higgs mass points, and it is only the signal yield and its uncertainties that vary. New datacards for this channel are therefore produced at new Higgs mass points by interpolating between the yields at the points for which Monte Carlo simulation is available.

The method used for the interpolation is as follows. The number of signal events can be obtained from the following formula:

Table 2: Higgs mass points where the signal is simulated in Monte Carlo for the three channels considered.

Channel	m_H (GeV) where signal is simulated
VBF	110,125,150,200,300,400
Z→ll+H→inv	105,115,125,135,145,150
Z→ $b\bar{b}$+H→inv	105,115,125,135,145,175,200,300

$$N_{Signal} = \text{efficiency x acceptance x } \mathcal{L} \text{ xœ}, \tag{1}$$

Where N_{Signal} is the signal yield, and $\mathcal{L}$ is the integrated luminosity, which is constant for all Higgs boson masses. The appropriate technique to interpolate between Higgs mass points is therefore to calculate the signal yield divided by the signal cross-section for the points where Monte Carlo simulation is available, linearly interpolate this to the desired mass point and then multiply by the new signal cross-section. The uncertainties due to each nuisance paramater are also linearly interpreted between Higgs mass points.

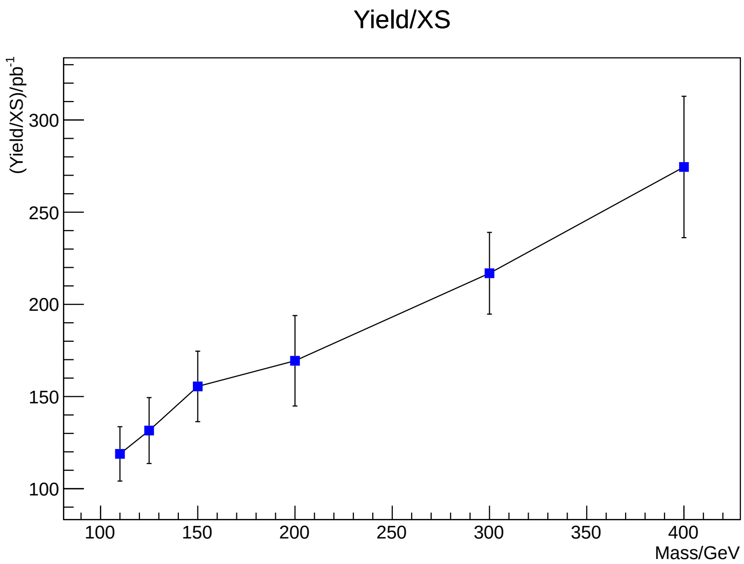

Figure 1: Signal yield divided by cross-section as a function of Higgs mass in the VBF channel assuming Standard Model production cross-sections. The error bars are illustrative only and represent the total systematic uncertainty for each Higgs mass point

4 Combination of ZH Searches

The 95% C.L. observed and median expected upper limits on ZH production cross section times invisible branching fraction are obtained from a combination of the Z→ll+H→inv and Z→ $b\bar{b}$+H→inv channels and are shown in Figure 2 (left). The same limits are also shown normalized to the SM production cross section in Figure 2 (right). For a Higgs boson with $m_{\mathrm{H}} = 125$ GeV, assuming the SM production rate, the observed (expected) upper limit on $\mathcal{B}(H \to inv)$is 81% (83%) at 95% CL.

