Imperial College London

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

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on behalf of the CMS Collaboration
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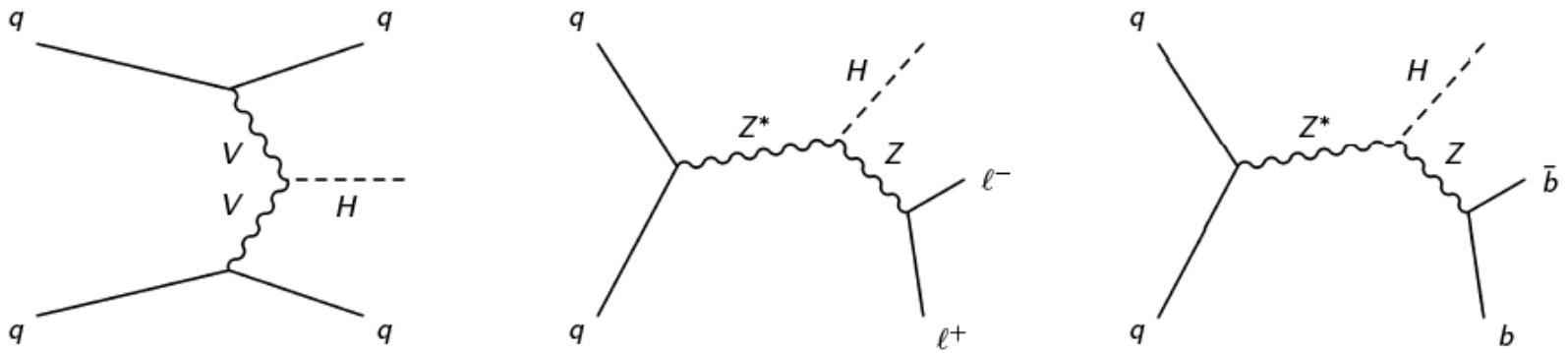
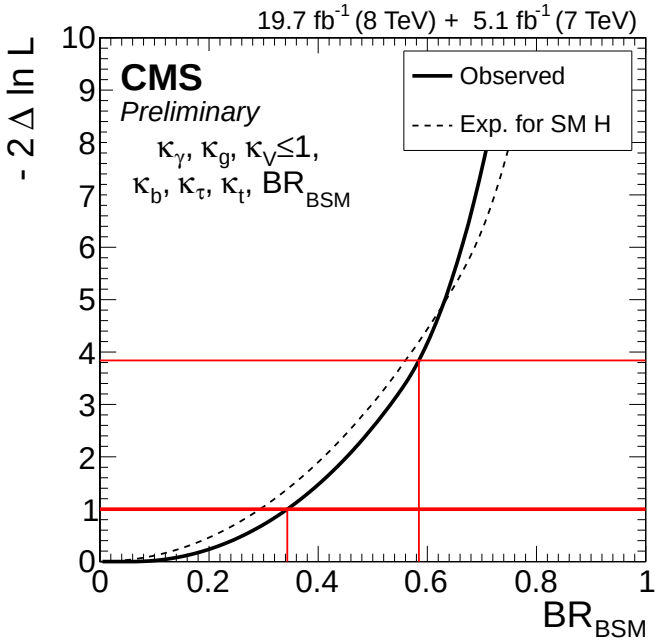


Why Higgs to Invisible?

