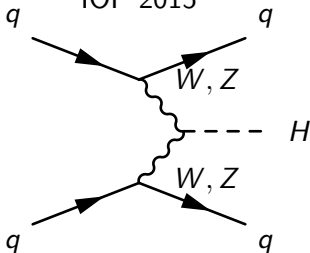


## Searches for invisible decays of the Higgs boson with the CMS detector

P. Dunne - Imperial College London  
on behalf of the CMS Collaboration

IOP 2015

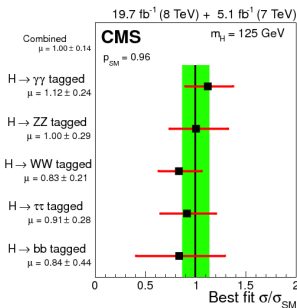


## Outline

- ▶ Why look for invisibly decaying Higgs bosons?
- ▶ Higgs to invisible at CMS
- ▶ New search in the vector boson fusion (VBF) channel
- ▶ Combination with ZH channel

## Why look for invisibly decaying Higgs bosons?

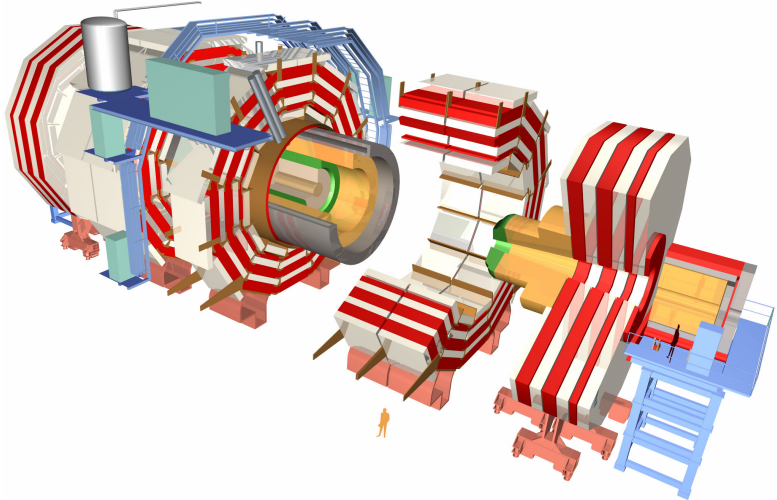
- ▶ SM compatible 125 GeV Higgs boson observed by ATLAS and CMS
  - ▶ SM compatible does not mean BSM incompatible



CMS-HIG-14-009

- ▶ Many BSM theories predict Higgs to invisible, e.g. SUSY
  - ▶ Often provide good DM candidates

## CMS



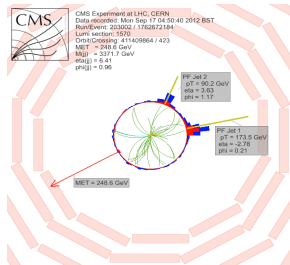
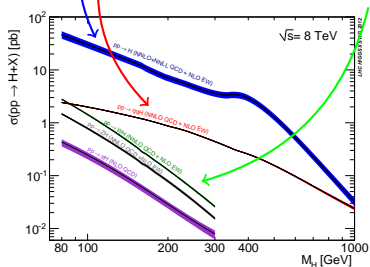
## Higgs to invisible at CMS

- ▶ Indirect: Look for effect of BSM Higgs decays on Higgs total width
- ▶ Direct: Use channels where the Higgs recoils against a visible system

ggH: high rate, no visible products (unless ISR/FSR, i.e. mono-X)

VBF: medium rate, jets+MET final state

ZH: low rate, leptons/b jets+MET final state

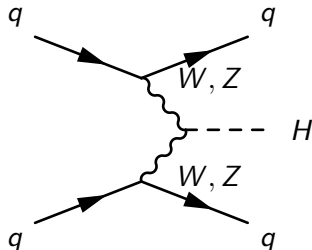


## CMS VBF History

- ▶ CMS ran two sets of triggers in 2012:
  - ▶ prompt: reconstructed immediately
  - ▶ parked: looser thresholds, reconstructed in long shutdown
- ▶ CMS published result using full run I prompt dataset
  - ▶ VBF only observed(expected) 95% C.L. limit on  $B(H \rightarrow inv)$  for  $m_H=125$  GeV is 0.65 (0.49)
- ▶ New analysis presented today uses full run I parked dataset

