IC Higgs to Invisible Activities

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Introduction

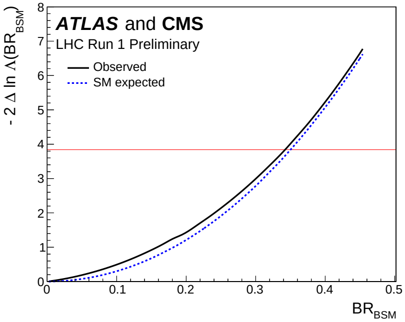
Motivation

- At the end of run 1 significant BSM Higgs properties are not excluded
  - Limit from ATLAS+CMS on $\mathrm{BR}_{\mathrm{BSM}} \sim 35\%$
- Many BSM theories predict $H \rightarrow$ invisible

Overview

- Reminder of Run I VBF analysis
- New combination of all run 1 direct searches
- Run 2 progress update and aims

Indirect only



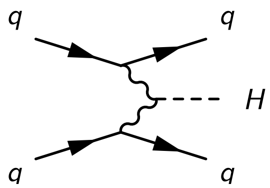
Run 1 VBF analysis - HIG-14-038

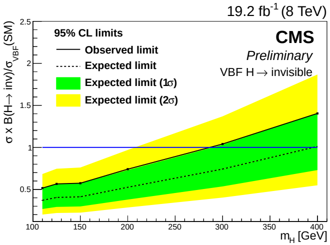
Context

- IC group works on the VBF channel
  - Cross-check and limit setting for prompt data
  - Main analysis for parked data

Analysis

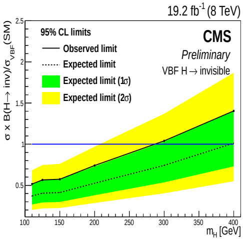
- Select 2 VBF jets (i.e. large $\Delta\eta$) + MET
- Remove QCD with tight selection
- Use data driven methods to estimate major backgrounds
- Single bin counting experiment
- 95% CL observed (expected) limit on B(H$\rightarrow$inv) 57(40)%

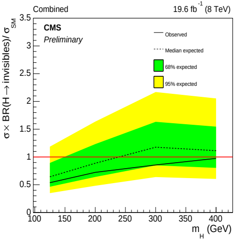


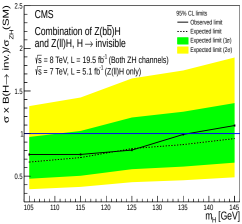


Run 1 combination

- CMS performed searches in VBF, Z(ll)H, Z(bb)H and ggH+ISR channels
- IC group has performed several combinations through run 1
  - HIG-13-030, HIG-14-038, HIG-15-012
- ZH and VBF analyses are exclusive by design
- ggH+ISR analysis has small overlap with VBF
  - Overlap region vetoed for combination







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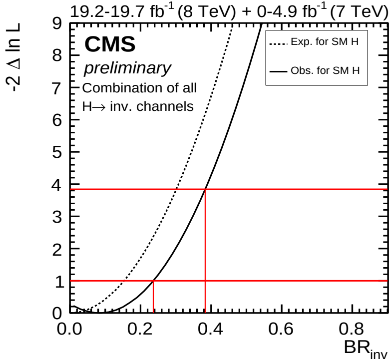
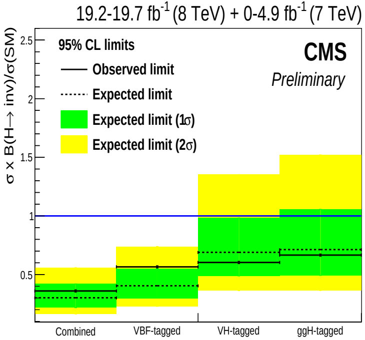
Run 1 combination - Limits

- 95% CL upper limits set using asymptotic method in combine assuming SM Higgs boson production and acceptance
- Observed (expected) limit is 36 (30)%





Run 2 - VBF

Overview

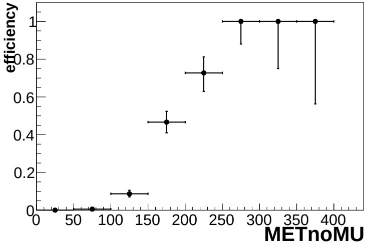
- Studying early data to ensure trigger is well understood
  - Trigger designed by IC+Bristol
- Initial analysis strategy is the same as run 1

