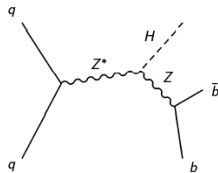
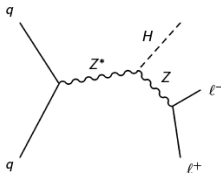
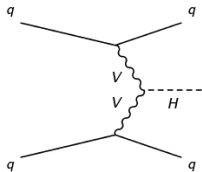


Searches for invisible decay modes of the Higgs boson with the CMS detector

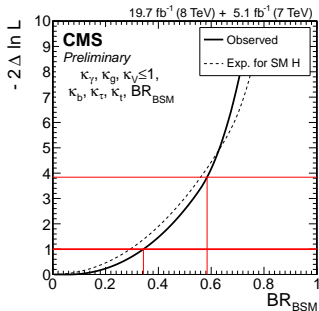
P. Dunne - Imperial College London
on behalf of the CMS Collaboration
PANIC 2014 - 26/08/2014



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



CMS-PAS-HIG-14-009

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

Direct and Indirect Searches

Indirect searches

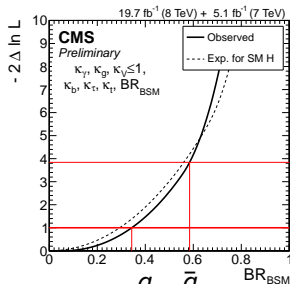
- ▶ BSM Higgs decays affect the total Higgs width:

$$- \Gamma_{tot} = \Gamma_{tot}^{SM} \cdot \frac{\sum_x^{obs} \kappa_x^2 \cdot BR_x^{SM}}{1 - BR_{BSM}}, \quad \kappa_x^2 = \frac{\Gamma_x^{obs}}{\Gamma_x^{SM}}$$

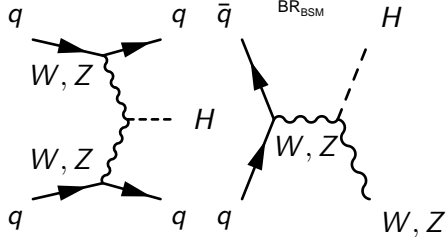
- ▶ Visible decays can, therefore, constrain the invisible branching fraction

Direct searches

- ▶ Direct searches must be performed in channels where the Higgs recoils against a visible system
- ▶ We look in the VBF (left) and ZH (right) channels
 - For ZH we study the case where the Z decays to two leptons $Z(\ell\ell)H$ or two b quarks $Z(bb)H$



CMS-PAS-HIG-14-009



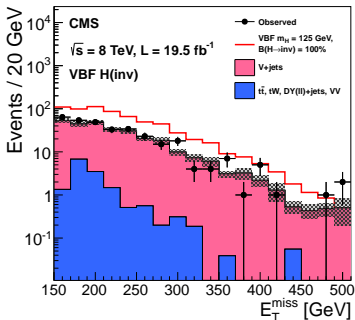
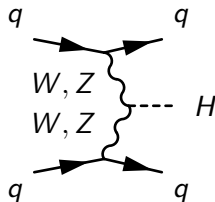
VBF outline

Signal Topology and Selection

- ▶ Two jets with large rapidity separation and missing transverse momentum (MET)
 - 2 jets, $p_T > 50\text{GeV}$, $\eta_{j1} \cdot \eta_{j2} < 0$, $\Delta\eta_{jj} > 4.2$
 - $M_{jj} > 1100\text{GeV}$, $\Delta\phi_{jj} < 1.0$
 - $MET > 130\text{GeV}$

Backgrounds and Rejection Cuts

- ▶ $W \rightarrow \ell\nu + \text{jets}$:
 - Veto any events with leptons with $p_T > 10\text{ GeV}$
- ▶ $Z \rightarrow \nu\nu + \text{jets}$: Irreducible
- ▶ QCD multijet events:
 - Veto events with jets with $p_T > 30\text{ GeV}$ between the two selected jets (CJV)
- ▶ Minor backgrounds from: $t\bar{t}$, single top, diboson and $Z \rightarrow \ell\ell + \text{jets}$



arXiv:1404.1344

VBF background estimation

Z+jets - Estimate using $Z \rightarrow \mu\mu$ +jets events

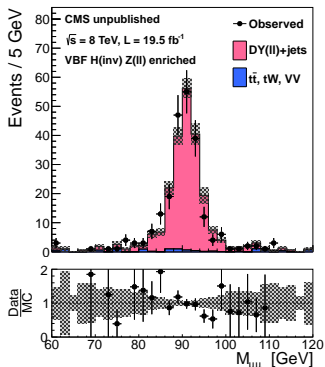
- Sig. sel.+two muons $60 < m_{\mu\mu} < 120$ GeV
- ▶ Control \rightarrow signal extrapolation factor from MC
- ▶ $N_{Z \rightarrow \mu\mu} = 99 \pm 29(\text{stat.}) \pm 25(\text{syst.})$