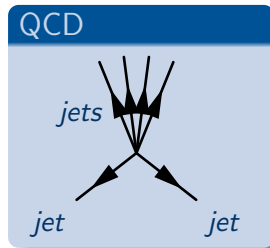
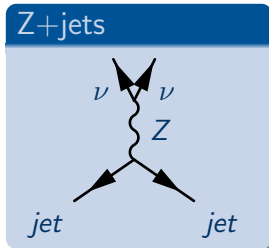
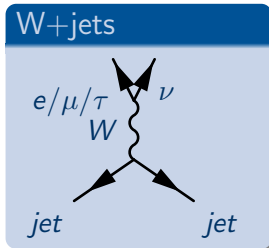
## VBF: strategy

- ▶ Select events with two VBF jets + MET:
  - ▶ no colour connection between jets means large  $\eta$  gap
- ▶ QCD background difficult to model:
  - ▶ use tight selection to remove



## VBF: selection

- ▶ Main backgrounds:  $W \rightarrow \ell\nu / Z \rightarrow \nu\nu + \text{jets}$ , QCD, top
  - ▶ Veto events with leptons present
  - ▶ Require MET to be well separated from any jets





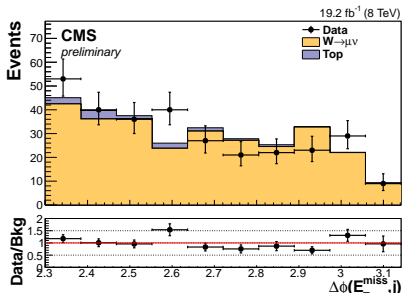
## VBF: background estimation

- ▶ All major backgrounds have data driven normalisation

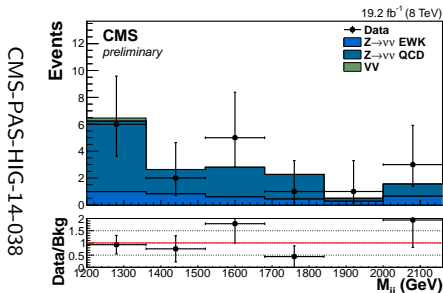
$$N_{bkg}^{sig} = \frac{(N_{obs}^{control} - N_{other\ bkgs}^{control})}{N_{MC}^{control}} \cdot N_{MC}^{sig}$$

- ▶ Most backgrounds from missed lepton or misreconstructed jet
  - ▶ use control region where object is reconstructed

$W \rightarrow \mu\nu$  control region



$Z \rightarrow \nu\nu$  control region



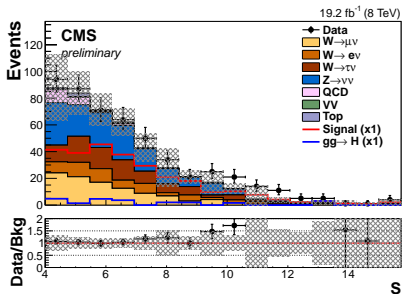
CMS-PAS-HIG-14-038

## VBF results

Total background	$439.7 \pm 41.0(\text{stat.}) \pm 55.8(\text{syst.})$
VBF H(inv.) assuming $B(H \rightarrow \text{inv})=100\%$	$273.4 \pm 31.2(\text{syst.})$
ggF H(inv.) assuming $B(H \rightarrow \text{inv})=100\%$	$22.6 \pm 15.6(\text{syst.})$
Observed data	508

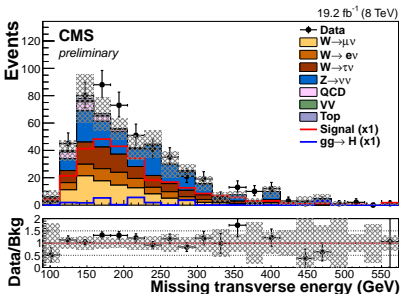
- Compatible with the background hypothesis

