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 are compatible with a SM Higgs boson, but:

- Associated uncertainties are large.
- 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% (ATLAS-CONF-2013-034)
- CMS: upper limit of 64% (CMS-PAS-HIG-13-005)

Motivations for 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.

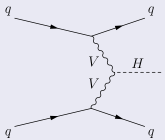
VBF Channel

Direct searches channels

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 separated jets and large missing energy.
- Use the distinct topology of the VBF jets to distinguish invisible Higgs decays from background.

Backgrounds

Major:

- $\mathrm{Z} \to \nu\nu$, in association with jets
- $\mathrm{W} \to \ell\nu$, with charged lepton misidentified

Minor:

- Mismeasured QCD events
- Other SM processes $(\mathrm{WW}, \mathrm{ZZ}, t\bar{t}, etc.)$

Analysis Definition

Dedicated trigger

Requirements:

- Any forward/backward pair of jets satisfying:
  - Jet $p_t > 40 GeV$
  - $\Delta\eta_{jj} = |\eta_{jet1} - \eta_{jet2}| > 3.5$
  - High invariant mass ($m_{jj} > 800$ GeV)
- $\not{E}_{\mathrm{T}}(\text{no } \mu) > 65$ GeV

Offline selection

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

Background Estimation Methods I

Method

We use data control regions and MC control to signal region ratios to extrapolate each major background contribution our signal region. For both Z and W background we use $\not{E}_{\mathrm{T}}(\text{no } \mu)$.

$\mathrm{Z}(\to \nu\nu)$+jets

- Estimated from data using observable $\mathrm{Z} \to \mu\mu$ decays:
- Identical selection for signal region except lepton veto is replaced with a $\mathrm{Z} \to \mu\mu$ requirement:
  - Require two muons with $p_t > 20$ GeV, and $60 < M_{\mu\mu} < 120$ GeV, Veto on additional leptons.

$\mathrm{W}(\to \ell\nu)$+jets

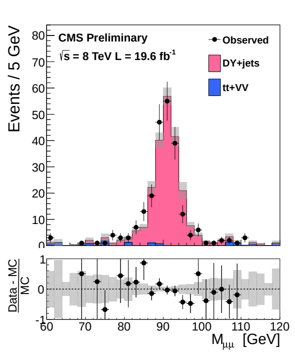
For $\mathrm{W} \to e\nu$ and $\mathrm{W} \to \mu\nu$

- Similar method as $\mathrm{Z}(\to \nu\nu)$+jets.
  - Require one reconstructed e/μ with $p_t > 20/10$ GeV, and $|\eta| < 2.4/2.1$ GeV. Veto additional leptons.
- Presence of W electron found to be negligible.

For $\mathrm{W} \to \tau\nu$ where the tau decays hadronically

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

$\mathrm{Z} \to \nu\nu$ mass



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 A,B and C by subtracting MC electroweak backgrounds from data. We then estimate the QCD multijet component in the signal region D, to be $N_D = N_B N_C / N_A$.

Other backgrounds

All other minor backgrounds are estimated from MC.

Event Yield and Background Estimation

The signal yield is given for a 125 GeV Higgs with 100% invisible branching fraction, produced via VBF with the SM production cross section.

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.)
$W \to e\nu$	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.)
VBF H(inv)	208
Observed	390

Systematics:

Largest source of uncertainty: statistical uncertainty in the $\mathrm{Z} \to \mu\mu$ control region.

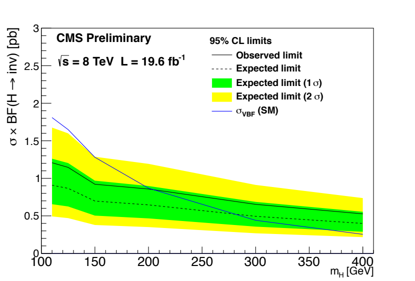
- V+jets backgrounds MC ratio: 20% uncertainty
- Jet and $\not{E}_{\mathrm{T}}$ energy scales and resolution for $\mathrm{Z} \to \nu\nu$ and $\mathrm{W} \to \ell\nu$: 5-10% uncertainty
- Jet and $\not{E}_{\mathrm{T}}$ energy scales and resolution for $\mathrm{W} \to \tau_{\mathrm{had}}\nu$: 15% uncertainty

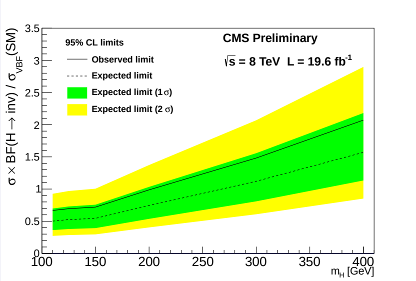
In the signal region in data, we observe 390 events, which is compatible with the background prediction within 1 σ.

Limits on invisible Higgs

We can place upper limit on an invisible Higgs signal.

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





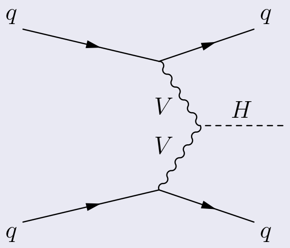
- On the left, observed and expected limits on the production cross section times invisible branching fraction as a function of the Higgs mass.
- On the right, the same limits, normalised to the SM VBF production cross section.