W+jets - Estimate using $W \rightarrow \ell\nu$ +jets events

- Sig. sel. + require one $e/\mu/\tau$
- ▶ Control \rightarrow signal extrapolation factor from MC
- ▶ $N_{W \rightarrow e\nu} = 63 \pm 9(\text{stat.}) \pm 18(\text{syst.})$
- ▶ $N_{W \rightarrow \mu\nu} = 67 \pm 5(\text{stat.}) \pm 16(\text{syst.})$
- ▶ $N_{W \rightarrow \tau\nu} = 53 \pm 18(\text{stat.}) \pm 18(\text{syst.})$

QCD - Use "ABCD method" in MET and CJV

- ▶ $N_{QCD} = 30.9 \pm 1.6(\text{stat.}) \pm 23.0(\text{syst.})$



CMS-TWIKI-HIG-13-030

CJV

pass

fail

B	A
D	C

<130

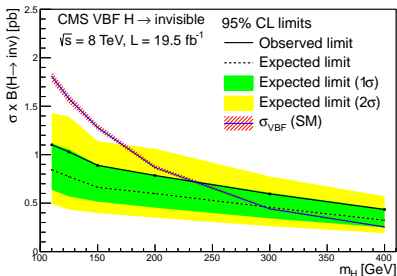
>130

MET

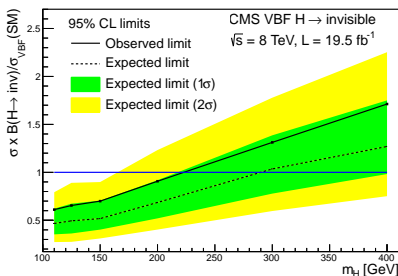
VBF results

Total background	$332 \pm 35(\text{stat.}) \pm 45(\text{syst.})$
VBF $H(\text{inv.})$ assuming $B(H \rightarrow \text{inv})=100\%$	$210 \pm 30(\text{syst.})$
ggF $H(\text{inv.})$ assuming $B(H \rightarrow \text{inv})=100\%$	$14 \pm 11(\text{syst.})$
Observed data	390

- ▶ Set limits on $\sigma \times B(H \rightarrow \text{inv})$
 - Perform a single bin counting experiment using CL_S method
- ▶ 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 65(49)%



arXiv:1404.1344



arXiv:1404.1344

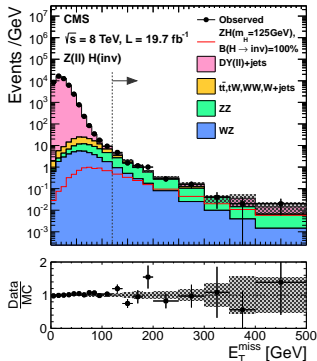
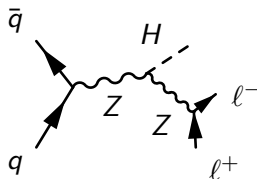
Z($\ell\ell$)H outline

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



arXiv:1404.1344

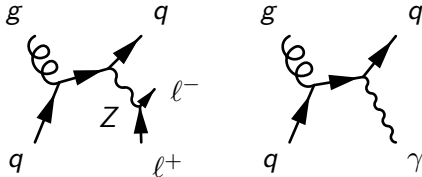
$Z(\ell\ell)H$ background estimation

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



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

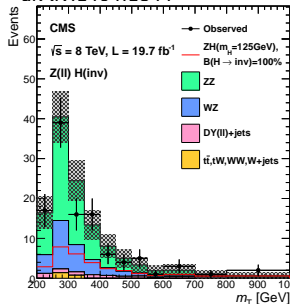
- ▶ Estimated from $e\mu$ events and Z peak sidebands:
 - $m_{\ell\ell}$ 40-70 and 110-200 GeV
 - $N_{\ell\ell}^{sig} = N_{e\mu}^{sig} \cdot N_{\ell\ell}^{SB} / N_{e\mu}^{SB}$