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

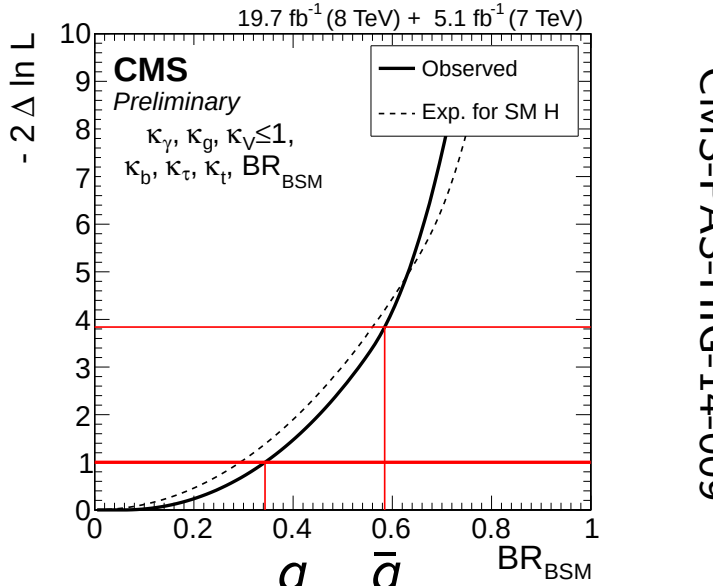
Direct and Indirect Searches

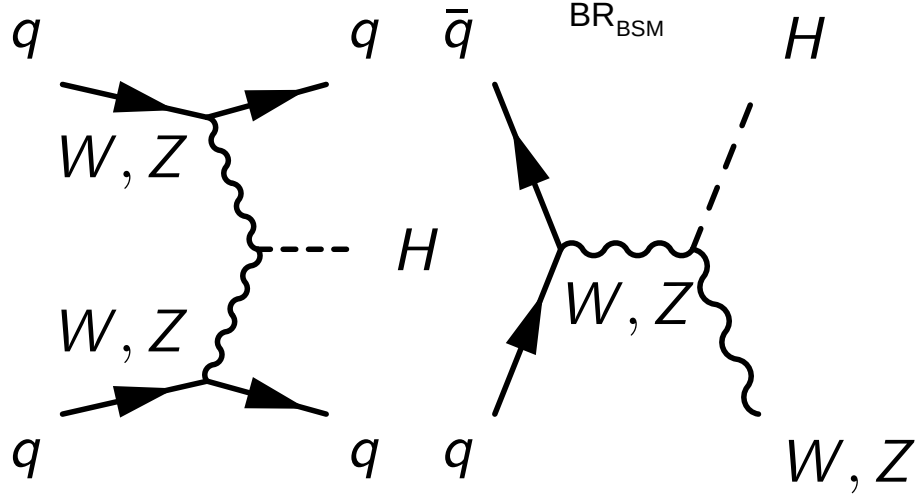
Indirect searches

- BSM Higgs decays affect the total Higgs width:
  - $\Gamma_{tot} = \Gamma_{tot}^{SM} \cdot \frac{\sum_x^{obs} \kappa_x^2 \cdot BR_x^{SM}}{1 - BR_{BSM}}, \kappa_x^2 = \frac{\Gamma_x^{obs}}{\Gamma_x^{SM}}$
- 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