Signal region



CMS-PAS-HIG-14-038

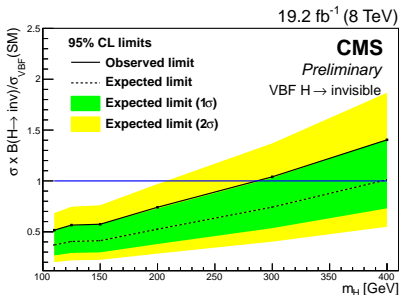
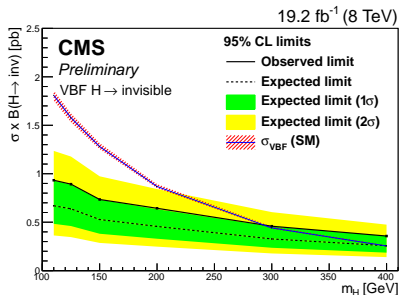
Signal region



CMS-PAS-HIG-14-038

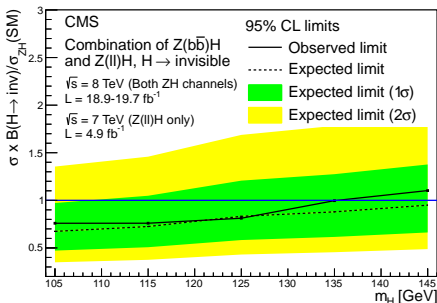
## VBF limits

- ▶ Perform a single bin counting experiment using  $CL_S$  method
- ▶ Observed(expected) 95% C.L. limit on  $B(H \rightarrow inv)$  for  $m_H=125$  GeV is 57(40)%



## ZH: summary

- Search also performed in  $ZH \rightarrow \ell\ell inv$  and  $ZH \rightarrow b\bar{b} inv$  channels at CMS
- Observed(expected) 95% C.L. limit on  $B(H \rightarrow inv)$  for  $m_H=125$  GeV is **81(83)%**



Eur. Phys. J. C 74 (2014) 2980

## Combined Results

- ▶ Separate limits on  $\sigma \times B(H \rightarrow inv)$  are combined at 125 GeV
- ▶ Assume SM production cross-sections to interpret as a limit on  $B(H \rightarrow inv)$

Observed (expected) limits  
on  $B(H \rightarrow inv)$  at 95% C.L.  
for  $m_H = 125$  GeV

Channel	Limit/%
VBF	57(40)
ZH( $\ell\ell + bb$ )	81(83)
VBF + ZH	47(35)

## Conclusions

- ▶ A direct search for Higgs boson decays to invisible final states has been carried out in the VBF channel
  - ▶ No significant excesses are seen over the background predictions
- ▶ This has been combined with the results in the  $Z(\ell\ell)H$  and  $Z(bb)H$  channels
- ▶ The combined limit is 47(35)% observed (expected) at 95% C.L. for  $m_H = 125\text{GeV}$

## Backup

## References

- ▶ CMS Higgs combination - CMS-HIG-14-009
- ▶ CMS VBF Higgs to invisible parked data PAS - CMS-PAS-HIG-14-038
- ▶ CMS Higgs to invisible paper - Eur. Phys. J. C 74 (2014) 2980



## Comparison to recent ATLAS result

- ▶ We see an excess where ATLAS see a deficit:
  - observed can move the post-fit expected limit
  - were we to see a similar deficit our expected limit improves by  $\sim 10\%$
- ▶ ATLAS use a single data driven normalisation factor for all  $V$ +jets backgrounds
  - statistical uncertainty on the factor is therefore lower
  - reducing our  $Z \rightarrow \nu\nu$  statistical uncertainty to the level we see in  $W \rightarrow \mu\nu$  our expected limit improves by  $\sim 10\%$

## W+jets

- ▶  $W \rightarrow e/\mu\nu$  control region formed by swapping lepton veto for  $e/\mu$  requirement
- ▶  $W \rightarrow \tau\nu$  control region formed by requiring a hadronic tau
  - not many events with hadronic taus, need to loosen requirements
  - assign a 20% systematic to  $W \rightarrow \tau\nu$  to compensate

$$N_{bkg}^{sig} = (N_{obs}^{control} - N_{other\ bkgs}^{control}) \cdot \frac{N_{MC}^{sig}}{N_{MC}^{control}}$$

$W \rightarrow \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \rightarrow e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \rightarrow \tau\nu$	$94.6 \pm 13.1 \pm 23.8$

