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Latest results on invisibly decaying Higgs bosons

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on behalf of the ATLAS and CMS Collaborations
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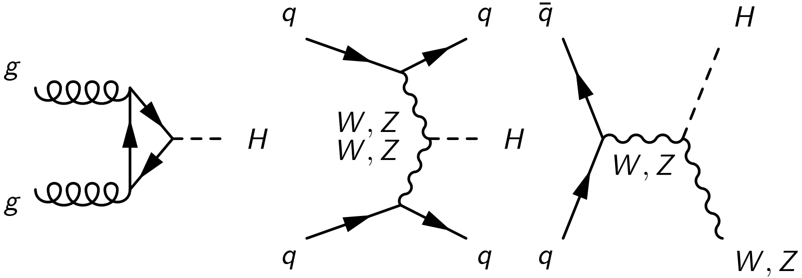


Outline

- 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

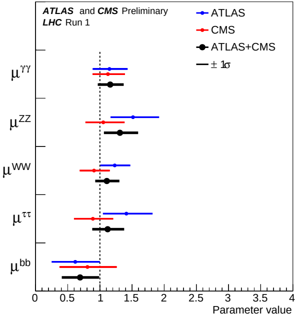
Why look for invisibly decaying Higgs bosons?

Theoretical Motivations

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

Experimental motivation

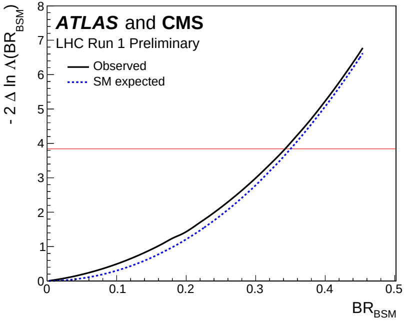
- Measurements of the Higgs boson made so far are impressive:
  - Mass measured with 0.2% error
- A lot of parameters are still relatively unconstrained:
  - Limit on width is $\sim 4\Gamma_{SM}$
- Plenty of room for Higgs boson couplings to dark matter



How to search for invisibly decaying Higgs bosons

Indirect searches

- Compare visible width to total width:
  - $BR_{BSM} = \frac{\Gamma_H - \Gamma_{vis}}{\Gamma_H}$
- No measurement of Γ_H, need to make an assumption
  - Usually assume SM width
- ATLAS+CMS combination gives an observed (expected) limit on BR_{BSM} of 0.34 (0.35)



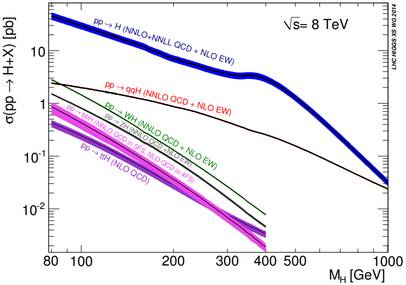
CMS-PAS-HIG-15-002
ATLAS-CONF-2015-044

How to search for invisibly decaying Higgs bosons

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

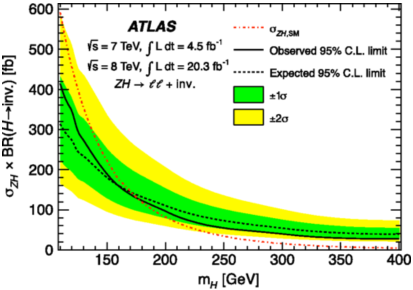
Production channels

- 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

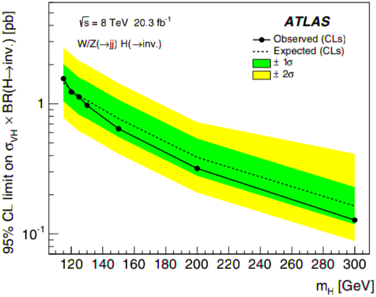
- Selects two leptons opposite large E_T^{miss}
- E_T^{miss} Shape analysis with data driven backgrounds
- Observed (expected) limit on $\mathcal{B}(H \to inv.)$ for m_H =125.5 GeV is 75 (62)%



PRL 112, 201802 (2014)

Run 1 ATLAS direct searches - V(had)H

- Targets $W/Z \rightarrow qq$ final state
- E_T^{miss} and dijet p_T shape analysis with data driven backgrounds
- Observed (expected) limit on $\mathcal{B}(H \rightarrow inv.)$ 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
  - $W \to e\nu$, $W \to \mu\nu$ and $W \to \tau\nu$ and $Z \to \nu\nu$ normalisation tied together
- Observed (expected) limit on $\mathcal{B}(H \to inv.)$ for m_H =125 GeV is 28 (31)%

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

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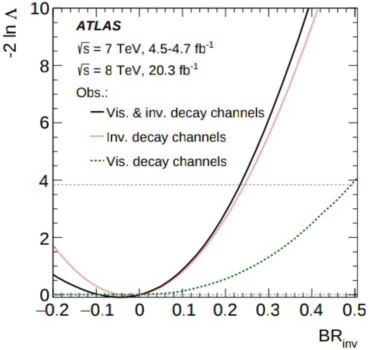
Run 1 ATLAS direct searches - Combination

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



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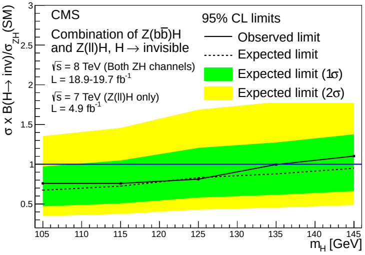
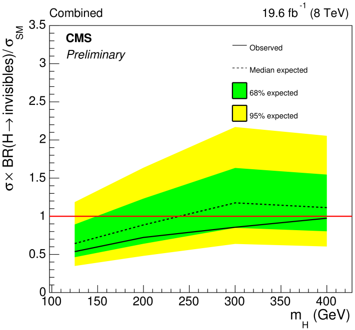
Run 1 CMS direct searches - ZH