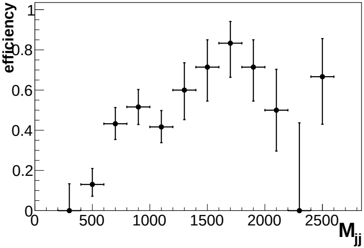
Possible improvements

- New γ+jets control region for $Z \to \nu\nu$ background
- New MC samples for QCD background estimation (more later)

Trigger Efficiencies

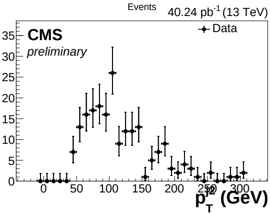
- Measure efficiency as a function of each variable
- Cut on all other variables at trigger threshold value
- Trigger: HLT_DiPFJet40_DEta3p5_MJJ600_PFMETNoMu140
- Made using 40.24 pb^{-1} of 50ns data

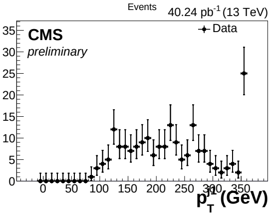


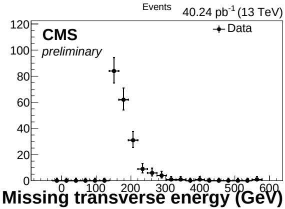


50ns Data - control-like region

- Apply a loose signal-like preselection
- Cut at trigger threshold plus lepton veto
  - Jet $p_T > 40$ GeV, $\Delta\eta_{jj} > 3.5$, $M_{jj} > 600$ GeV, $METnoMU > 140$ GeV







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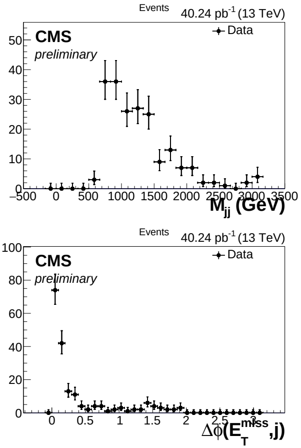
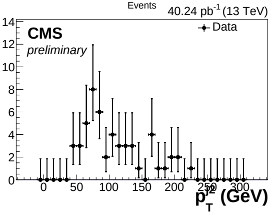
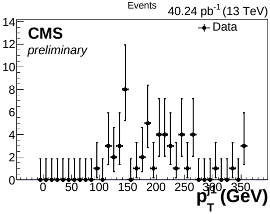
50ns Data - signal-like region

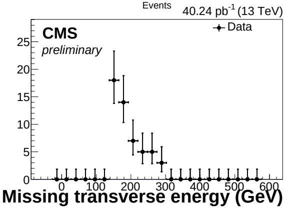


50ns Data - signal-like region

- Invert lepton veto to examine control-like region
- Only single muon region has sufficient statistics
  - Jet $p_T > 40$ GeV, $\Delta\eta_{jj} > 3.5$, $M_{jj} > 600$ GeV, $METnoMU > 140$ GeV, one tight muon





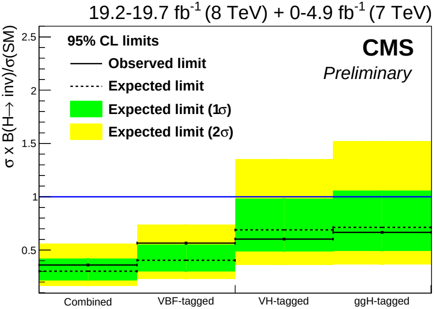


MC Validation

QCD MC samples

Summary

- All CMS Run I H→invisible analyses have been combined
- The observed (expected) 95% CL upper limit on B(H→inv) is 36 (30)%
-

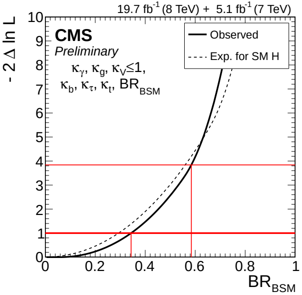


Backup

Why Higgs to Invisible?

