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Higgs to Invisible Analyses at CMS
PAS-HIG-13-013, HIG-13-030

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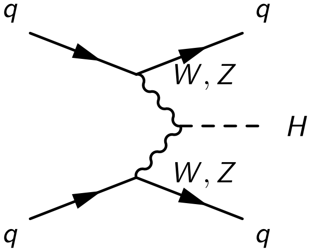
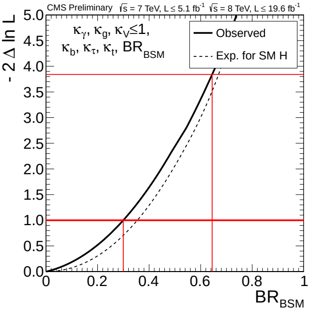


Introduction

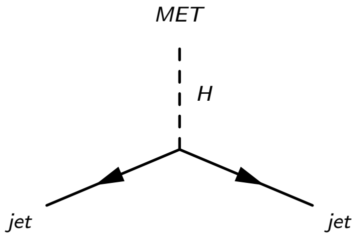
- Searching for VBF produced Higgs decaying to invisible final state
- Visible decays constrain invisible BF to less than 64% at 95% C.L. (assumes standard model width)
- Many theoretical possibilities for BSM invisible final states:
  - $H \to 2LSPs$ (SUSY)
  - $H \to$ dark matter (Extra Dimensions)
  - etc.



Measurement Strategy

General Strategy

- 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



Select VBF Topology

- 2 jets with a large η separation
- Nothing in the gap between the jets
- Need dedicated VBF trigger

Cuts

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

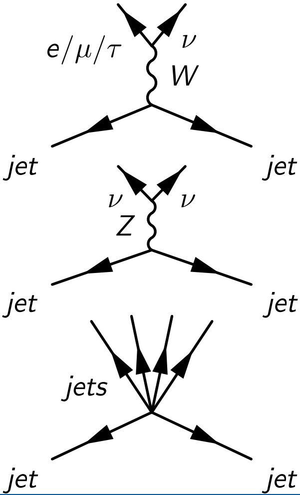
Backgrounds Overview

Main backgrounds:

- W + jets where lepton is missed
  - AM+Patrick cross check
- $Z \to \nu\nu$ + jets
- QCD: Sasha

Data driven W/Z + jets estimation:

- 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/$Z \to \nu\nu$
- Check data/MC shape agreement in control regions
- Assume MC signal/control ratio is the same as that in data



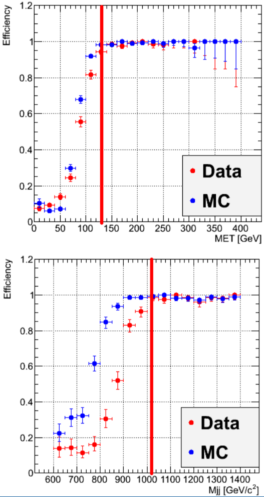
Datasets and Trigger

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 $|\Delta\eta_{j_1 j_2}| > 3.5$
- IC heavily involved in design of the trigger

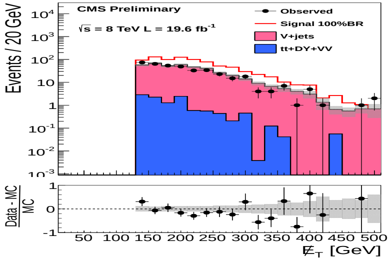


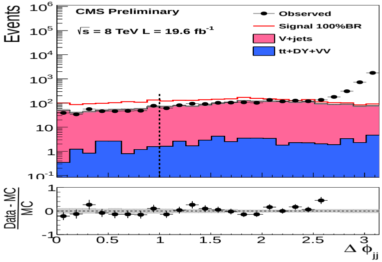
Signal Event Selection

Signal Region Selection:

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

Data MC difference is QCD





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W+jets Background Estimation

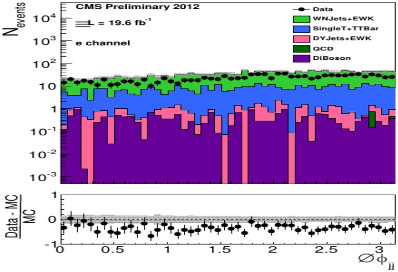
Background estimation formula:

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

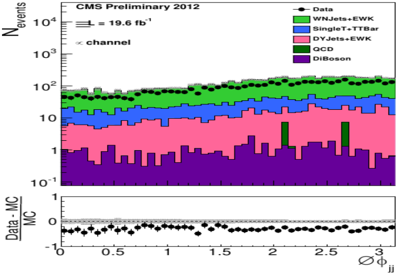
$W \to \mu/e$ Control Region Selection:

- 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:

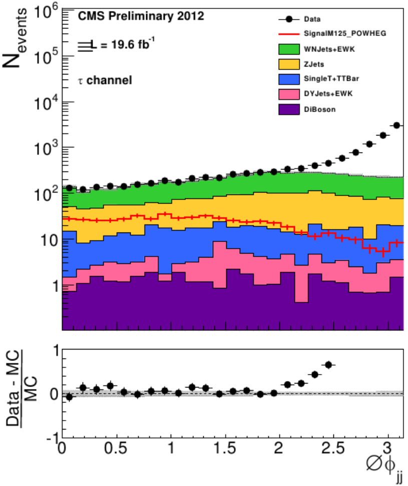
$$N^{S}_{data}(W \to \tau\nu) = (N^{C}_{data} - N^{C}_{bkg})\frac{N^{S}_{W\to\tau\nu MC}}{N^{C}_{W\to\tau\nu MC}}$$

$W \to \tau$ 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

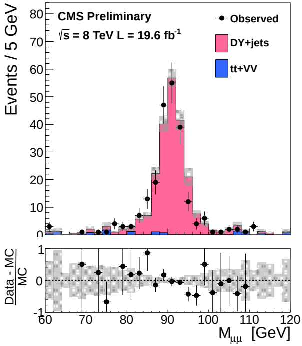
Z+jets background estimation formula:

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

$Z \to \nu\nu$ 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

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

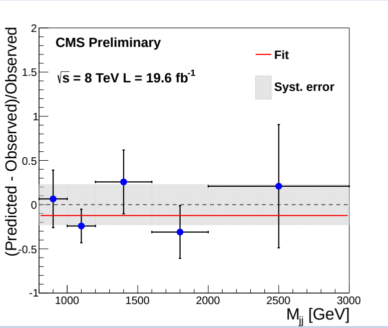


Consistency Tests

Method

- To check W/Z+Jets estimates the $W \to \mu\nu$ 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

$W \to e\nu$ from $W \to \mu\nu$



QCD

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 $\Delta\phi_{jj}$

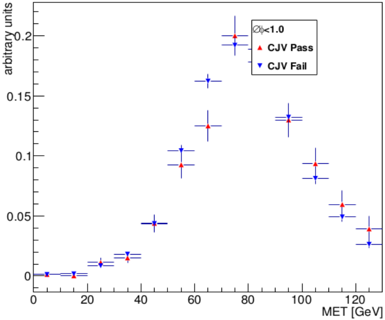
QCD ABCD method:

- Choose 4 regions:

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

- $N_D = N_B N_C / N_A$

- $N_{QCD} = 36.8 \pm 5.6(stat.) \pm 30.6 syst.$

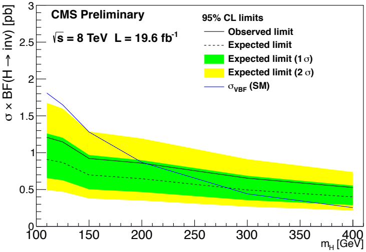


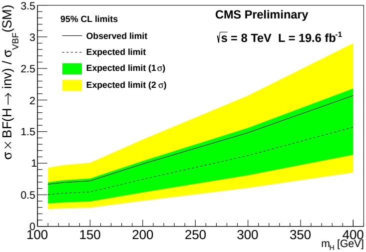
Uncertainties

Background	Source	Uncertainty
$Z \to \nu\nu$	Statistics in control region	29%
	MC statistics	14%
	Theory uncertainty	20%
	Jet/MET scale/resolotion	5%
$W \to \mu\nu$	Statistics in control region	5%
	MC statistics	10%
	Theory uncertainty	20%
	Jet/MET scale/resolotion	4%
$W \to e\nu$	Statistics in control region	10%
	MC statistics	10%
	Theory uncertainty	20%
	Jet/MET scale/resolotion	$^{+5}_{-11}\%$
$W \to \tau\nu$	Statistics in control region	30%
	MC statistics	20%
	Theory uncertainty	20%
	Jet/MET scale/resolotion	$^{+16}_{-2}\%$
	Tau ID efficiency	8%
	Electron contamination	5%

Background	Source	Uncertainty
QCD	Statistics in control region	2%
	MC statistics (background)	2%
	Jet/MET scale/resolution	$^{+45}_{-75}\%$
	MET shape	35%
Other backgrounds	Luminosity	4%
	MC statistics	10 %
	Jet/MET scale/resolution	28-81%
	Cross-section uncertainty	8-20%
Signal	MC statistics	10%
	Jet/MET scale/resolution	11%
	PDF uncertainty	5%
	QCD scale uncertainty	4%

Results



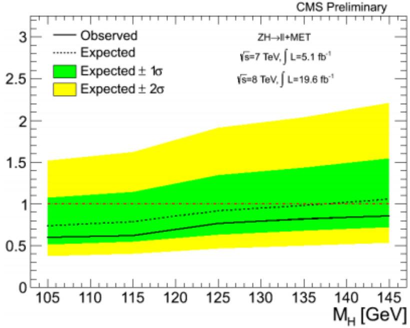


- Expected $339 \pm 36(\textit{stat.}) \pm 50(\textit{syst.})$ events, observed 390 events
- Limits produced with standard CMS Higgs combination package
- 95% CL observed (expected) limit on the invisible BR for 125 GeV: 69(53)%