Z($\ell\ell$)H results

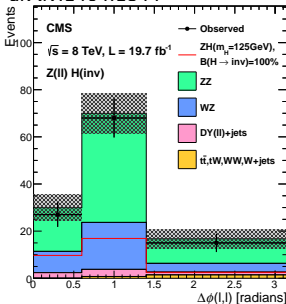
Process		$\sqrt{s} = 7\text{TeV}$		$\sqrt{s} = 8\text{TeV}$	
		ee	$\mu\mu$	ee	$\mu\mu$
0 jets	Total backgrounds	8.7 ± 6.5	11.0 ± 3.3	37.4 ± 3.7	51.6 ± 4.8
	ZH(125)	2.3 ± 0.2	3.1 ± 0.3	10.3 ± 1.2	14.7 ± 1.5
	Observed data	9	10	36	46
S/B for B(H \rightarrow inv) 100%		0.26	0.28	0.28	0.24
1 jet	Total backgrounds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

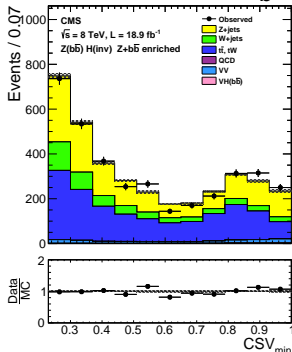
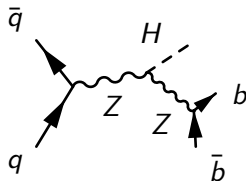
- ▶ Two b-tagged jets:
 - $p_T > 30/60$ GeV, $p_{Tij} > 100 - 130$ GeV
- ▶ Three bins in MET
 - 100-130, 130-170, > 170 GeV

Backgrounds and Rejection Cuts

- ▶ $Z(\nu\nu)+$ jets, $W(l\nu)+$ jets
- ▶ $ZZ(\nu\nu b\bar{b})$
- ▶ $WZ(l\nu b\bar{b})$, $t\bar{t}$, 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), $t\bar{t}$

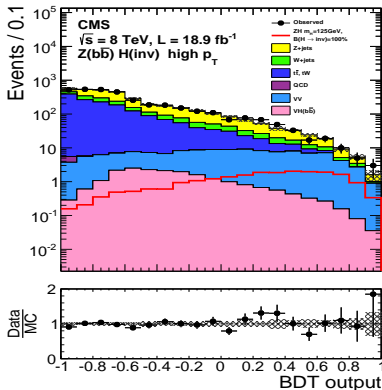


arXiv:1404.1344

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

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

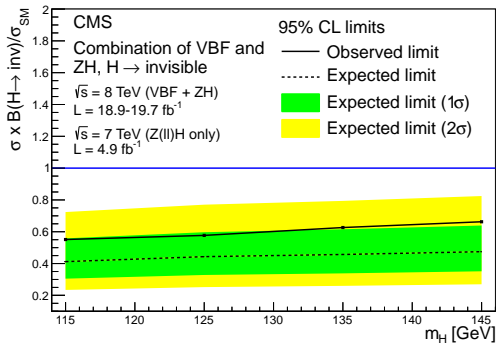
- ▶ Multivariate analysis (BDT):
 - performed for each mass hypothesis and boost region
- ▶ Limits from a fit to the BDT output distribution
- ▶ Assuming SM Higgs production cross-section and acceptance:
 - observed(expected) 95% C.L. limit on $B(H \rightarrow inv)$ for $m_H=125$ GeV is 182(199)%



arXiv:1404.1344

Combined Results

- ▶ The individual limits on $\sigma \times B(H \rightarrow inv)$ from the three channels are combined
 - SM production cross-sections are used to interpret this as a limit on $B(H \rightarrow inv)$



arXiv:1404.1344

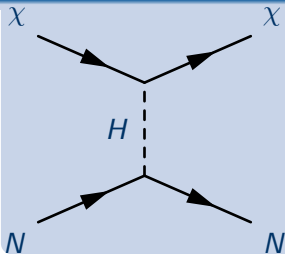
Observed (expected) limits on
 $B(H \rightarrow inv)$ at 95% C.L. for
 $m_H = 125$ GeV

Channel	Limit/%
VBF	65(49)
ZH($ll+bb$)	81(83)
VBF + ZH	58(44)

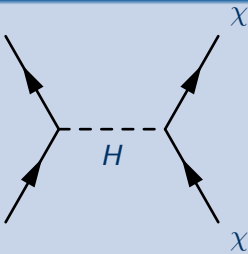
Signatures of Dark Matter (DM)