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

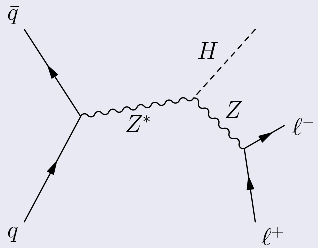
Combining VBF H and ZH

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

VBF Higgs Diagram



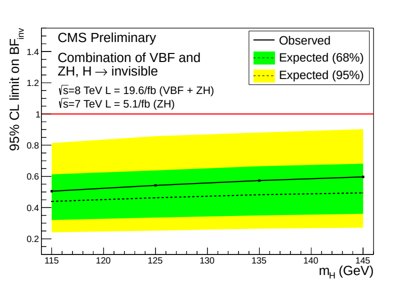
ZH Diagram



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 of mass 125 GeV the observed (expected) upper limit on the invisible branching fraction is 54 (46)%.
- Systematic errors between analyses are considered uncorrelated.
- Combination result including $ZH, (Z \rightarrow b\bar{b})$ are in final stages of approval/publication and takes into account all correlations.

Summary

- A search for an invisibly decaying Higgs boson produced via vector boson fusion has been performed.
- The analysis used a dedicated trigger and an offline cut based 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, in the signal region:
  - Expected background of 339 ± 36 (stat.) ± 50 (syst.) events;
  - Expected signal of 208 events ($m_H = 125$ BR(Inv.)=100%);
  - Observed 390 events in data $\Rightarrow$ compatible with the expected background at the 1 σ level.
- In the VBF channel the observed (expected) 95% CL upper limit on the invisible branching fraction of the 125 GeV Higgs is 69 (53)%
- A combination with $ZH, (Z \rightarrow \ell\ell)$ is presented and the observed (expected) upper limit on the invisible branching fraction is 54 (46)%
- This combination is the most sensitive to invisible decays of the Higgs boson to date

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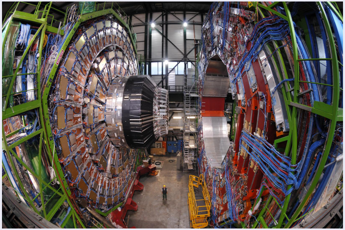
Backup Slides

Compact Muon Solenoid

- Located at point 5 of the Large Hadron Collider
- General purpose experiment
- Objective of studying a broad spectrum of physics
- Classical onion structure
- One of the most powerful solenoid ever built (3.8 T)



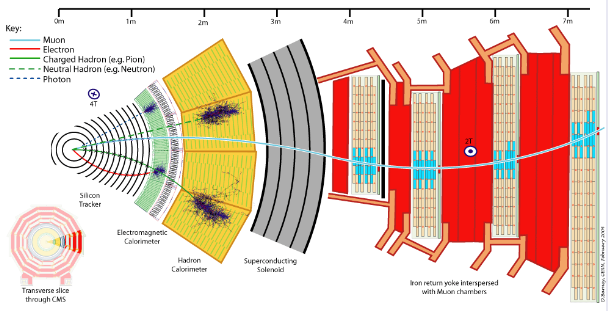
CMS strong points for VBF Higgs to invisible search

- High detector coverage ($\sim 4\pi$)
  - Precise measurement of event properties
  - Accurate missing transverse energy calculation (MET)
- Excellent object position/energy resolution capabilities
- Dedicated VBF trigger
- This analysis utilises the information from all parts of the detector.

Particle Detection on CMS

When a collision happens then resulting particles need to be identified and measured

Detector Structure



- Tracker
  - Charged particle trajectory
- ECAL and HCAL
  - Energy Measurement
- Solenoid
  - Charge and Momentum
- Muon Chambers
  - Muon identification and measurement
- Trigger (L1+HLT)
  - Event Selection

- Detector subsystems are designed to take advantage of particle characteristics in order to identify and measure their properties.
- Trigger System is responsible to select only the most interesting events.

Indirect Mesurements (CMS-PAS-HIG-13-005)

An alternative more general scenario than C6 can be obtained by allowing for a non-vanishing Γ_{BSM}, but constraining $\kappa_{\mathrm{V}} \leq 1$, a requirement motivated by electroweak symmetry breaking:

Assumptions:

- The couplings to W and Z bosons are scaled by a common factor κ_{V};
- The couplings to third generation fermions, i.e. the top quark, bottom quark, and tau lepton, are scaled independently by κ_t, κ_b, κ_τ;
- The scale factors for couplings to the first and second generation fermions are equal to those for the third;
- The effective couplings to gluons and photons, induced by loop diagrams, are given independent scaling factors κ_{g} and κ_γ, respectively;
- The partial width $\kappa_{\mathrm{V}} \leq 1$.

Likelihood scan vs $\mathrm{BR}_{\mathrm{BSM}}$

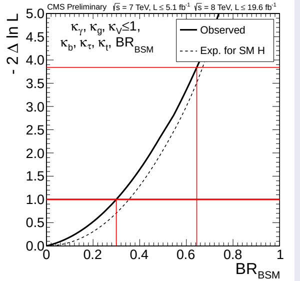


Figure shows the likelihood scan versus $\mathrm{BR}_{\mathrm{BSM}}$ derived in this scenario while profiling all the other coupling modifiers and nuisance parameters. Within these assumptions, the data allow us to conclude that $\mathrm{BR}_{\mathrm{BSM}}$ is in the interval [0.00,0.64] at 95% CL.

Asymptotic CL_s

The statistical significance of an observed signal can be quantified by means of a p-value or its equivalent Gaussian significance.

- Useful to characterize the sensitivity of an experiment by reporting the expected (e.g., mean or median) significance that one would obtain for a variety of signal hypotheses.
- Finding both the significance for a specific data set and the expected significance can involve Monte Carlo calculations that are computationally expensive.

With asymptotic approximate methods one can obtain, without recourse to Monte Carlo:

- Significance for given data
- Full sampling distribution of the significance under the hypothesis of different signal models

In this way one can find:

- The median significance
- A measure of how much one would expect this to vary as a result of statistical fluctuations in the data