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

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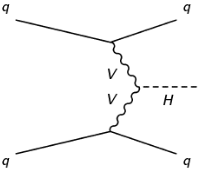
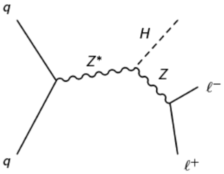
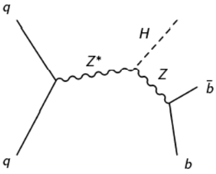
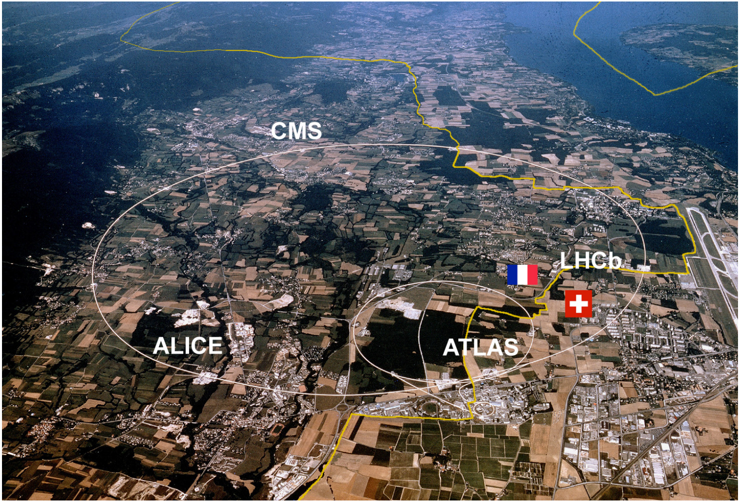


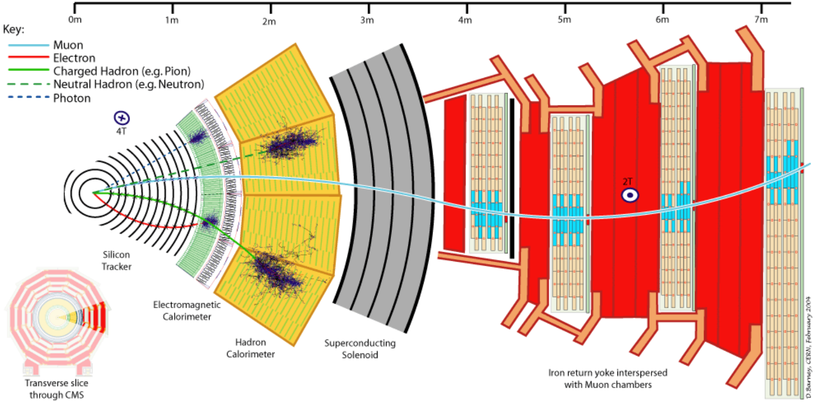




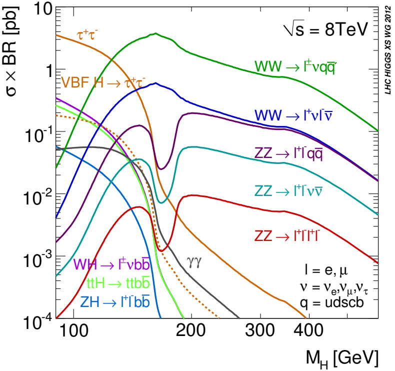
CMS and the LHC

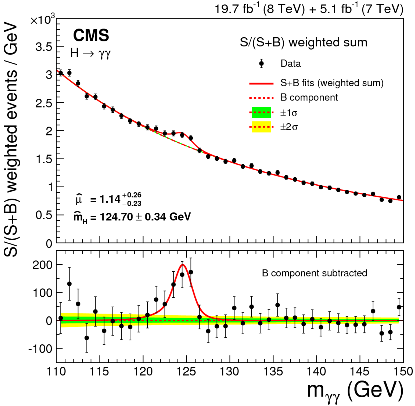


CMS

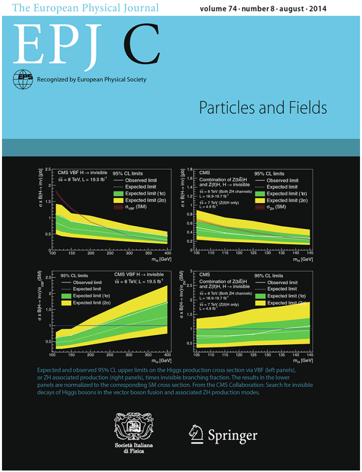

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

The Higgs Boson





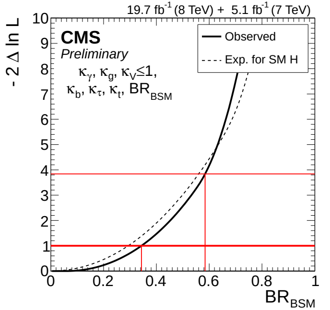
Why Higgs to Invisible?