ZH→invisible

Current ZH→ invisible analyses

- The Higgs to invisible analysis is also done in the ZH channel where the Z boson decays to two leptons (HIG-13-018)
  - 95% CL observed (expected) limit on the invisible BR for 125 GeV: 75(91%)
- A further analysis where the Z boson decays to two b quarks is in progress (HIG-13-028)



Combining the ZH and VBF channels

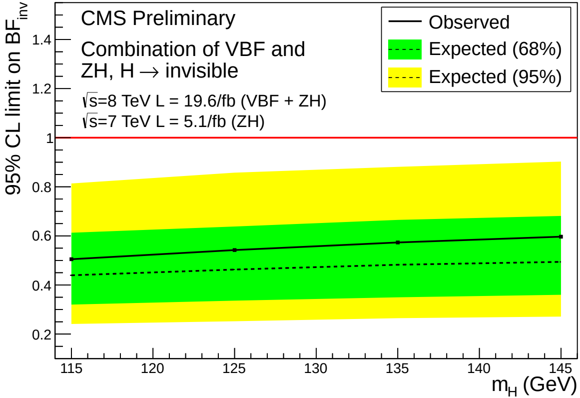
Datacards

- VBF and ZH analysis have datacards at different Higgs boson mass points
- For the VBF channel only the signal yield is Higgs boson mass dependent
- New datacards can therefore be made by interpolating the signal yields (details in backup)

Combination method

- These new datacards were combined with the ZH cards using the standard Higgs group combination tool
- Luminosity uncertainties are considered correlated between analyses
- All other uncertainties are considered to be uncorrelated (see discussion later)

Preliminary Results



- Observed (expected) limit at 125 GeV is 54(46)%
- Made public through analysis twikis

Improvements for Paper

Consideration of uncertainties

- Current VBF channel datacards do not consider correlations between uncertainties
  - New datacards are being produced which separate out the uncertainty sources
- The following uncertainties will be considered correlated between the two channels
  - luminosity, jet energy scale and resolution, met scale, pdf uncertainties

W$\rightarrow \tau\nu$ background

- Disagreement seen between IC cross-check and main analysis
  - Disagreement found to be from different jet smearing methods
  - Work is being done to synchronise these methods

Summary

Current Status

- A limit has been placed on the invisible branching fraction of the Higgs boson produced in the VBF channel:
  - Observed(Expected) limit at 95% CL is 69(53)% for a 125 GeV Higgs
- This result has been combined with the ZH$\rightarrow$ll+invisible channel
  - Observed(Expected) limit at 95% CL is 54(46)% for a 125 GeV Higgs
- This combined result is the current strongest limit on BR(invisible)

Plans

- A paper for the prompt data is being written with the improvements discussed above
- An improved analysis is planned using the parked data

Parked Data

- IC pushed strongly for data parking
- 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

BACKUP

Objects

VBF Selections

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

MET

- Using Type $0 + 1$ Corrections

Electrons

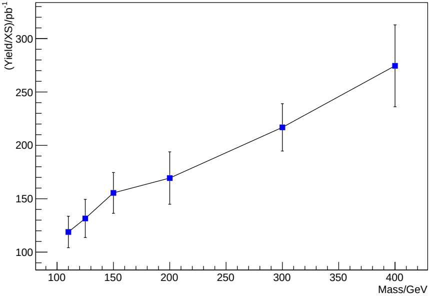
- Veto:
  - $p_T > 10 GeV$, $|\eta < 2.5|$
  - rel PF Iso < 0.2
- Tight:
  - $p_T > 20 GeV$, $|\eta < 2.5|$

Muons

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

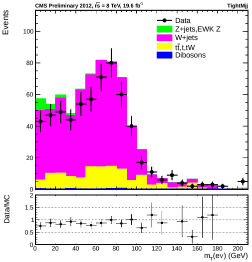
Signal Yield interpolation

- $N_{Signal} = eff. \times acc. \times \mathcal{L}\sigma$
- Luminosity is constant
- Yield over cross-section is thus proportional to efficiency times acceptance
- Signal yields were produced at 115, 125(to cross-check), 135 and 145 GeV for the VBF channel
  - Cross-sections from LHC-HXSWG were used

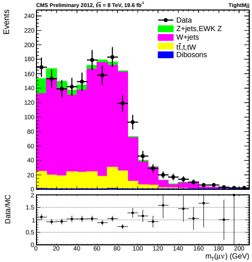


W+jets background m_T plots

$e\nu$



$\mu\nu$



$\tau\nu$