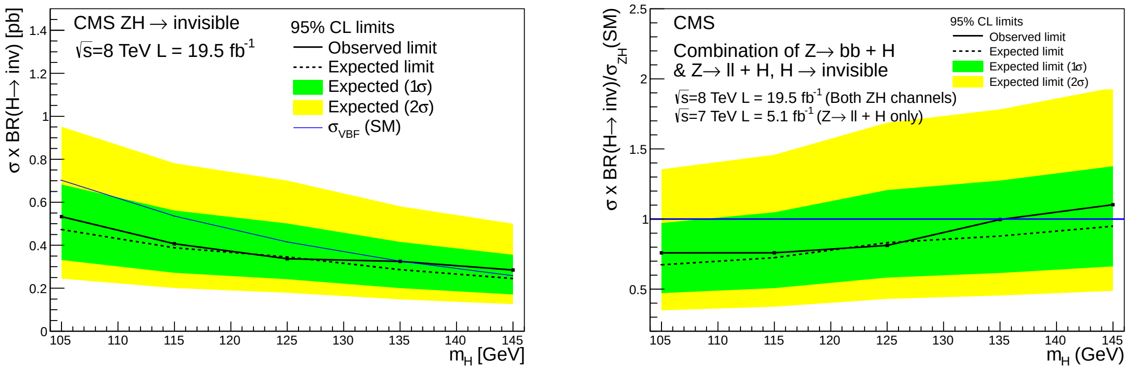

Figure 2: Expected and observed 95% CL upper limits on the ZH production cross section times invisible branching fraction (left), and normalized to the SM Higgs boson production cross section (right).

5 Combination of VBF and ZH Searches

By assuming Standard Model production cross-sections, the results of the three individual searches may be combined and interpreted as a limit on the invisible branching fraction of a Higgs boson. As for the ZH combined result presented above, the statistical combination is performed as described in [7], fully accounting for correlations between nuisance parameters between the individual searches. The resulting limit is shown in Figure 3. For $m_H = 125$ GeV, the observed (expected) limit on the invisible branching fraction is 58(46)%. The upper limits on $\mathcal{B}(H \to inv)$obtained in the VBF, ZH channels and the combination, are also shown separately for several Higgs mass points in Table 3.

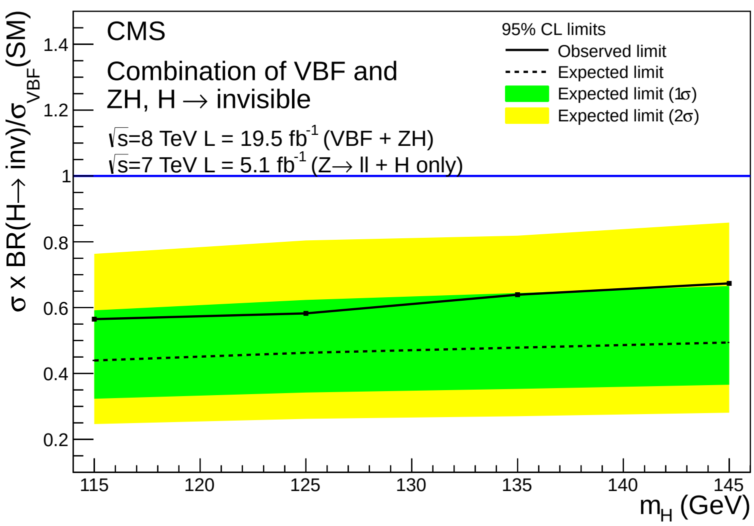

Figure 3: Combined limit on the invisible branching fraction of a Higgs boson, as a function of mass, assuming Standard Model production cross-sections.

As can be seen from Table 2 the results of the analyses in the VBF and Z→ll+H→inv channels both extend up to Higgs masses of 300 GeV. A combination of just these two channels has been performed in the range 115-300 GeV and the results can be seen in Fig. 4

Table 3: Summary of upper limits on $\mathcal{B}(H \to inv)$obtained from the VBF search, the combined ZH search, and the combination of all three searches.

m_H (GeV)	Observed (expected) upper limits on $\mathcal{B}(H \to inv)$(%)		
	VBF	ZH	VBF+ZH
115	65 (51)	76 (72)	57 (44)
125	67 (52)	81 (83)	58 (46)
135	69 (54)	100 (88)	64 (48)
145	70 (54)	110 (95)	67 (49)