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

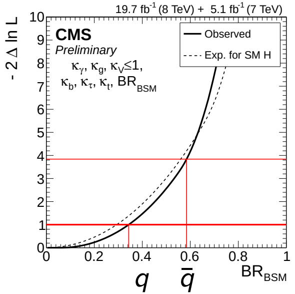
Direct and Indirect Searches

Indirect searches

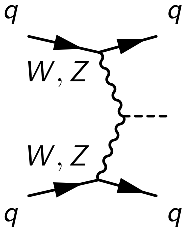
- BSM Higgs decays affect the total Higgs width:
- Visible decays can, therefore, constrain the invisible branching fraction

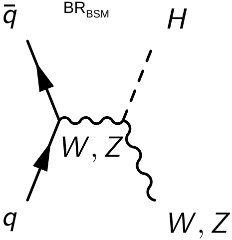
Direct searches

- 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





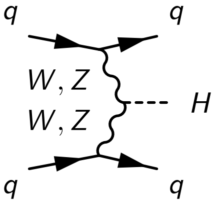
VBF outline

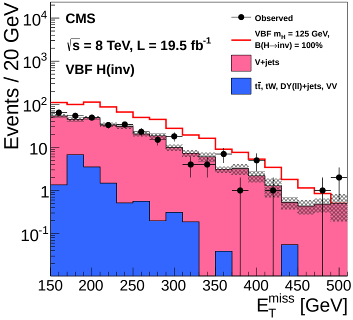
Signal Topology and Selection

- Two high p_T VBF jets with large rapidity separation:
  - large invariant mass and rapidity separation
  - low azimuthal angle separation
- Large missing transverse momentum (MET)

Backgrounds and Rejection Cuts

- $W \to \ell\nu$+jets: Veto leptons
- $Z \to \nu\nu$+jets: Irreducible
- QCD multijet events:
  - Veto events with additional jets between the two selected jets (CJV)
- Minor backgrounds from: top and diboson





arXiv:1404.1344

VBF background estimation

Data Driven Background Estimation

- Choose control region enriched in background
- Use MC signal-control ratio to go to signal region:

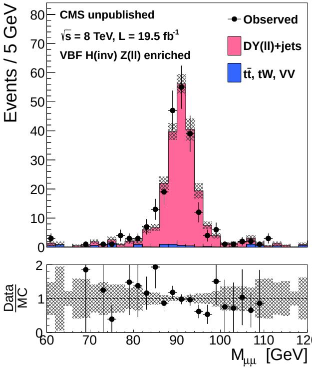
$$N^{signal}_{Bkg} = (N^{control}_{obs} - N^{control}_{otherbkgs}) \cdot \frac{N^{signal}_{MC}}{N^{control}_{MC}}.$$

- Z+jets: Estimate using $Z \rightarrow \mu\mu$+jets events
  - Correct for difference in cross section
- W+jets: Estimate using $W \rightarrow \ell\nu$+jets events

$Z \rightarrow \mu\mu$	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$	$W \rightarrow \tau\nu$
99 ± 38	63 ± 20	67 ± 17	53 ± 25

QCD - Use "ABCD method" in MET and CJV

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



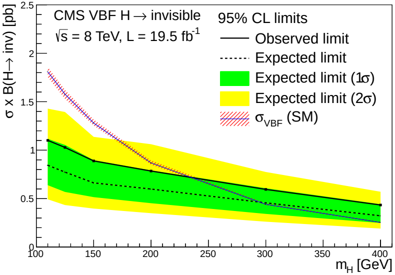
CMS-TWIKI-HIG-13-030

CJV			
pass	B	A	
fail	D	C	
	<130	>130	MET

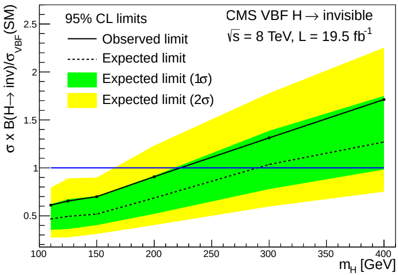
VBF results

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

- Set limits on $\sigma x B(H \rightarrow inv)$
  - 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 $B(H \rightarrow inv)$ for m_H=125 GeV is 65(49)%

