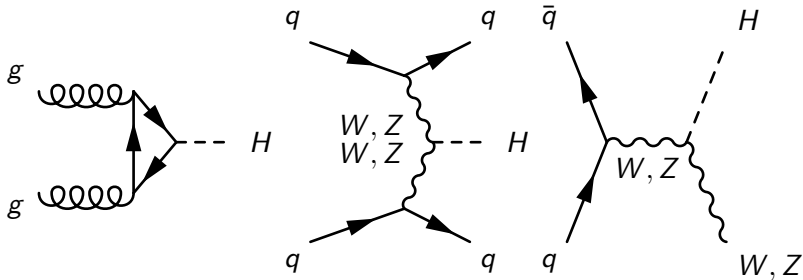


## Latest results on invisibly decaying Higgs bosons

Patrick Dunne - Imperial College London  
on behalf of the ATLAS and CMS Collaborations  
DM@LHC 2016 - 31/03/2016



## Outline

- ▶ How to search for invisibly decaying Higgs bosons:
  - direct and indirect searches
- ▶ Run 1 results from ATLAS and CMS
- ▶ Run 2 results from CMS
- ▶ Projections of future sensitivity
- ▶ nb all limits at 95% CL unless stated otherwise

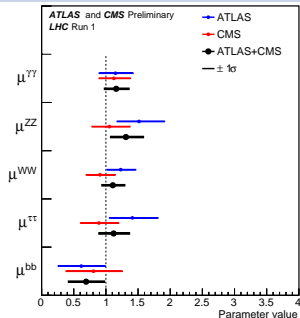
## Why look for invisibly decaying Higgs bosons?

### Theoretical Motivations

- ▶ All SM massive particles get their mass through Higgs boson couplings
- ▶ Why not dark matter?

### Experimental motivation

- ▶ Measurements of the Higgs boson made so far are impressive:
  - Mass measured with 0.2% error
- ▶ A lot of parameters are still relatively unconstrained:
  - Limit on width is  $\sim 4\Gamma_{SM}$
- ▶ Plenty of room for Higgs boson couplings to dark matter



CMS-PAS-HIG-15-002  
ATLAS-CONF-2015-044

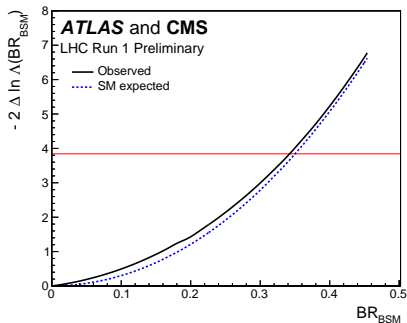
## How to search for invisibly decaying Higgs bosons

### Indirect searches

- ▶ Compare visible width to total width:

$$- \text{BR}_{\text{BSM}} = \frac{\Gamma_H - \Gamma_{\text{vis}}}{\Gamma_H}$$

- ▶ No measurement of  $\Gamma_H$ , need to make an assumption
- Usually assume SM width
- ▶ ATLAS+CMS combination gives an observed (expected) limit on  $\text{BR}_{\text{BSM}}$  of 0.34 (0.35)



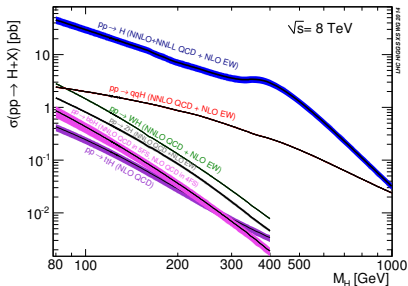
CMS-PAS-HIG-15-002  
ATLAS-CONF-2015-044

## How to search for invisibly decaying Higgs bosons

- ▶ Look for associated Higgs boson products plus  $E_T^{miss}$

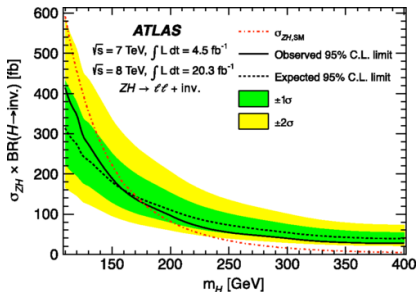
### Production channels

- ▶ VBF mode is most sensitive
  - Second highest rate and distinctive topology
- ▶ Gluon fusion has no visible products, needs ISR
  - High rate, difficult final state
- ▶ VH has clean final states but low rate