- ▶ If DM couples to the Higgs the following diagrams are possible

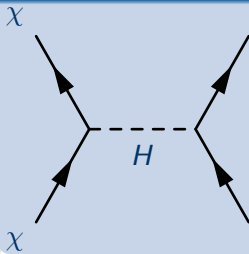
Direct Detection - e.g. LUX



Invisible Higgs - LHC



Annihilation - e.g. WMAP



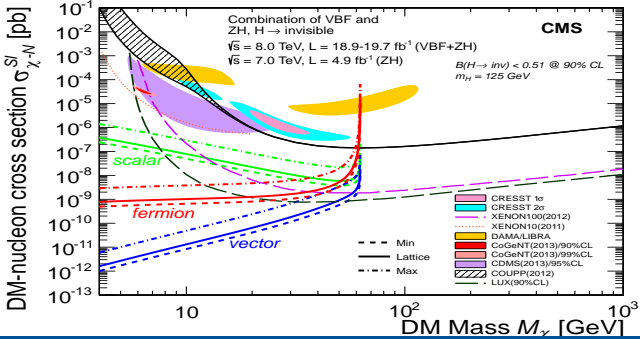
- ▶ Limits on $\mathcal{B}(H \rightarrow \text{inv})$ therefore constrain Higgs Portal DM models
 - These constraints are directly comparable to those from other experiments



Dark Matter Interpretation - Results

- ▶ Use an effective field theory Higgs Portal model which translates $B(H \rightarrow inv)$ into a DM-nucleon cross-section (details in backup)
- ▶ At 90% C.L. the CMS limit on $B(H \rightarrow inv)$ is 51% for a 125 GeV Higgs
- ▶ Consider three DM spin scenarios: scalar, vector, Majorana fermion:
 - CMS limits shown in green, blue and red respectively

arXiv:1404.1344



Min, lattice and max are varying values of Higgs-nucleon coupling (see backup)

$B(H \rightarrow inv)$ gives important exclusion in the $M_\chi < m_h/2$ region

Conclusions

- ▶ Direct searches for Higgs boson decays to invisible final states have been carried out using the 2011 and 2012 CMS data sets:
 - The VBF, $Z(\ell\ell)H$ and $Z(bb)H$ channels have been considered
 - The mass range searched in is 105-400 GeV
- ▶ No significant excesses are seen over the background predictions
- ▶ The combined limit is 58(44)% observed (expected) at 95% C.L. for $m_H = 125\text{GeV}$
 - This is the most sensitive direct Higgs to invisible limit to date
 - It is broadly comparable with CMS indirect limits
- ▶ A Higgs portal dark matter interpretation of the above results has been presented
 - The results are competitive with direct DM detection experiments in the low DM mass region

References

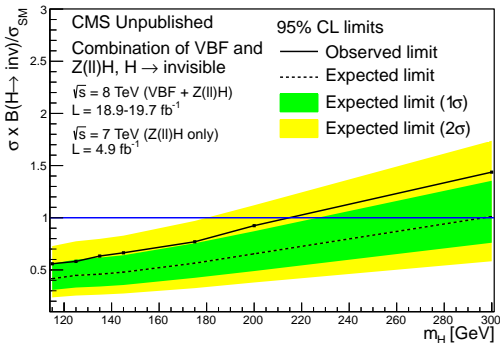
- ▶ CMS Higgs combination - CMS-PAS-HIG-14-009
- ▶ CMS Higgs to Invisible paper - arXiv:1404.1344
- ▶ CMS TWIKI with addition Higgs to Invisible results - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13030PubTWiki>



Backup

High mass combination

- ▶ $Z(\ell\ell)H(\text{inv})$ and VBF searches both go up to at least $m_H=300$ GeV
- ▶ The same combination method as used above was used to combine these two channels between 115 and 300 GeV



Other direct Limits

- ▶ ATLAS also produce a limit in the $Z(\ell\ell)H$ channel:
 - observed (expected) 75% (62%) at 95% C.L.

DM model

Formulae

- ▶ EFT model as described in [Phys.Lett. B709 \(2012\) 6569](#)

$$\sigma_{S-N}^{SI} = \frac{4\Gamma_{inv}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma_{V-N}^{SI} = \frac{16\Gamma_{inv} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

$$\sigma_{f-N}^{SI} = \frac{8\Gamma_{inv} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$$

- m_N is the nucleon mass, 0.939 GeV
- f_N is the Higgs-nucleon coupling, central value 0.326, from [Phys. Rev. D 81 \(2010\) 01453](#)
- Min and max values of f_N from MILC collaboration [Phys. Rev. Lett. 103 \(2009\) 122002](#)
- v is the Higgs vacuum expectation, 174 GeV
- $\beta = \sqrt{1 - 4M_\chi^2/m_H^2}$
- $B(H \rightarrow inv.) = \Gamma_{inv}/(\Gamma_{SM} + \Gamma_{inv})$