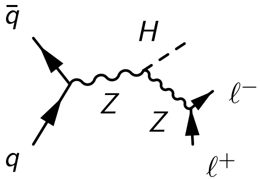


arXiv:1404.1344



arXiv:1404.1344

$Z(\ell\ell)H$ outline

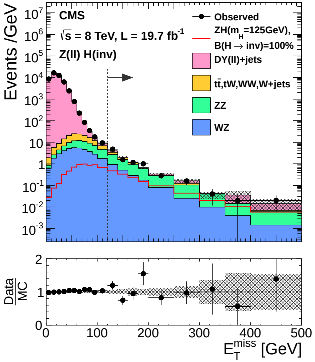


Signal Topology and Selection

- Two opposite sign electrons or muons
  - Consistent with Z mass
- Large MET that balances leptons
- $\leq$1 jet, no b-tagged jets, no extra leptons

Backgrounds

- $ZZ(\ell\ell\nu\nu)$+jets, $WZ(\ell\nu\ell\ell)$+jets: From MC
- $WW(\ell\nu\ell\nu)$+jets, $t\bar{t}$, single top, $W(\ell\nu)$, QCD:
  - No real Z: use $m_{\ell\ell}$ side bands
  - $N_{\ell\ell}^{sig} = N_{e\mu}^{sig} \cdot N_{\ell\ell}^{SB} / N_{e\mu}^{SB}$
- $Z(\ell\ell)$+jets: normalised in γ+jets region

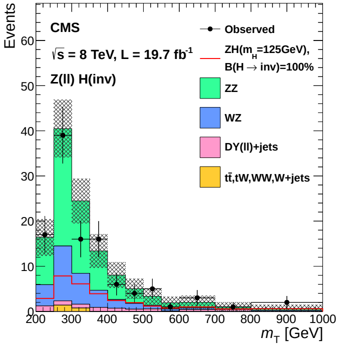


arXiv:1404.1344

$Z(\ell\ell)H$ results

- 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 $B(H \rightarrow inv)$ for m_H=125 GeV is 83(86)%

arXiv:1404.1344



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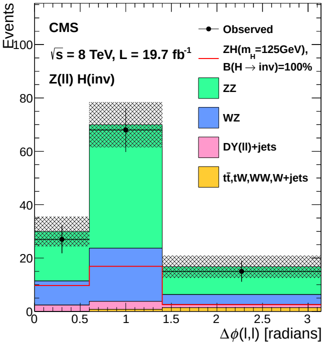


Z(bb)H outline and backgrounds

Signal Topology and Selection

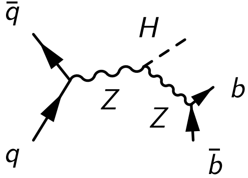
- Two b-tagged jets: high invariant mass
- Three categories in MET

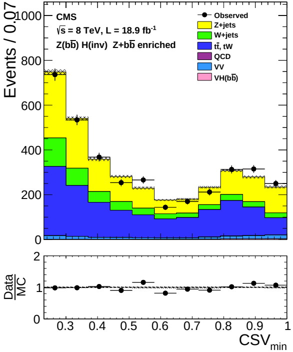
Backgrounds and Rejection Cuts

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

Background estimation - data normalised MC

- Use MC normalised with a simultaneous fit in seven control regions



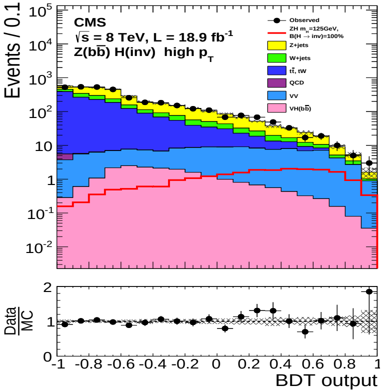


arXiv:1404.1344

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

Process	High MET	Intermediate MET	Low MET
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

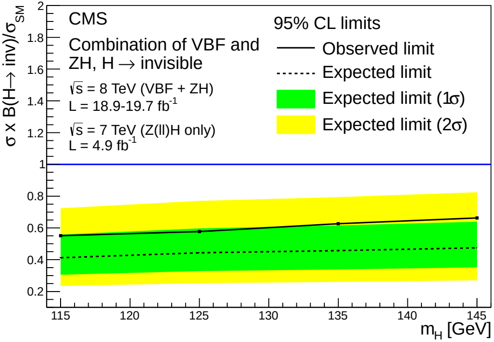
- Multivariate analysis (BDT):
  - performed for each mass hypothesis and boost region
- Limits from a fit to the BDT output distribution
- Assuming SM Higgs production cross-section and acceptance:
  - observed(expected) 95% C.L. limit on $B(H \to inv)$ for m_H=125 GeV is 182(199)%



arXiv:1404.1344

Combined Results

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



arXiv:1404.1344

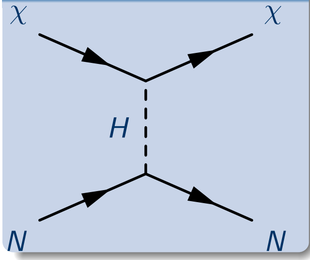
Observed (expected) limits on B(H→inv) at 95% C.L. for m_H=125 GeV