## Run 1 ATLAS direct searches - $Z(\ell\ell)H$

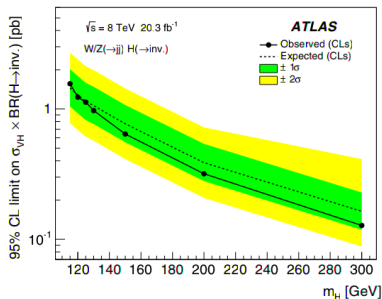
- Selects two leptons opposite large  $E_T^{miss}$
- $E_T^{miss}$  Shape analysis with data driven backgrounds
- Observed (expected) limit on  $\mathcal{B}(H \rightarrow inv.)$  for  $m_H = 125.5$  GeV is 75 (62)%



PRL 112, 201802 (2014)

## Run 1 ATLAS direct searches - $V(\text{had})H$

- Targets  $W/Z \rightarrow qq$  final state
- $E_T^{\text{miss}}$  and dijet  $p_T$  shape analysis with data driven backgrounds
- Observed (expected) limit on  $\mathcal{B}(H \rightarrow \text{inv.})$  for  $m_H = 125$  GeV is 78 (86)%



Eur. Phys. J. C (2015) 75:337

## Run 1 ATLAS direct searches - VBF

- ▶ Select two jets with large  $\Delta\eta$  opposite large  $E_T^{miss}$
- ▶ Counting experiment with data driven background estimation
- $W \rightarrow e\nu$ ,  $W \rightarrow \mu\nu$  and  $W \rightarrow \tau\nu$  and  $Z \rightarrow \nu\nu$  normalisation tied together
- ▶ Observed (expected) limit on  $\mathcal{B}(H \rightarrow inv.)$  for  $m_H = 125$  GeV is 28 (31)%

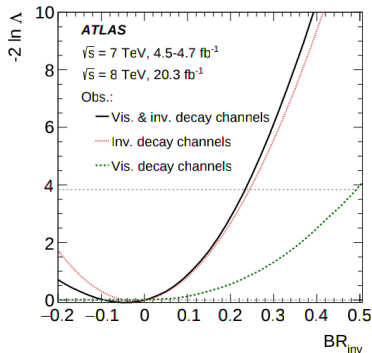
Signal region Process	SR1	SR2a	SR2b
ggF signal	$20 \pm 15$	$58 \pm 22$	$19 \pm 8$
VBF signal	$286 \pm 57$	$182 \pm 19$	$105 \pm 15$
$Z(\rightarrow \nu\nu)+jets$	$339 \pm 37$	$1580 \pm 90$	$335 \pm 23$
$W(\rightarrow \ell\nu)+jets$	$235 \pm 42$	$1010 \pm 50$	$225 \pm 16$
Multijet	$2 \pm 2$	$20 \pm 20$	$4 \pm 4$
Other backgrounds	$1 \pm 0.4$	$64 \pm 9$	$19 \pm 6$
Total background	$577 \pm 62$	$2680 \pm 130$	$583 \pm 34$
Data	539	2654	636

JHEP 01 (2016) 172



## Run 1 ATLAS direct searches - Combination

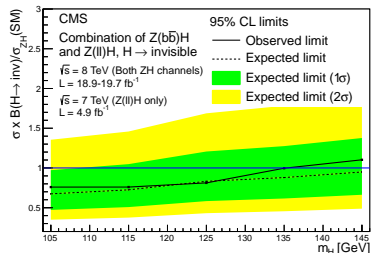
- ▶ Combining searches significantly improves limits
- ▶ Direct searches provide most sensitivity
  - Observed (expected) limit on  $\mathcal{B}(H \rightarrow \text{inv.})$  for  $m_H = 125$  GeV is 25 (27)%
- ▶ Adding indirect results adds assumption on Higgs total width
  - Observed (expected) limit on  $\mathcal{B}(H \rightarrow \text{inv.})$  for  $m_H = 125$  GeV is 23 (24)%