Experimental motivation

- Current measurements of the 125 GeV Higgs boson are compatible with Standard Model (SM) expectations
  - large uncertainties can still accommodate significant beyond the SM (BSM) properties
- Additional Higgs bosons with exotic decays are not excluded



Theoretical motivation

- Many BSM theories predict Higgs boson decays to invisible final states:
  - e.g. SUSY, extra dimensions, fourth-generation neutrinos
- These final state particles are often dark matter candidates

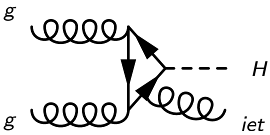
Monojet+V(had)H-tagged - EXO-12-055, AN-2014/206

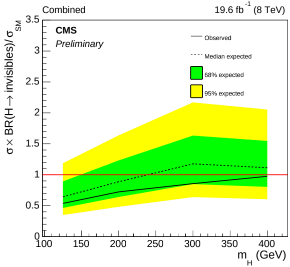
Strategy

- Select a high energy jet+MET
- Categorise events as boosted or resolved V-tagged or no V-tag
- Use data driven methods to estimate major backgrounds

Signal extraction and results

- Simultaneous fit to MET in signal and control regions
- 95% CL observed (expected) limit on $B(H \rightarrow inv)$ 54(62)%





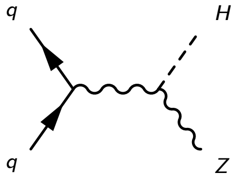
Z(ll)H - HIG-13-030, AN-2013/333

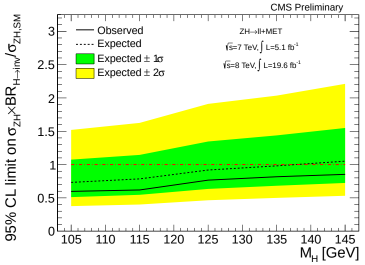
Strategy

- Select two electrons or muons compatible with a Z decay + MET
- Categorise by lepton flavour and presence of a jet
- Use data driven methods to estimate remaining backgrounds

Signal extraction and results

- 2D (1D) fit to m_{ll} and m_T (m_T) in 8 (7) TeV
- 95% CL observed (expected) limit on B(H→inv) 83(86)%





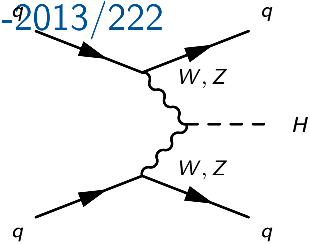
Z(bb)H - HIG-13-030, AN-2013/222

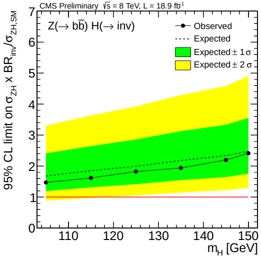
Strategy

- Based on H(bb)Z(inv) analysis:
  - Require two jets consistent with $Z \rightarrow$bb+MET
- Categorise according to MET
- Backgrounds from MC normalised in simultaneous fit to signal and control regions

Signal extraction and results

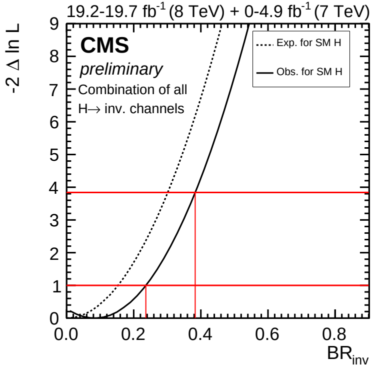
- Fit to BDT
- 95% CL observed (expected) limit on B(H→inv) 182(199)%

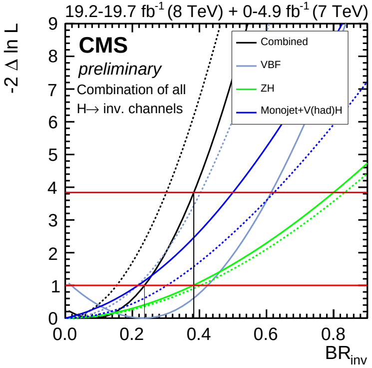




Likelihood scans

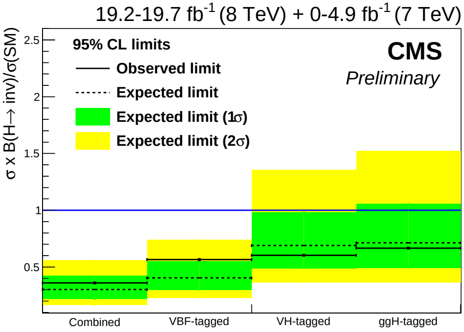
- Likelihood plotted as a function of B(H→inv):
  - for combination (left) and by analysis (right)