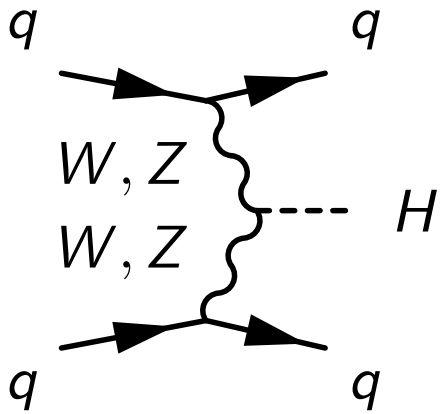
VBF outline

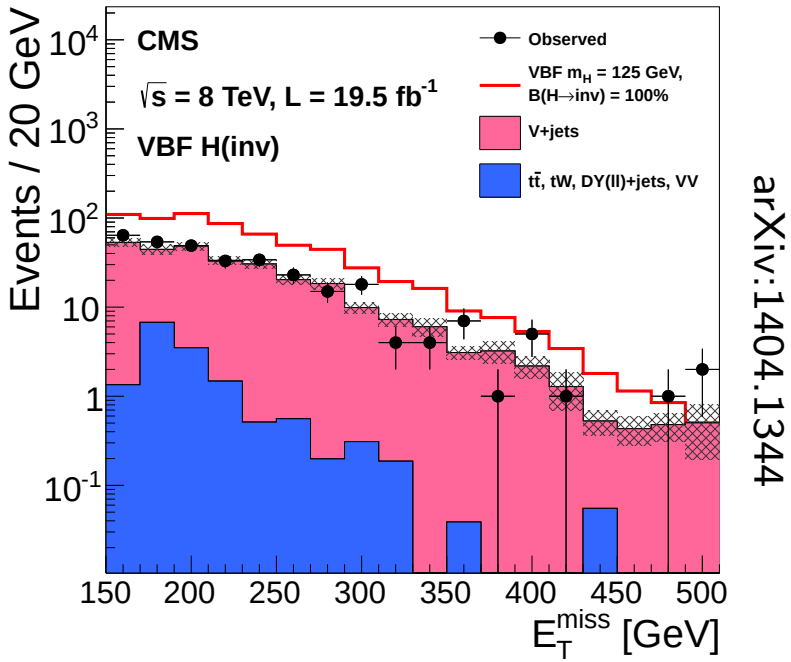
Signal Topology and Selection

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

Backgrounds and Rejection Cuts

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





VBF background estimation

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

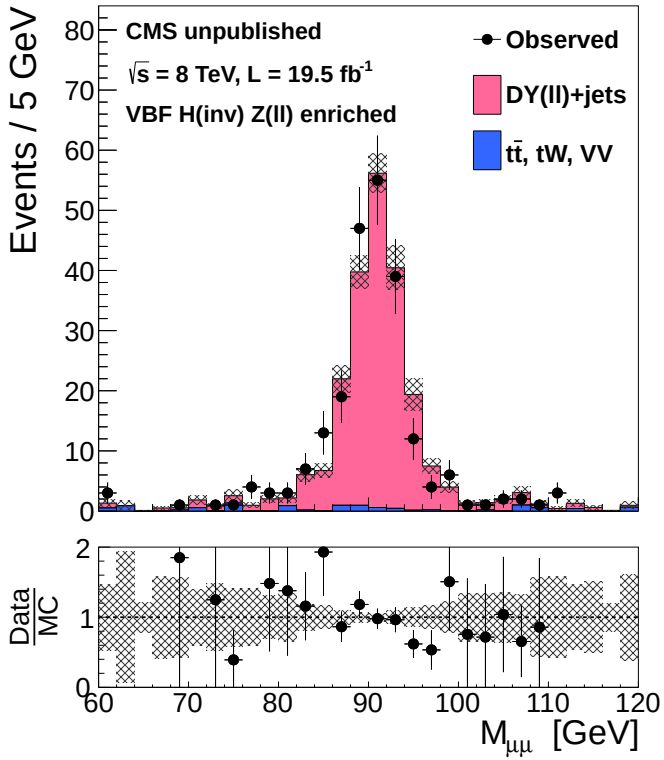
- Sig. sel.+two muons $60 < m_{\mu\mu} < 120$ GeV
- Control→signal extrapolation factor from MC
- $N_{Z\to\mu\mu} = 99 \pm 29(stat.) \pm 25(syst.)$