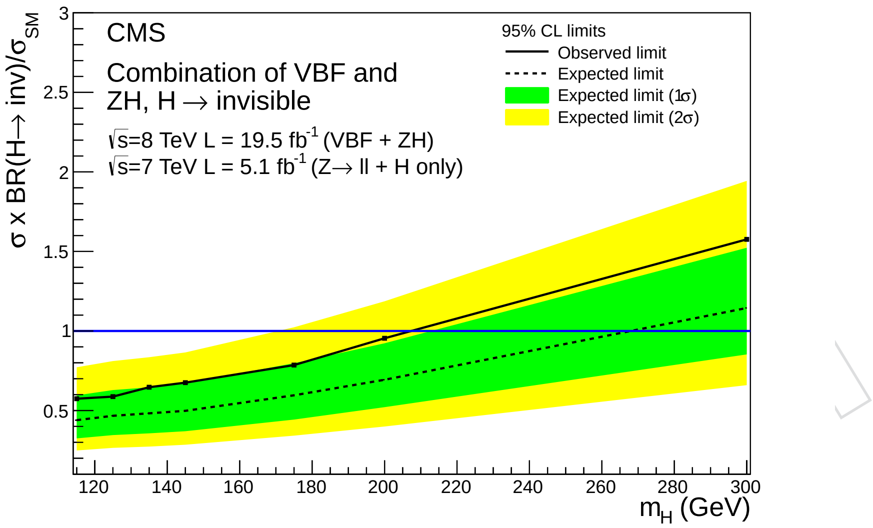

Figure 4: Limit on the invisible branching fraction of a Higgs boson, as a function of mass, assuming Standard Model production cross-sections, obtained from the combination of the VBF and Z→ll+H→inv production channels.

6 Dark Matter Interactions

The combined limit on the invisible branching fraction of the Higgs boson can be interpreted as a limit on the coupling between the Higgs boson and dark matter. Here we interpret the limit in the context of a "Higgs portal" model of dark matter (DM). The method is described in Ref [2]. The results are presented in Fig. 5, and the parameters used are given in Table 4.

7 Conclusions

The results of searches for an invisibly decaying Higgs boson in the vector boson fusion and associated ZH production modes, with Z→ll or Z→ $b\bar{b}$ have been combined. No evidence for a signal is observed in any channel, either individually or in combination. Using a CLs method, 95% CL upper limits are placed on the Higgs boson production cross section times invisible branching fraction, for the VBF and ZH channels separately. By assuming SM production cross sections, the upper limit on the invisible branching fraction of the Higgs from the combination of all channels is found to be 58% for m_H = 125 GeV, with an expected limit of 46%. This limit has been interpreted in terms of a Higgs portal model of dark matter.

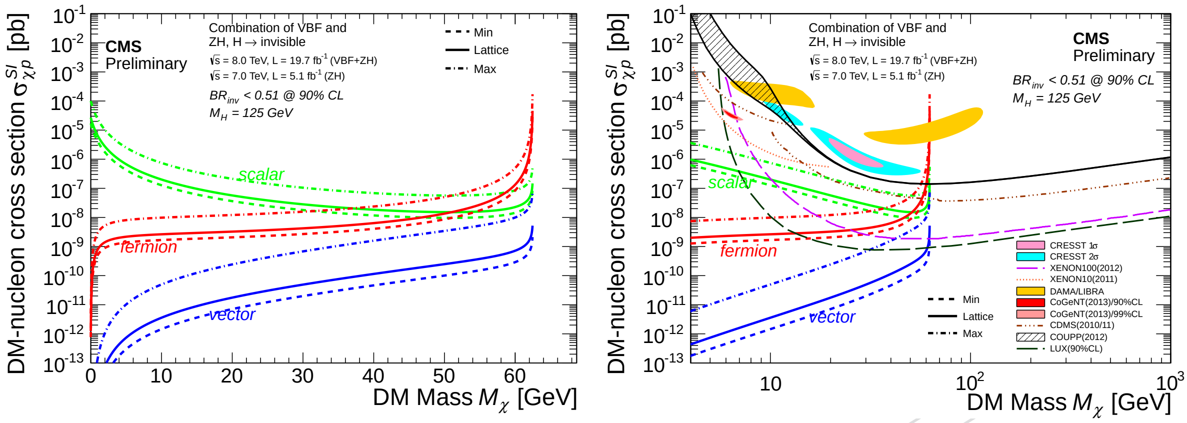

Figure 5: Maximum allowed values of the spin-independent direct detection cross section $\sigma^{SI}_{\chi-N}$, $(\chi = S, V, f)$ in "Higgs portal" models derived for m_h = 125 GeV and $\mathcal{B}(H \to inv)$=54% at 95% C.L. (left). For comparison, other experimental limits are also showed (right).

parameter	value
v	174.0 GeV
m_h	125.0 GeV
m_N	938.95 MeV
Γ_H^{SM}	4.07 MeV
f_N Lattice	0.326
f_N Min	0.260
f_N Max	0.629

Table 4: Value of parameters used in Figure 5.

The limits presented above are competitive with indirect limits obtained from visible Higgs boson decays, and can be expected to further constrain new physics in the Higgs and dark matter sectors.

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