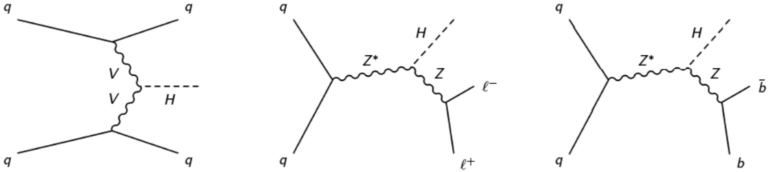
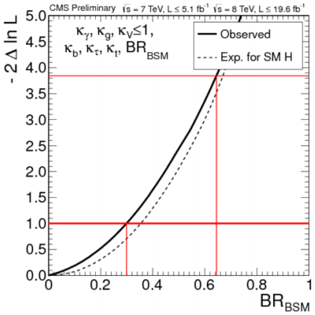
Higgs to Invisible Analyses at CMS

P. Dunne



Introduction

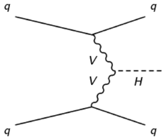
- Many BSM theories predict invisible Higgs decays:
  - SUSY, Extra Dimensions, etc.
- Visible decays constrain invisible BF to less than 64% at 95% C.L. (assuming SM production)
- Direct searches must be performed in associated production channels
- There are three approved CMS Higgs to invisible results in the following channels:
  - VBF (HIG-13-013), $Z(\ell\ell)H(inv)$ (HIG-13-018), $Z(b\bar{b})H(inv)$ (HIG-13-028)
- These results have been combined for a paper (HIG-13-030)



The Three Channels

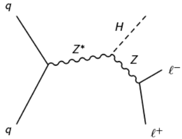
VBF

- Highest production cross-section
- Difficult all hadronic final state



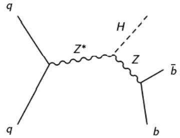
Z($\ell\ell$)H(inv)

- Production cross-section lower than VBF
- Clean all leptonic final state



Z($b\bar{b}$)H(inv)

- Also much lower production cross-section than VBF
- Same final state as Z(inv)H($b\bar{b}$)



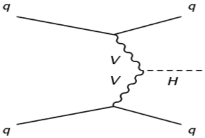
VBF Measurement Strategy

General Strategy

- Select VBF Topology
  - 2 jets with a large η separation
  - Nothing in the gap between the jets
  - Need dedicated VBF trigger
- Clean data from pileup and mismeasured MET
- Use hard cuts to restrict backgrounds
- Remaining background estimation must be data driven as hard cuts make MC unreliable

Main backgrounds:

- W + jets where lepton is missed
- $Z \rightarrow \nu\nu$ + jets
- QCD



Cuts

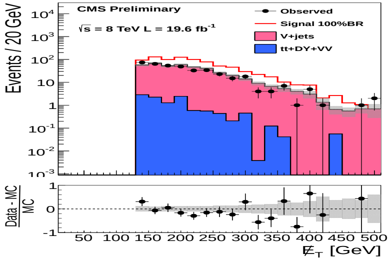
- Require 2 jets in all regions:
  - Both jets must pass loose PUJetID
  - $p_T > 50 GeV$, $|\eta| < 4.7$
  - $|\Delta\eta| > 4.2$, $\eta_{j_1} * \eta_{j_2} < 0$
  - $m_{jj} > 1100 GeV$
- Central Jet Veto (CJV)
  - Veto events with jets with $p_T > 30$GeV between the tag jets unless stated otherwise

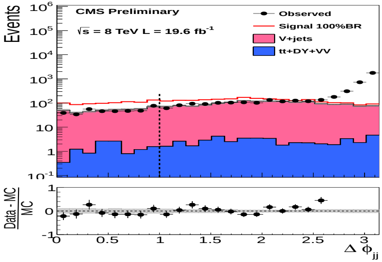
VBF Signal Event Selection

Signal Region Selection:

- PFMET $> 130 GeV$, $\Delta\phi_{jj} < 1.0$ to reduce QCD
- e/μ veto to reduce W/Z+jets