Limits - by production mode tag

- VBF tagged is VBF analysis
- VH-tagged is Z(ll)H + Z(bb)H + boosted and resolved from monojet+V(had)H
- ggH-tagged is monojet from monojet+V(had)H



Reminder of Analysis

Overlaps

Overlaps between VBF, Z(ll)H, Z(bb)H

- VBF, Z(ll)H and Z(bb)H analyses are exclusive by design:
  - VBF requires no leptons and high M_{jj}
  - Z(ll)H requires two leptons
  - Z(bb)H requires no leptons and low M_{jj}

Overlaps between monojet+V(had) and other analyses

- Z(bb)H and resolved category of monojet+V(had) have potential overlap
  - Not expected to impact result
  - Completely removing resolved category has no effect on expected limit
- VBF and monojet+V(had)-tagged analyses do have overlap:
  - Veto events from monojet+V(had) analysis with 1st (2nd) jet with $p_T >$50 (45) GeV, $M_{jj} >$1200 GeV, $\eta_{j1} \cdot \eta_{j2} < 0$ and $\Delta\eta_{jj} > 3.6$
  - Veto is solely for clean statistical combination not for further separation of production modes

Effect of VBF veto

Events rejected by VBF veto

Sample	Monojet	Boosted	Resolved
VBF	13.2%	11.0%	0.0%
ggH	1.52%	0.0%	0.0%
Data	0.4%	0.2%	0.5%
Expected signal composition	70% ggH, 20% VBF, 6% WH, 3% ZH	47% WH, 25% ggH, 23% ZH, 5% VBF	39% ggH, 32% WH, 18% ZH, 11% VBF

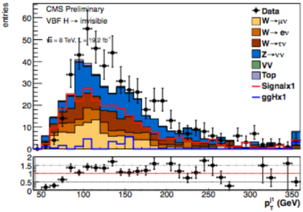
- Explicitly checked overlap after veto in signal and dimuon control regions
- 3 out of 89,304 events found to overlap
  - All in monojet category at low MET
  - All have a 2nd jet rejected by PU ID - thought to be from small input differences
- Full monojet+V(had) analysis is rerun after veto:
  - All results shown are after veto

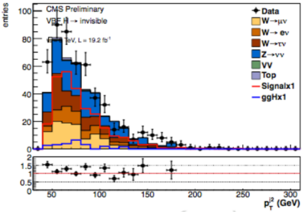
Correlated Nuisances

Nuisance	Analyses which it affects
Jet energy scale	VBF, Z($\ell\ell$)H(inv)
PDF uncertainties	VBF, Z($b\bar{b}$), Z($\ell\ell$)H(inv), monojet+V(had)
QCD scale	VBF, Z($b\bar{b}$), Z($\ell\ell$)H(inv), monojet+V(had)
Luminosity	VBF, Z($b\bar{b}$)H(inv), Z($\ell\ell$)H(inv), monojet+V(had)
Jet energy resolution	VBF, Z($\ell\ell$)H(inv)
Unclustered energy scale	VBF, Z($b\bar{b}$)H(inv), Z($\ell\ell$)H(inv)
Muon identification efficiency	VBF, Z($\ell\ell$)H(inv), monojet+V(had)
Electron identification efficiency	VBF, Z($\ell\ell$)H(inv)
Diboson cross-section	VBF, monojet+V(had)

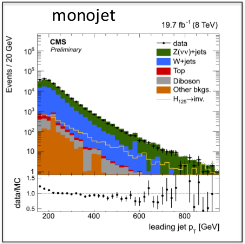
- JES/R in Z(bb)H is not correlated with others because it comes from jet energy regression method also used in $H \to b\bar{b}$ analysis
- Monojet+V(had) MET uncertiainties are not correlated with others
  - Monojet+V(had) uses uncorrected pfmet with recoil corrections
  - Other analyses use type 1 corrected pfmet