JHEP11(2015)206

## Run 1 CMS direct searches - ZH

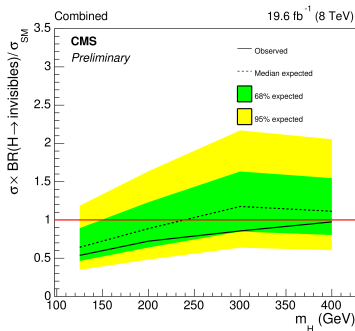
- ▶ Searches in  $Z \rightarrow \ell\ell$  and  $Z \rightarrow b\bar{b}$  channels
- ▶  $Z(\ell\ell)H$  search is a 2D shape analysis with data driven backgrounds
- ▶  $Z(b\bar{b})H$  search is a BDT shape analysis with data driven backgrounds
- ▶ Combined  $ZH$  searches observed (expected) limit on  $\mathcal{B}(H \rightarrow \text{inv.})$  for  $m_H = 125$  GeV is 81 (83)%



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

## Run 1 CMS direct searches - Monojet+V(had)H

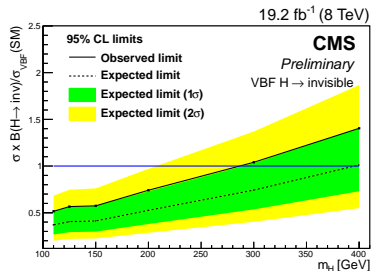
- Search has categories targeting  $V(had)H$  and  $ggH$  production modes
- $E_T^{miss}$  shape analysis with data driven background estimation
- Observed (expected) limit on  $\mathcal{B}(H \rightarrow inv.)$  for  $m_H = 125$  GeV is 53 (62)%



CMS-PAS-EXO-12-055

## Run 1 CMS direct searches - VBF

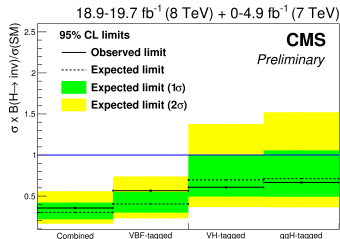
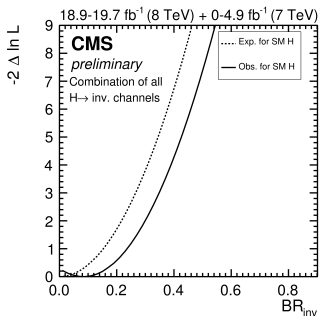
- ▶ Select two jets with large  $\Delta\eta$  separated from large  $E_T^{miss}$
- ▶ Dedicated “parked data” trigger
- ▶ Counting experiment with data driven backgrounds
  - V+jets backgrounds separately normalised
  - If all normalisations had same uncertainty as  $W \rightarrow \mu\nu$  expected limit would be 33%
- ▶ Observed (expected) limit on  $\mathcal{B}(H \rightarrow inv.)$  for  $m_H = 125$  GeV is 57 (40)%



CMS-PAS-HIG-14-038

## Run 1 CMS direct searches - Combination

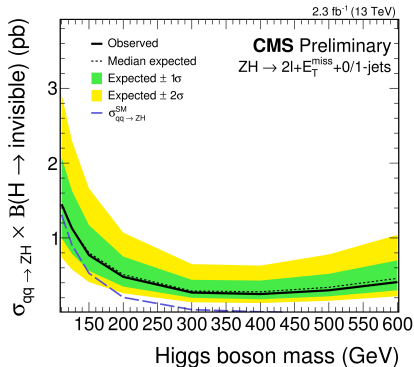
- Combine by production mode as well as full combination
  - ggH-tagged is monojet, VH-tagged is  $Z(\ell\ell)H+Z(bb)H+V(\text{had})H$ , VBF-tagged is VBF
- Obs. (exp.) limit on  $\mathcal{B}(H \rightarrow \text{inv.})$  at  $m_H = 125$  GeV is 36 (30)%