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

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

QCD - Use "ABCD method" in MET and CJV

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



CJV

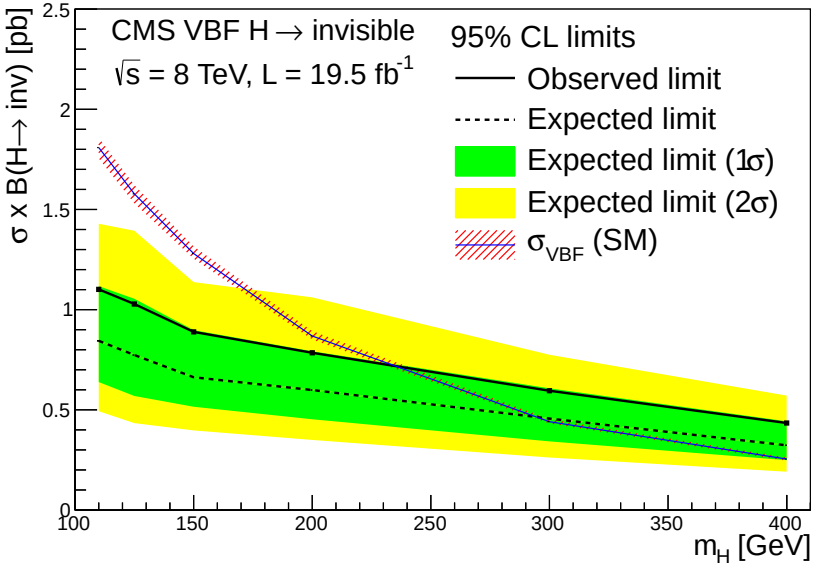
	<130	>130
pass	B	A
fail	D	C

MET

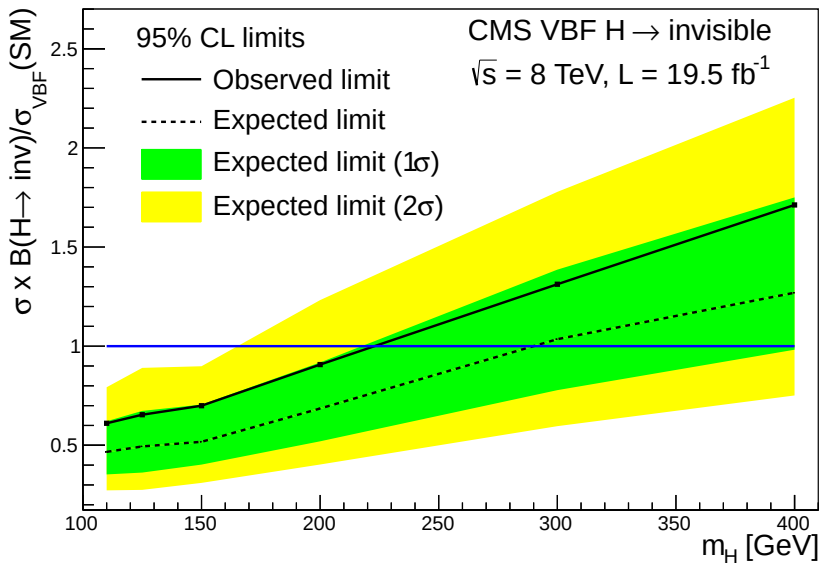
VBF results

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 $\sigma \times B(H \rightarrow inv)$
  - 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

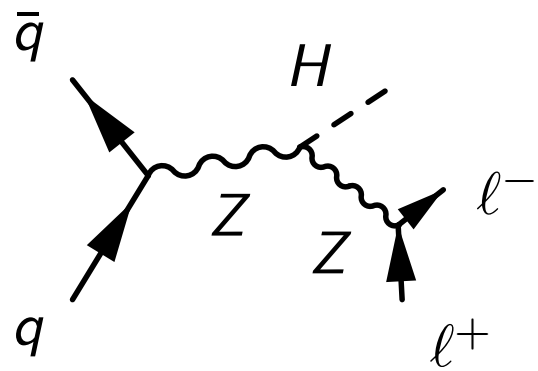
Z($\ell\ell$)H outline

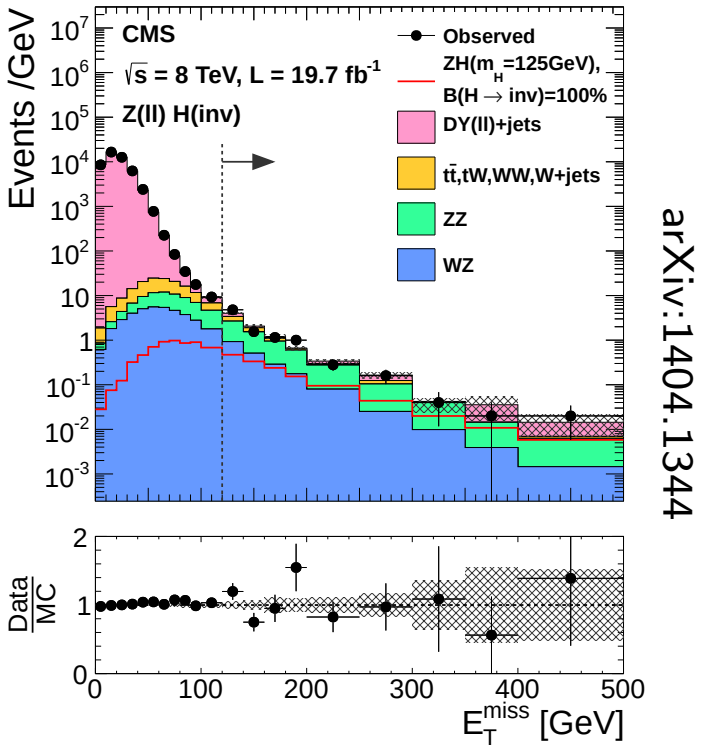
Signal Topology and Selection

- Two 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($\ell\ell\nu\nu$)+jets, WW($\ell\nu\ell\nu$)+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
  - $\leq$1 jet, p_T>30 GeV
  - no b-tagged jets, $p_T > 30$ GeV