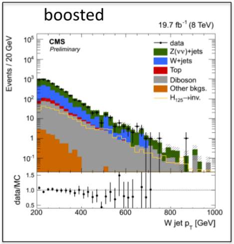
JES/R Correlation - check jet p_T

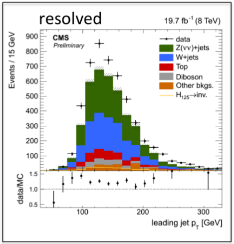




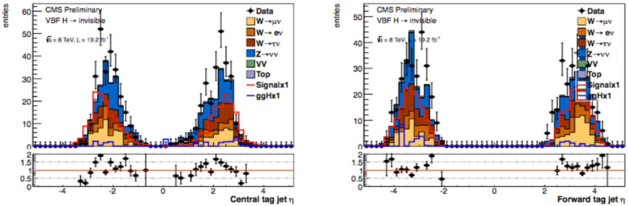
VBF leading (left) and subleading (right) jet p_T



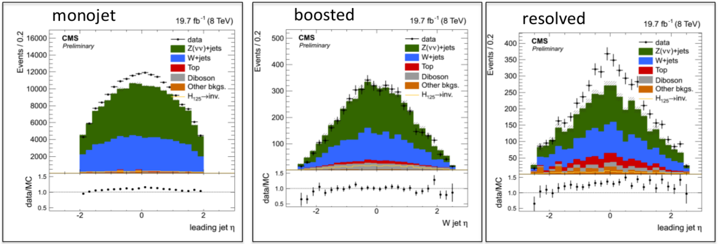




JES/R Correlation - check jet η



VBF most central (left) and most forward (right) tag jet η



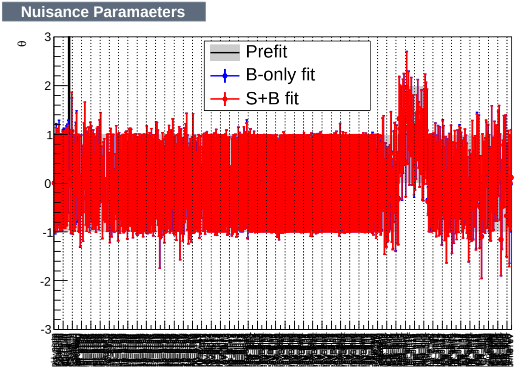
JES/R Correlation

- Significantly different jet kinematics seen in VBF and monojet+V(had)H
- Jets used in Z(ll)H analysis are low p_T additional jets
  - These are similar to additional jets used for min$\Delta\phi$(j,MET) in VBF
  - Different from high p_T jets in monojet+V(had)H analysis
- We therefore do not correlate JES/R between monojet+V(had)H and these analyses
- We tried a number of scenarios for the correlation model and found that they all gave no change to the expected limit:
  - VBF+Z(ll)H correlated, all correlated, none correlated
  - Expected limit was 30% for all scenarios

Channel	Observed (expected) upper limits on $\frac{\sigma}{\sigma_{SM}} \cdot$B(H$\rightarrow$inv) (%)
VBF	57 (40)
Monojet+V(had)H	54 (62)
Z(ll)H	83 (86)
Z(bb)H	182 (199)
Combined	36 (30)

Pulls

- Usual full table of pulls and post-fit nuisances in AN/2014-206
- Generally distributed around their pre-fit values
  - Apologies for x axis below



VBF Objects

PFMET

- Ignore muons
- Type0+1 corrections
- Smeared PFMET for MC

AK5 PFJets

- L1FastJet+L2+L3(+L2L3Residual) JEC
- "Loose" PF Jet ID
- Cleaned with veto leptons
- "Loose" PU jet ID
- Smeared jet collection for MC (JER is smeared to match data)

Veto leptons

- loose+PFiso muons $p_T > 10$ GeV, $|\eta| < 2.1$
- veto+PFiso electrons $p_T > 10$ GeV, $|\eta| < 2.4$

Tight leptons

- As veto leptons but "tight" ID and $p_T > 20$ GeV

Hadronic taus

- $p_T > 20$ GeV, $|\eta| < 2.3, d_Z < 0.2$ cm
- Tight ID, discriminant "byTightCombinedIsolationDelta-BetaCorr3Hits"
- Efficiency $\sim$0.55, fake rate 0.02(barrel),0.03(endcap)