Search for invisible Higgs decays in the VBF channel using the CMS detector

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Introduction

SM Higgs boson compatibility

All measurements of the 125 GeV boson to date indicate compatibility with a SM Higgs boson, but:

- associated uncertainties are large
- the possibility for non-SM properties remains

Additional SM-like Higgs bosons have been excluded over a wide mass range, additional Higgs bosons with exotic decay modes remains a possibility, and are predicted by many models.

BSM invisible Higgs boson decay modes:

- Neutralinos in supersymmetric models.
- Graviscalars in models with extra dimensions.

Indirect measurements

The ATLAS and CMS collaborations have used the visible decay modes to infer limits on the invisible branching fraction of the 125 GeV Higgs boson:

- ATLAS: upper limit of 60%
- CMS: upper limit limit is 64%

Motivations direct searches for invisible decays:

- Observation of a signal in such searches would be a clear indication of physics beyond the SM.
- Non-observation provides the opportunity to further constrain the properties of the newly discovered boson.

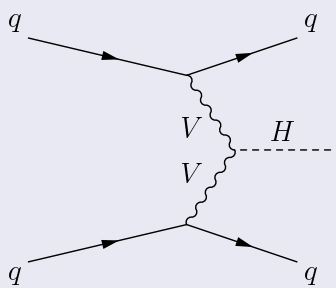
VBF Channel

Direct searches channels

On direct searches rely on associated production modes, where the Higgs recoils against a visible system.

- Z Associated production: Low production cross section; Clear final state, but low sensitivity with the available data.
- VBF mode: Substantially higher cross section. Shown to offer greater sensitivity to invisible decays.

VBF Higgs Diagram



VBF Higgs to invisible search

Search for final states with:

- two jets and large missing energy
- use the distinct topology of the VBF jets to distinguish invisible Higgs decays from background

Backgrounds

Major:

- $Z \to \nu\nu$, in association with jets
- $W \to l\nu$, with charged lepton misidentified

Minor:

- Mismeasurement of QCD events
- Other SM processes

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Analysis Definition

Dedicated trigger

- Any forward/backward pair of jets satisfying:
  - pair of jets $p_t > 40 GeV$
  - $\Delta\eta_{jj} = |\eta_{jet1} - \eta_{jet2}| > 3.5$
  - High invariant mass ($m_{jj} > 800$ GeV)
- $MET > 65$ GeV

Offline selection

- Standard MET filters: remove anomalous calorimeter signals, beam halo, calorimeter laser calibration events and tracking failure.
- Good vertex: ($|z| < 24$ cm, $r < 2$ cm) and $+10$ tracks
- e/μ veto: electron or muon with $p_t > 10$ GeV
- Dijet: leading PF AK5 jet pair that pass pile-up jet rejection:
  - $\eta_{jet1} \cdot \eta_{jet2} < 0$
  - $p_t > 50$ GeV, $\eta < 4.7$
  - $m_{jj} > 1100$ GeV
  - $\Delta\phi_{jj} < 1.0$
- $PF_{MET} > 130$ GeV
- Central Jet Veto (CJV): Veto if any jet at $\eta_{jet1} < \eta < \eta_{jet2}$ and $p_t > 30$ GeV

Background Estimation Methods I

$Z(\to \nu\nu)$+jets

Estimated from data using observable $Z \to \mu\mu$ decays:

- Identical selection for signal region except lepton veto is replaced with a $Z \to \mu\mu$ requirement.
- reconstructed muons with $p_t > 20$ GeV, and $60 < M_{\mu\mu} < 120$ GeV,
- veto on additional leptons,
- $\not{E}_T$ recomputed after removing the Zmuons.
- We use MC to extrapolate obtained control region yield to background contribution of this channel in the signal region

$W(\to \ell\nu)$+jets

For $W \to e\nu$ and $W \to \mu\nu$

- Same method as $Z(\to \nu\nu)$+jets
- Remove lepton veto and require a single charged lepton (e/μ)
- Veto additional leptons
- $\not{E}_T$ is recomputed after removing the W muon (not for the electron since was included on trigger)