arXiv:1404.1344

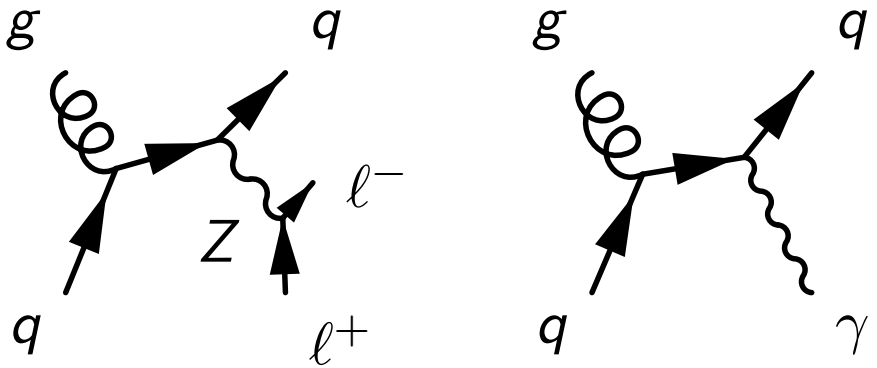
Z($\ell\ell$)H background estimation

ZZ($\ell\ell\nu\nu$)+jets and WZ($\ell\nu\ell\ell$+jets)

- Estimated from MC prediction

Z($\ell\ell$)+jets

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



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

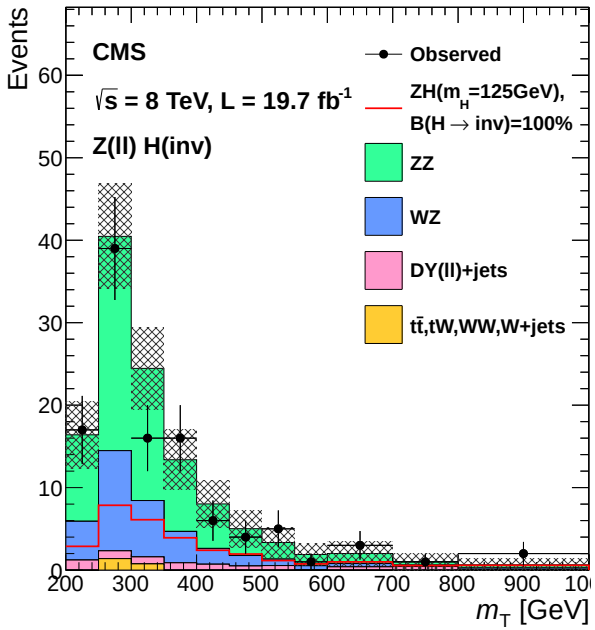
- Estimated from $e\mu$ events and Z peak sidebands:
  - $m_{\ell\ell}$ 40-70 and 110-200 GeV
  - $N^{sig}_{\ell\ell} = N^{sig}_{e\mu} \cdot N^{SB}_{\ell\ell} / N^{SB}_{e\mu}$

Z($\ell\ell$)H results

	Process	$\sqrt{s}$ = 7TeV ee	$\sqrt{s}$ = 7TeV $\mu\mu$	$\sqrt{s}$ = 8TeV ee	$\sqrt{s}$ = 8TeV $\mu\mu$
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→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→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 $B(H \to inv)$ for m_H=125 GeV is 83(86)%

arXiv:1404.1344



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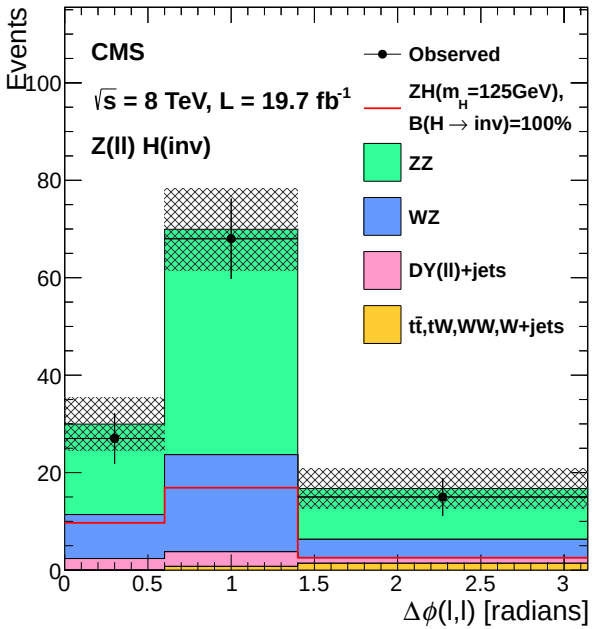