Data MC difference is QCD





VBF W/Z + jets Background Estimation

Data Driven Estimation Method:

- Pick W/Z dominated control region in same trigger sample with same VBF selection
  - For muons recalculate MET after removing leptons from W & Z to mimic W with missed muon/$Z \rightarrow \nu\nu$
- Check data/MC shape agreement in control regions
- Assume MC signal/control ratio is the same as that in data

Results

- $W \rightarrow e\nu$: 63 $\pm$ 9 (stat.) $\pm$ 18 (syst.)
- $W \rightarrow \mu\nu$: 67 $\pm$ 5 (stat.) $\pm$ 16 (syst.)
- $W \rightarrow \tau\nu$: 53 $\pm$ 18 (stat.) $\pm$ 18 (syst.)
- $Z \rightarrow \nu\nu$: 99 $\pm$ 29 (stat.) $\pm$ 25 (syst.)

$W \rightarrow \mu/e$ Control Region:

- 1 tight muon/electron:
- MET $> 130 GeV$

$W \rightarrow \tau$ Control Region:

- Remove CJV
- Require 1 $\tau_{hadronic}$ candidate

$Z \rightarrow \nu\nu$ Control Region:

- Require 2 tight muons with $60 < M_{\mu\mu} < 120$ GeV
- MET without Z candidate $> 130 GeV$
- Correct for different cross-section for the two processes

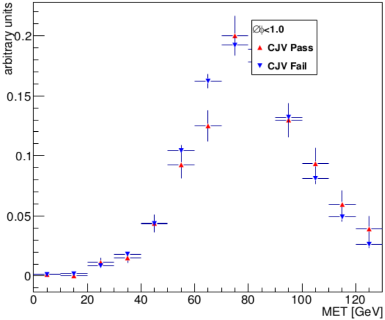
VBF QCD Estimation

QCD Background Strategy

- V. low MC statistics

1) Reduce background with cuts
2) Estimate using data driven ABCD method in MET and CJV
3) Cross-check using ABCD method in MET and $\Delta\phi_{jj}$

- N_{QCD} =31 ± 2 (stat.) ± 23 (syst.)



QCD ABCD method:

- Choose 4 regions:

	Fail MET	Pass MET
Fail CJV	A	B
Pass CJV	C	D (signal)

- $N_D = N_B N_C / N_A$

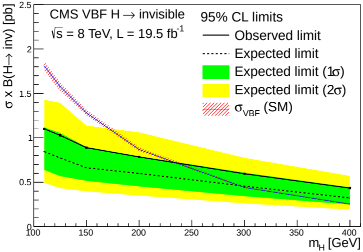
Combination Method

- Datacards for the three channels were combined using the standard Higgs combination tool
- The following uncertainties were considered correlated between channels in decreasing order of importance:

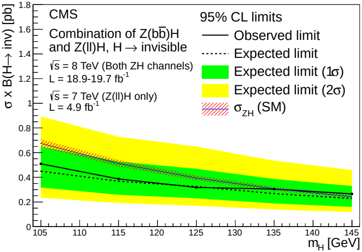
Nuisance	Analyses which it affects
Jet energy scale	VBF, Z($\ell\ell$)H(inv)
PDF uncertainties	VBF, Z($b\bar{b}$), Z($\ell\ell$)H(inv)
QCD scale	VBF, Z($b\bar{b}$), Z($\ell\ell$)H(inv)
Luminosity	VBF, Z($b\bar{b}$)H(inv), Z($\ell\ell$)H(inv)
Jet energy resolution	VBF, Z($\ell\ell$)H(inv)
Unclustered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

Separate results: Cross-Section limits

- VBF



- ZH

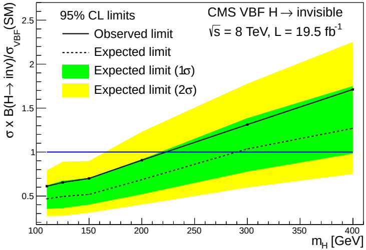


- Observed (expected) limit of 65% (49%) at 95% C.L. on BR_{inv} for a 125 GeV Higgs