- Searches in $Z \to \ell\ell$ and $Z \to b\bar{b}$ 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 $\mathcal{B}(H \to inv.)$ for $m_H =$125 GeV is 81 (83)%



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

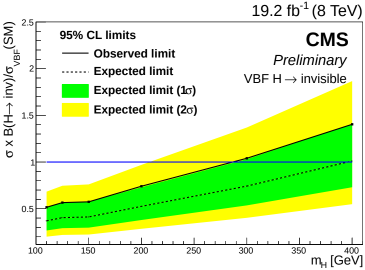
- Search has categaries targeting $V(had)H$ and ggH production modes
- E_T^{miss} shape analysis with data driven background estimation
- Observed (expected) limit on $\mathcal{B}(H \rightarrow inv.)$ for m_H =125 GeV is 53 (62)%



CMS-PAS-EXO-12-055

Run 1 CMS direct searches - VBF

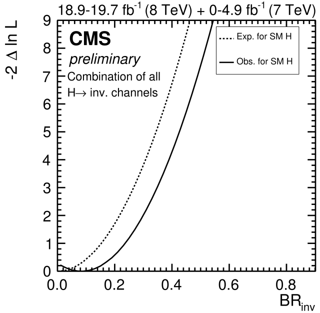
- Select two jets with large $\Delta\eta$ separated from large E_T^{miss}
- Dedicated "parked data" trigger
- Counting experiment with data driven backgrounds
  - V+jets backgrounds separately normalised
  - If all normalisations had same uncertainty as $W \rightarrow \mu\nu$ expected limit would be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

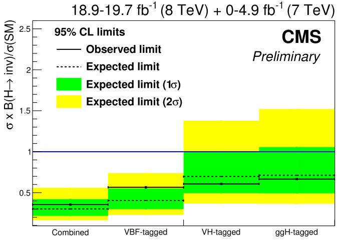


CMS-PAS-HIG-14-038

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(had)H, VBF-tagged is VBF
- Obs. (exp.) limit on $\mathcal{B}(H \to inv.)$ at m_H =125 GeV is 36 (30)%

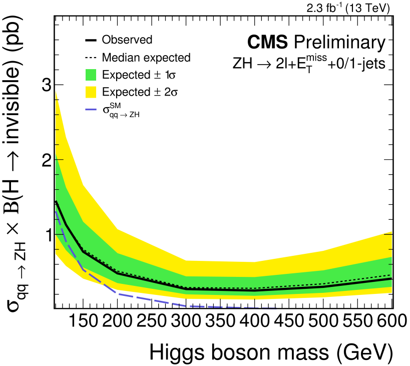




CMS-PAS-HIG-15-012

Run 2 CMS direct searches - ZH

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



CMS-PAS-HIG-16-008

Run 2 CMS direct searches - VBF

- Dedicated trigger used again
- Counting experiment with data driven background estimation
- V+jets backgrounds all taken to have same normalisation
- Observed (expected) limit on $\mathcal{B}(H \to inv.)$ for m_H =125 GeV is XX (YY)%

CMS-PAS-HIG-16-009

Run 2 CMS direct searches - Combination

- First CMS analysis combining 8 and 13 TeV results
- Limit calculated both by production mode and overall
- Combined observed (expected) limit on $\mathcal{B}(H \rightarrow inv.)$ for m_H =125 GeV is XX (YY)%

CMS-PAS-HIG-16-009

Projections

- CMS VBF analysis projected to increased luminosity at 13 TeV

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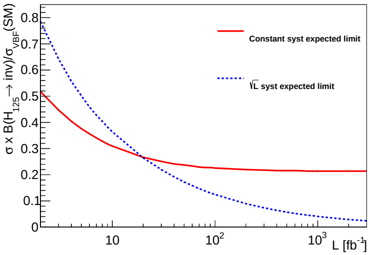
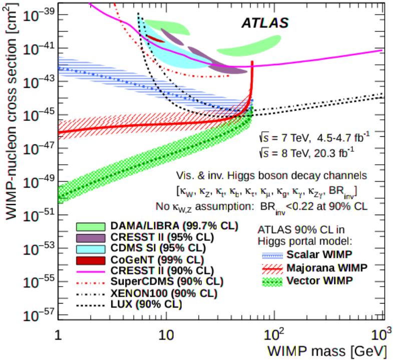
- If systematics scale as $\sqrt{\mathcal{L}}$ can exclude $\mathcal{B}(H \rightarrow inv.) = 5\%$ with full LHC dataset



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



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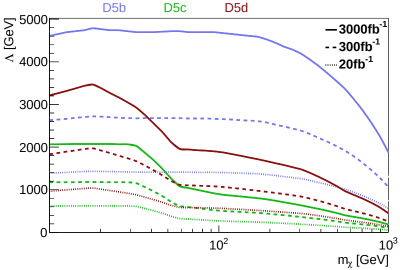
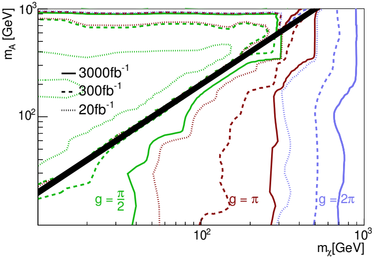
Dark matter interpretations - Projections

- 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





Summary

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