For $W \to \tau\nu$ where the tau decays hadronically

- Control region is defined in the same way as $W \to \ell\nu$
- Required one hadronic tau, no additional leptons
- The central jet veto is not applied in order to increase the yield

Again for all $W(\to \ell\nu)$+jets we using MC to extrapolate control region yield to background contribution of this channel in the signal region

Background Estimation Methods II

QCD Multijets

Use the fractions of events passing the $\not{E}_{\mathrm{T}}$ and CJV cuts, after the full remaining selection. We define regions ABCD as follows:

- A : fail $\not{E}_{\mathrm{T}}$, fail CJV
- B : pass $\not{E}_{\mathrm{T}}$, fail CJV
- C : fail $\not{E}_{\mathrm{T}}$, pass CJV
- D : pass $\not{E}_{\mathrm{T}}$, pass CJV

We estimate the QCD multijet component in regions ABC by subtracting MC electroweak backgrounds from data. We then estimate the QCD multijet component in the signal region D, to be $D = BC/A$

Other backgrounds

All other minor backgrounds were estimated from MC.

Event Yield and Bkg. Estimation

The results of the background estimation are summarised here:

Yields

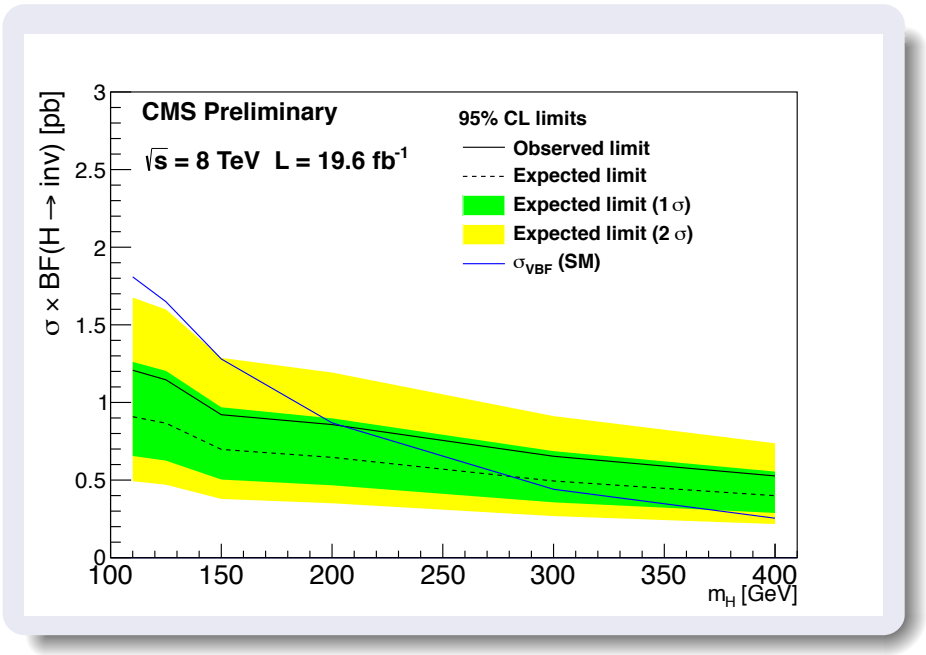
Background	N_{est}
$Z \to \nu\nu$	102 ± 30 (stat.) ± 26 (syst.)
$W \to \mu\nu$	67.2 ± 5.0 (stat.) ± 15.1 (syst.)
$W \to \mathrm{e}\nu$	68.2 ± 9.2 (stat.) ± 18.1 (syst.)
$W \to \tau\nu$	54 ± 16 (stat.) ± 18 (syst.)
QCD multijet	36.8 ± 5.6 (stat.) ± 30.6 (syst.)
Other SM	10.4 ± 3.1 (syst.)
Total background	339 ± 36 (stat.) ± 50 (syst.)
Observed	390