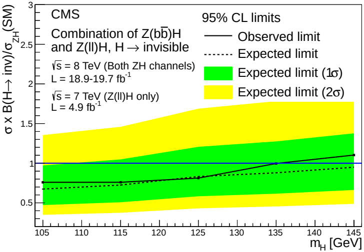
- Observed (expected) limit of 81% (83%) at 95% C.L. on BR_{inv} for a 125 GeV Higgs

Separate results: Direct

- VBF



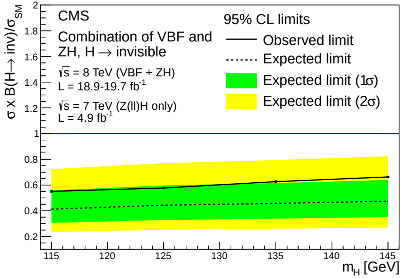
- ZH

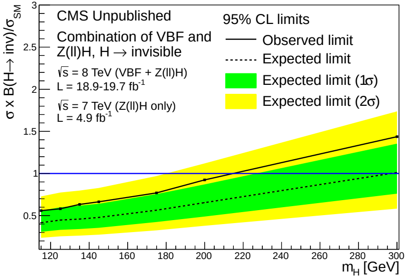


- Observed (expected) limit of 65% (49%) at 95% C.L. on BR_{inv} for a 125 GeV Higgs

- Observed (expected) limit of 81% (83%) at 95% C.L. on BR_{inv} for a 125 GeV Higgs

Combined Results





- Observed (expected) limit at 125 GeV is 58(44)%

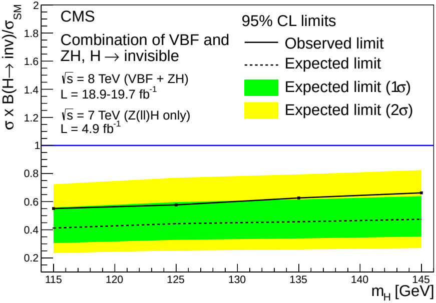
- $Z(\ell\ell)H(\text{inv})$ and VBF both have datacards up to 300 GeV
- The method above was used to combine these two channels between 115 and 300 GeV

Conclusions

- All three H$\rightarrow$invisible channels have been combined using the standard Higgs combination tool
- The result is compatible with the SM
- The combined result gives the strongest limit on the invisible branching fraction of the 125 GeV Higgs

Plans

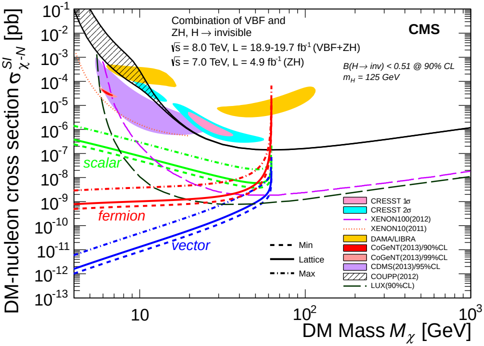
- A paper for the prompt data has just been submitted to EPJC
- An improved analysis is under way using the parked data



BACKUP

Other Interpretations

- Limits can also be interpreted as constraints on dark matter models (arXiv:1205.3169)
- Competitive with dedicated experiments at very low mass



Datacards

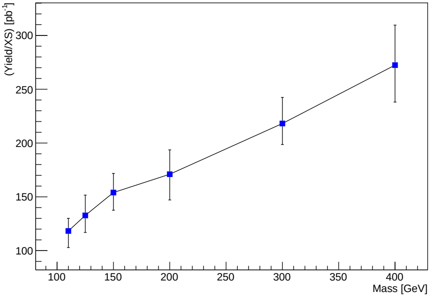
- All three channels have signal MC at different mass points