## Z+jets

- ▶ Use  $Z \rightarrow \mu\mu$  MC ignoring muons to emulate  $Z \rightarrow \nu\nu$
- ▶ Correct for difference in cross-section
- ▶ Efficiency correction takes into account EWK vs QCD difference

$$N_S^{Z \rightarrow \nu\nu} = \left( N_C^{Data} - N_C^{bkg} \right) \cdot \frac{\sigma(Z \rightarrow \nu\nu)}{\sigma(Z \rightarrow \mu\mu)} \cdot \frac{\epsilon_S^{ZMC}}{\epsilon_C^{ZMC}}$$

$Z \rightarrow \nu\nu$	$158.1 \pm 37.3 \pm 21.2$
------------------------	---------------------------

## QCD

- ▶ Take shape from region with third jet near MET
- ▶ Normalise in sideband region
  - normalisation highly selection dependent
  - parameterise as function of selection and extrapolate
- ▶ Final estimate  $17 \pm 14$

## Other backgrounds

- ▶ Taken from MC

top	$5.5 \pm 1.8$
VV	$3.9 \pm 0.7$

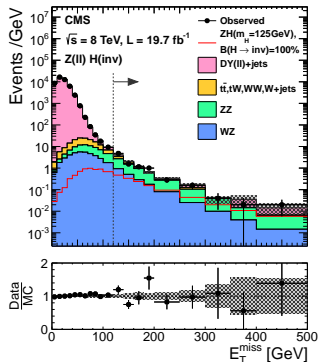
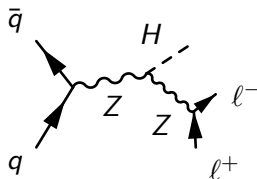
## Z( $\ell\ell$ )H outline

### Signal Topology and Selection

- ▶ Two same flavour opposite sign electrons or muons
  - $p_T > 20$  GeV,  $|M_{\ell\ell} - m_Z| < 15$  GeV
- ▶ Large MET
  - $MET > 120$  GeV

### Backgrounds and Rejection Cuts

- ▶  $ZZ(\ell\nu\nu)+\text{jets}$ ,  $WW(\ell\nu\nu)+\text{jets}$
- ▶  $WZ(\ell\nu\ell\ell)+\text{jets}$ 
  - Veto events with  $>3$  leptons,  $p_T > 10$  GeV
- ▶  $Z(\ell\ell)+\text{jets}$ 
  - MET cut, MET- $\ell\ell$  balance requirement
- ▶  $t\bar{t}$ , single top,  $W(\ell\nu)$ , QCD
  - $\leq 1$  jet,  $p_T > 30$  GeV
  - no b-tagged jets,  $p_T > 30$  GeV



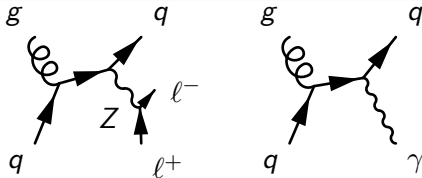
## $Z(\ell\ell)H$ background estimation

### $ZZ(\ell\nu\nu)+\text{jets}$ and $WZ(\ell\nu\ell\ell)+\text{jets}$

- ▶ Estimated from MC prediction

### $Z(\ell\ell)+\text{jets}$

- ▶ Estimated from photon + jets events
  - Photon  $p_T$  spectrum reweighted to match Z spectrum



### $WW(\ell\nu\ell\nu)+\text{jets}$ , single top, $t\bar{t}$ , $Z(\tau\tau)$

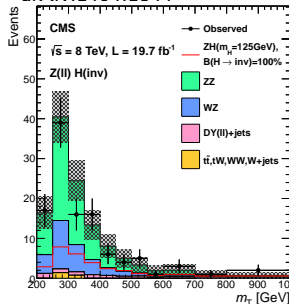
- ▶ Estimated from  $e\mu$  events and Z peak sidebands:
  - $m_{\ell\ell}$  40-70 and 110-200 GeV
  - $N_{\ell\ell}^{sig} = N_{e\mu}^{sig} \cdot N_{\ell\ell}^{SB} / N_{e\mu}^{SB}$