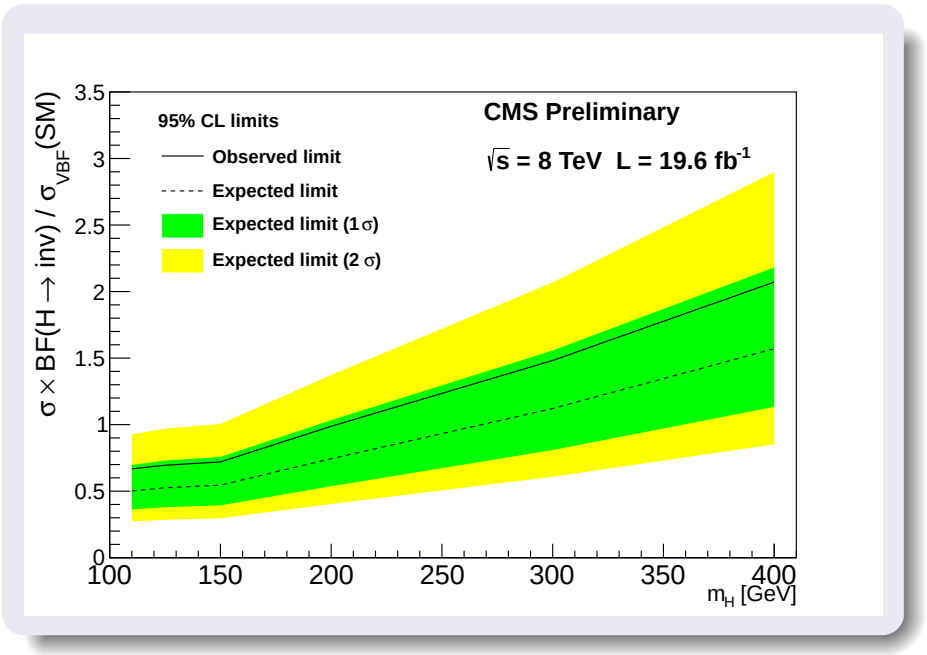
Assuming a 125 GeV Higgs with 100% invisible branching fraction, produced via VBF with the SM production cross-section, the expected yield is 208 events. In the signal region in data, we observe 390 events, which is compatible with the background prediction.

Limits on invisible Higgs

Assuming a background-only hypothesis, we place upper limits on an invisible Higgs signal.

- Calculated to 95% C.L. with an asymptotic $\mathrm{CL_S}$ method
- Using the standard CMS Higgs combination technique





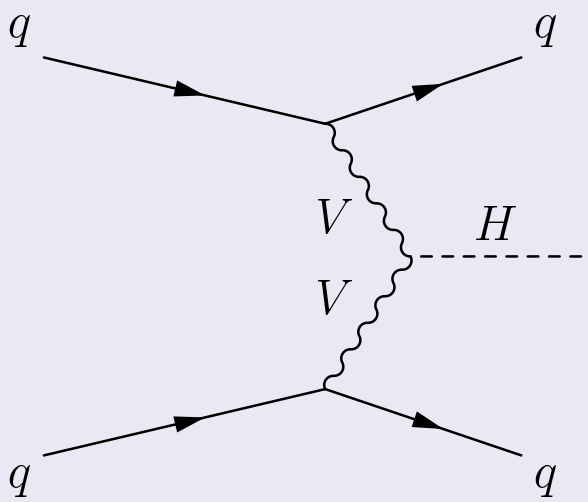
- On the left, observed and expected limits on the production cross-section times invisible branching fraction as a function of the Higgs mass.
- On the right, the same limits, normalised to the SM VBF production cross section.

Assuming the SM VBF production cross section, the observed limit on the invisible branching fraction of the 125 GeV Higgs 69% and the expected limit is 53%.