Channel	Mass Points/GeV
$Z(\ell\ell)H(\text{inv})$	105, 115, 125, 135, 145, 175, 200 & 300
$Z(b\bar{b})H(\text{inv})$	105, 115, 125, 135, 145 & 150
VBF	110, 125, 150, 200, 300 & 400

- New VBF datacards were produced for 115,135 and 145 GeV
  - Nuisances are linearly interpolated between mass points.
  - Signal yields are interpolated using the method described below.
  - Combination between direct and indirect methods is being investigated e.g. talk by M. Zanetti

Signal Yield interpolation

- $N_{Signal} = eff. \times acc. \times \mathcal{L}\sigma$
- Luminosity is constant
- Yield over cross-section is thus proportional to efficiency times acceptance
- Cross-sections from LHC-HXSWG were used



Parked Data

- Jet $E_T > 35(30) GeV$, $\Delta\eta_{jj} > 3.5$, $m_{jj} > 700 GeV$
- Trigger with $E_T > 30 GeV$ added for run D
- Good efficiency for visible and invisible VBF Higgs channels
- Plan to update result with parked data included after paper

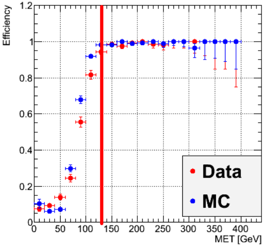
VBF Datasets and Trigger

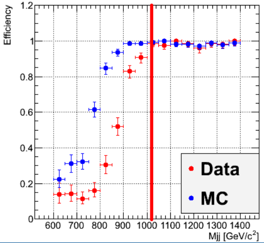
Datasets:

- 8 TeV MET datasets
  - Total of 19.6 fb^{-1}
- MET filters are used to cut out events with mismeasured MET

Trigger:

- HLT_DiPFJet40_PFMET noMu65_MJJ800VBF_AllJets
  - VBF means $|\Delta\eta_{j_1 j_2}| > 3.5$





W+jets Background Estimation

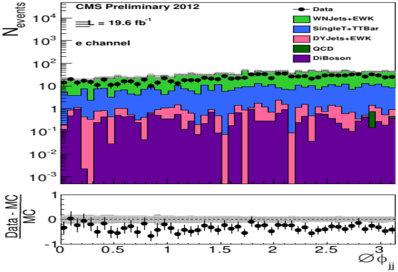
Background estimation formula:

$$N^S_{data}(W \to e/\mu) = (N^C_{data} - N^C_{bkg})\frac{N^S_{MC}}{N^C_{MC}}$$

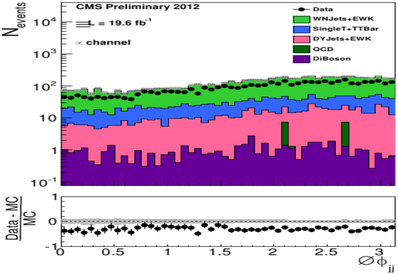
$W \to \mu/e$ Control Region Selection:

- 1 tight muon/electron:
- MET $> 130 GeV$

$W \to e\nu$



$W \to \mu\nu$



$N^S_{data} = 68.2 \pm 9.2(stat.) \pm 13.1(syst.)$ events

$N^S_{data} = 67.2 \pm 5.0(stat.) \pm 7.5(syst.)$ events

$W \to \tau_{had}\nu$ Background Estimation

Background estimation formula:

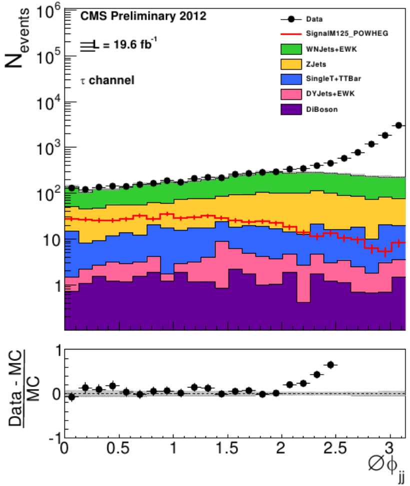
$$N^S_{data}(W \to \tau\nu) = (N^C_{data} - N^C_{bkg})\frac{N^S_{W\to\tau\nu MC}}{N^C_{W\to\tau\nu MC}}$$