## $Z(\ell\ell)H$ results

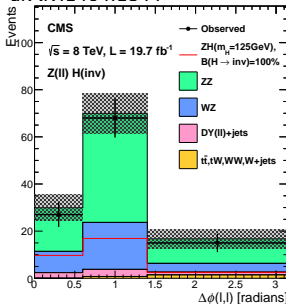
Process		$\sqrt{s} = 7\text{TeV}$		$\sqrt{s} = 8\text{TeV}$	
		ee	$\mu\mu$	ee	$\mu\mu$
0 jets	Total backgrounds	$8.7 \pm 6.5$	$11.0 \pm 3.3$	$37.4 \pm 3.7$	$51.6 \pm 4.8$
	ZH(125)	$2.3 \pm 0.2$	$3.1 \pm 0.3$	$10.3 \pm 1.2$	$14.7 \pm 1.5$
	Observed data	9	10	36	46
S/B for $B(H \rightarrow \text{inv})$ 100%		0.26	0.28	0.28	0.24
1 jet	Total backgrounds	$2.6 \pm 0.7$	$2.8 \pm 0.9$	$10.6 \pm 4.2$	$13.8 \pm 5.8$
	ZH(125)	$0.4 \pm 0.1$	$0.5 \pm 0.1$	$1.6 \pm 0.2$	$2.5 \pm 0.3$
	Observed data	1	4	11	17
S/B for $B(H \rightarrow \text{inv})$ 100%		0.15	0.18	0.15	0.18

- Limits obtained from a 2D fit to  $m_T$  and  $\Delta\phi(\ell\ell)$
- 1D fit to  $m_T$  for 7 TeV data
- Assuming SM Higgs production cross-section and acceptance:
  - observed(expected) 95% C.L. limit on  $B(H \rightarrow \text{inv})$  for  $m_H=125$  GeV is 83(86)%

arXiv:1404.1344



arXiv:1404.1344



## Z(bb)H outline and backgrounds

### Signal Topology and Selection

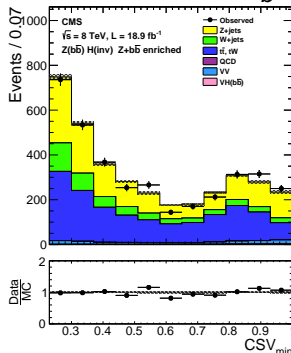
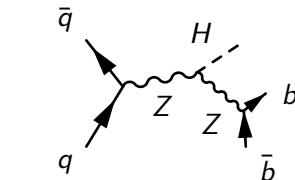
- ▶ Two b-tagged jets:
  - $p_T > 30/60$  GeV,  $p_{Tjj} > 100 - 130$  GeV
- ▶ Three bins in MET
  - 100-130, 130-170,  $> 170$  GeV

### Backgrounds and Rejection Cuts

- ▶  $Z(\nu\nu)+\text{jets}$ ,  $W(\ell\nu)+\text{jets}$
- ▶  $ZZ(\nu\nu b\bar{b})$
- ▶  $WZ(\ell\nu b\bar{b})$ ,  $t\bar{t}$ , single top
  - Veto events with leptons,  $p_T > 15$  GeV
- ▶ QCD
  - MET quality requirements

### Background estimation - data normalised MC

- ▶ Normalisation from a simultaneous fit in seven control regions:
  - Z+jets (0,1,2 b-jets), W+jets (0,1,2 b-jets),  $t\bar{t}$



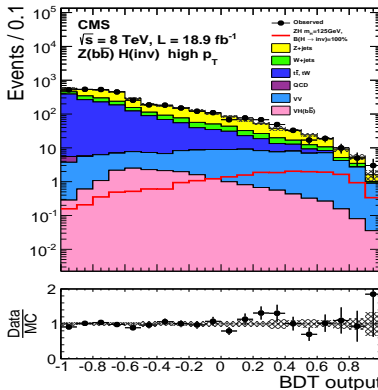
arXiv:1404.1344



## $Z(b\bar{b})H$ results

Process	High $p_T(V)$	Intermediate $p_T(V)$	Low $p_T(V)$
Total backgrounds	$181.3 \pm 9.8$	$64.8 \pm 4.1$	$40.5 \pm 4.1$
$Z(b\bar{b})H(\text{inv})$	$12.6 \pm 1.1$	$3.6 \pm 0.3$	$1.6 \pm 0.1$
Observed data	204	61	38

- Multivariate analysis (BDT):
  - performed for each mass hypothesis and boost region
- Limits from a fit to the BDT output distribution
- Assuming SM Higgs production cross-section and acceptance:
  - observed(expected) 95% C.L. limit on  $B(H \rightarrow \text{inv})$  for  $m_H=125$  GeV is 182(199)%



arXiv:1404.1344