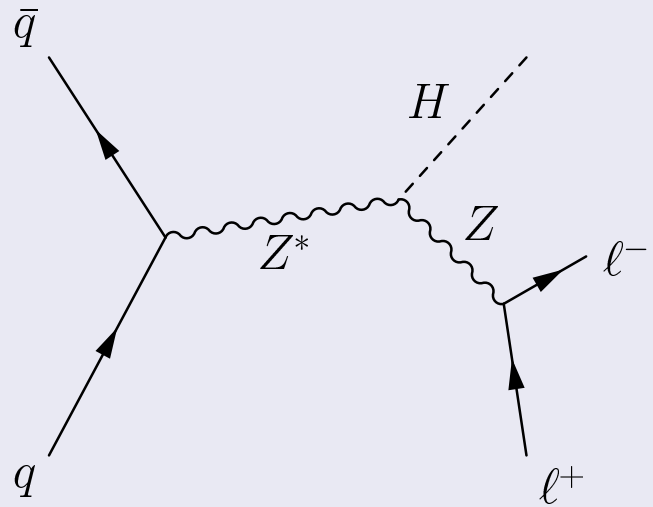
Combining VBF Inv. and ZH

Our results were combined with the ones from $ZH, (Z \to \ell\ell)$ analysis to obtain further sensitivity.

VBF Higgs Diagram



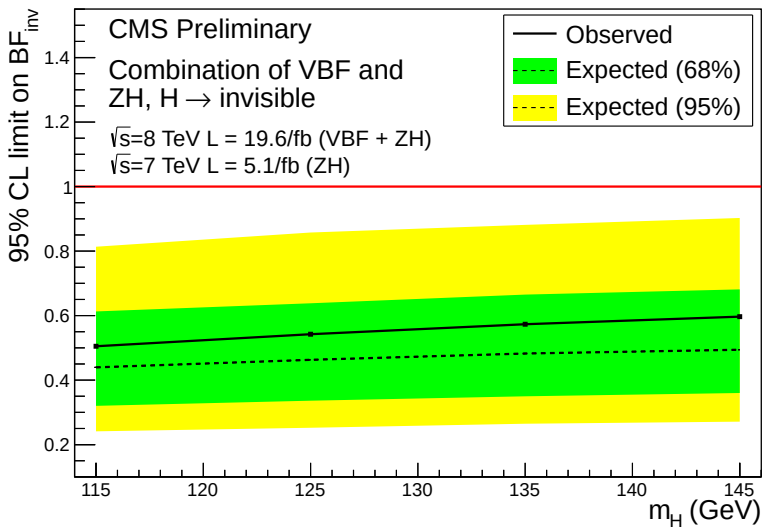
ZH Diagram



We used recently published results from CMS analysis HIG-13-018 which reported an upper limits on the invisible branching fraction of a 125 GeV Higgs of 75%.

Combination Results

Combined Limits on invisible Higgs



- 95% CL upper limit on the branching fraction of a Higgs boson to invisible final states as a function of the Higgs boson mass
- SM production cross-sections for the Higgs boson have been assumed
- For a Higgs boson mass of 125 GeV the observed (expected) upper limit on the invisible branching fraction is 54 (46)%
- Systematic errors between analysis considered uncorrelated
- New combination result including $ZH, (Z \to b\bar{b})$ under final stages of approval/publication.

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Summary

- A search for an invisibly decaying Higgs boson produced via vector boson fusion has been performed.
- The analysis used of a dedicated trigger and offline selection to isolate events with significant missing energy and two jets with vector boson fusion characteristics
- Major background estimated using data driven methods.
- Using the full $\sqrt{s} = 8$ TeV dataset recorded by CMS in 2012, a total of 339 ± 36 (stat.) ± 50 (syst.) events are expected in the signal region, from a background only hypothesis.
- Assuming a 125 GeV Higgs produced via vector boson fusion, with 100% invisible branching fraction, would be expected to yield 208 events. Yet observe 390 events in the signal region in data, which compatible with the expected background.
- Using an asymptotic $\mathrm{CL_S}$ method, 95% CL upper limits are placed on the production cross section times invisible branching fraction. The observed limit on the invisible branching fraction of the 125 GeV Higgs is 69%, with an expected limit of 53%.
- This measurement is the most sensitive to invisible decays of the Higgs boson to date.
- Combination with $ZH, (Z \to b\bar{b})$ is presented and the obtained observed (expected) upper limit on the invisible branching fraction is 54 (46)%

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