$W \to \tau$ Control Region Selection:

- Require signal region criteria except CJV
- Require 1 $\tau_{hadronic}$ candidate
  - No tau veto so this is a subsample of signal region without CJV

Result

- $N^{data}_{W\to\tau\nu} = 54 \pm 16(stat.) \pm 18(syst.)$



Z+jets Background Estimation

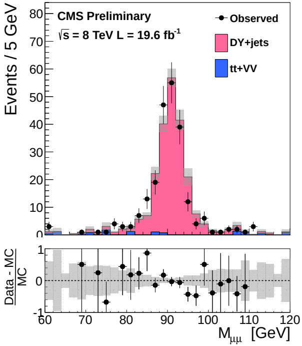
Z+jets background estimation formula:

$$N^S_{data}(Z \to \nu\nu) = (N^C_{data} - N^C_{bkg}) \frac{\sigma(Z \to \nu\nu)}{\sigma(Z/\gamma^* \to \mu\mu)} \frac{\epsilon^S_{VBF}/\epsilon^C_{VBF}}{\epsilon_{\mu\mu}}$$

$Z \to \nu\nu$ Control Region Selection:

- Select $Z \to \mu\mu$ and extrapolate to $Z \to \nu\nu$
  - 2 tight muons with $60 < M_{\mu\mu} < 120$ GeV
  - MET after Z candidate removed $> 130 GeV$
  - No additional veto muons/electrons

$$N^S_{data} = 102 \pm 30(stat.) \pm 14(syst.)$$



Imperial College
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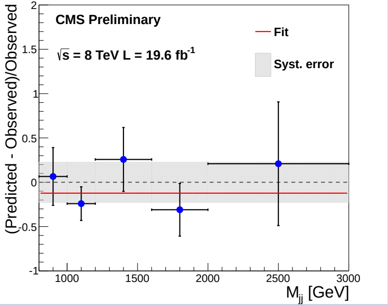
Consistency Tests

Method

- To check W/Z+Jets estimates the $W \rightarrow \mu\nu$ sample is used to predict the other control region yields
- The predictions are consistent with the observed yields for all control regions
  - Some regions with significant QCD contamination show deviations

$W \rightarrow e\nu$ from $W \rightarrow \mu\nu$



Objects

VBF Selections

- Applied to all regions
- 2 jets:
  - Both jets must pass loose PUJetID
  - $p_T > 50GeV$, $|\eta| < 4.7$
  - $|\Delta\eta| > 4.2$, $\eta_{j_1} * \eta_{j_2} < 0$
  - $m_{jj} > 1100GeV$

MET

- Using Type $0 + 1$ Corrections

Electrons

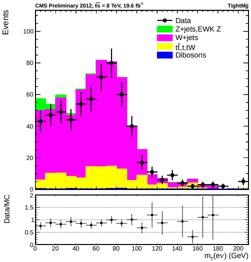
- Veto:
  - $p_T > 10GeV$, $|\eta < 2.5|$
  - rel PF Iso < 0.2
- Tight:
  - $p_T > 20GeV$, $|\eta < 2.5|$

Muons

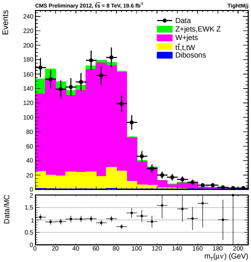
- Veto:
  - $p_T > 10GeV$, $|\eta < 2.1|$
  - rel PF Iso < 0.2
- Tight:
  - $p_T > 20GeV$, $|\eta < 2.1|$

W+jets background m_T plots

$e\nu$



$\mu\nu$



$\tau\nu$