CMS-PAS-HIG-15-012

## Run 2 CMS direct searches - ZH

- Targets  $Z \rightarrow \ell\ell$  final state
- 2D shape analysis with leading backgrounds estimated using MC
- Observed (expected) limit on  $\mathcal{B}(H \rightarrow \text{inv.})$  for  $m_H = 125$  GeV is 124 (124)%



CMS-PAS-HIG-16-008

## Run 2 CMS direct searches - VBF

- Discussion of HIG-16-009

Plot from HIG-16-009

CMS-PAS-HIG-16-009

## Run 2 CMS direct searches - Combination

- Discussion of HIG-16-009

- Plot from HIG-16-009

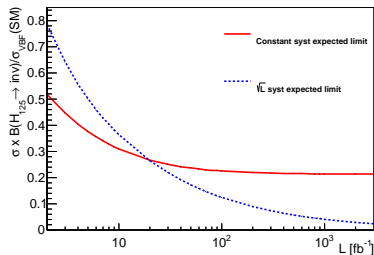
- Plot from HIG-16-009

CMS-PAS-HIG-16-009



## Projections

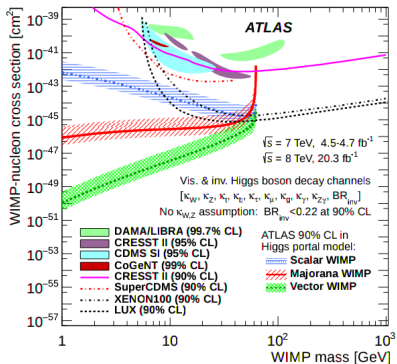
- CMS VBF analysis projected to increased luminosity at 13 TeV
- If systematics scale as  $\sqrt{\mathcal{L}}$  can exclude  $\mathcal{B}(H \rightarrow inv.) = 5\%$  with full LHC dataset



arXiv:1603.07739

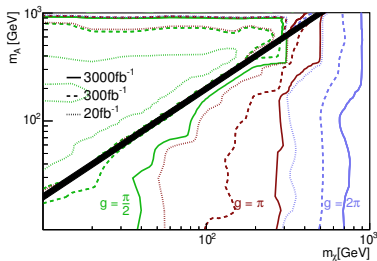
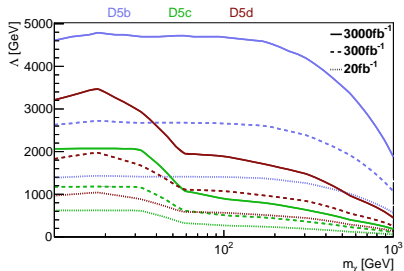
## Dark matter interpretations - Run 1 results

- ▶ Several models for interpreting invisible Higgs limits
- ▶ “Higgs portal” has been quite commonly used
  - Assume 125 GeV Higgs acts as mediator between visible and dark matter sectors
  - Assume scalar, fermion or vector dark matter
- ▶ Scalar dark matter would mix with Higgs boson
  - mixing angle must be small
- ▶ Vector dark matter width goes to infinity as mass decreases



## Dark matter interpretations - Projections

- ▶ Models with electroweak couplings studied: favours VBF channel
- ▶ VBF topology allows looser  $E_T^{miss}$  selection making EFTs valid
- ▶ Also investigate simplified models with scalar/pseudoscalar mediator
- ▶ Projections of CMS VBF channel sensitivity at several luminosities



arXiv:1603.07739

## Summary

- ▶ Both collaborations are sensitive to  $\mathcal{B}(H \rightarrow inv.) \sim 25\%$  with current datasets
  - Current 95% CL upper observed (expected) limits from direct searches are CMS: XX (YY)%, ATLAS: 25 (27) %
  - Combinations of channels allow sensitivity to be greatly improved
- ▶ Projected limit on  $\mathcal{B}(H \rightarrow inv.) \sim 10\text{-}20\%$  from VBF alone by the end of LHC Run 2 and 5% by end of LHC running