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

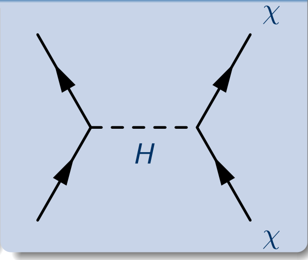
Signatures of Dark Matter (DM)

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

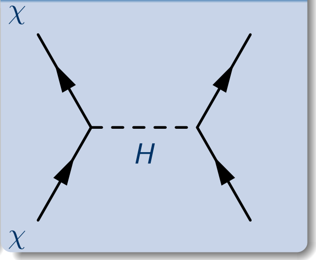
Direct Detection - e.g. LUX



Invisible Higgs - LHC



Annihilation - e.g. WMAP

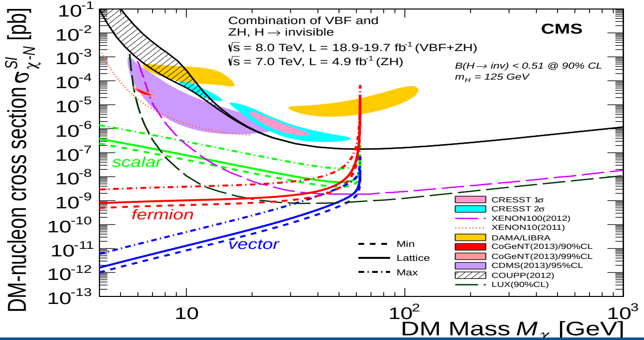


- Limits on $\mathcal{B}(\mathrm{H}\rightarrow\mathrm{inv})$ therefore constrain Higgs Portal DM models
  - These constraints are directly comparable to those from other experiments

Dark Matter Interpretation - Results

- Use an effective field theory Higgs Portal model which translates B($H \to inv$) into a DM-nucleon cross-section (details in backup)
- At 90% C.L. the CMS limit on B(H→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

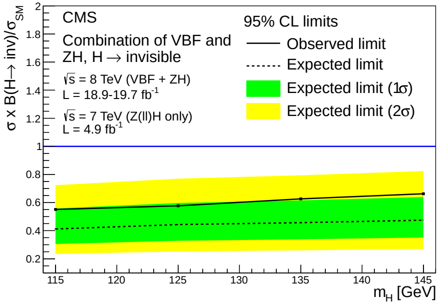


Min, lattice and max are varying values of Higgs-nucleon coupling (see backup)

$\mathcal{B}(H \to inv)$ gives important exclusion in the $M_\chi < m_h/2$ region

Conclusions

- A Direct search for Higgs to invisible decays has been performed at CMS:
  - The VBF, $Z(\ell\ell)H$ and $Z(bb)H$ channels have been considered
- No significant excesses are seen over the background predictions
- The combined limit is 58(44)% observed (expected) at 95% C.L. for $m_H = 125\text{GeV}$
  - It is broadly comparable with CMS indirect limits
- A dark matter interpretation has been presented



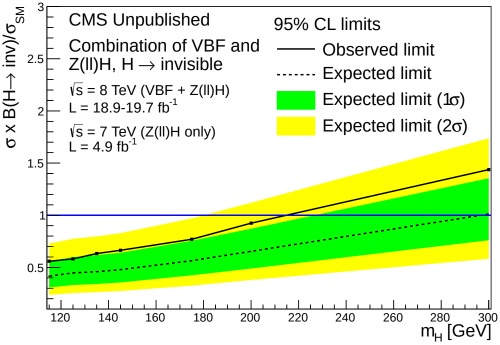
References

- 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
- $\sigma^{SI}_{S-N} = \frac{4\Gamma_{inv}}{m_H^3 v^2 \beta} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$
- $\sigma^{SI}_{V-N} = \frac{16\Gamma_{inv} M_\chi^4}{m_H^3 v^2 \beta (m_H^4 - 4M_\chi^2 m_H^2 + 12M_\chi^4)} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$
- $\sigma^{SI}_{f-N} = \frac{8\Gamma_{inv} M_\chi^2}{m_H^5 v^2 \beta^3} \frac{m_N^4 f_N^2}{(M_\chi + m_N)^2}$

- 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 fN from MILC collaboration Phys. Rev. Lett. 103 (2009) 122002
- v is the Higgs vacuum expectation, 174 GeV
- $\beta = \sqrt{1 - 4M_\chi^2/m_H^2}$
- $B(H \rightarrow inv.) = \Gamma_{inv}/(\Gamma_{SM} + \Gamma_{inv})$