Z(bb)H outline and backgrounds

Signal Topology and Selection

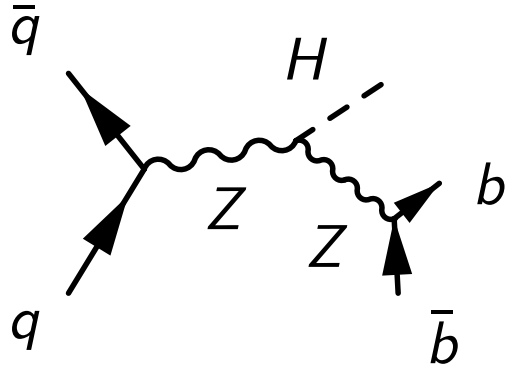
- Two b-tagged jets:
  - $p_T > 30/60$ GeV, $p_{Tjj} > 100 - 130$ GeV
- Three bins in MET
  - 100-130, 130-170, > 170 GeV

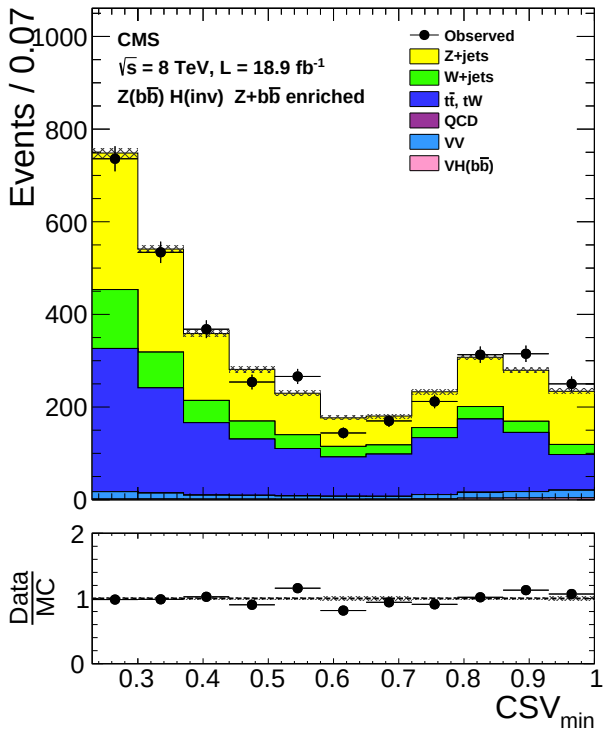
Backgrounds and Rejection Cuts

- $Z(\nu\nu)$+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, $p_T > 15$ 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), $t\bar{t}$



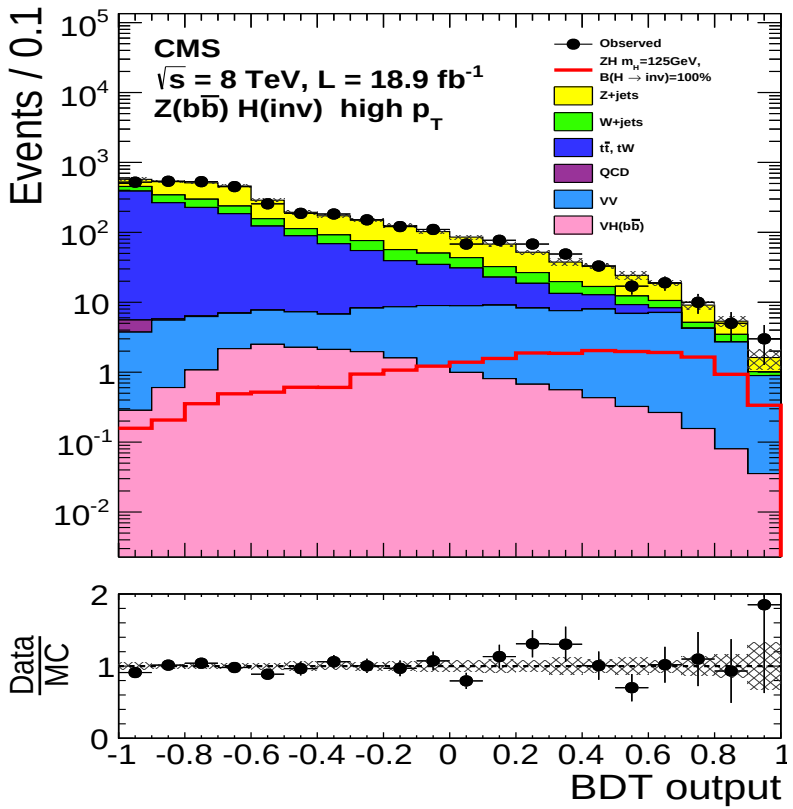


arXiv:1404.1344

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(inv)	12.6 $\pm$ 1.1	3.6 $\pm$ 0.3	1.6 $\pm$ 0.1
Observed data	204	61	38

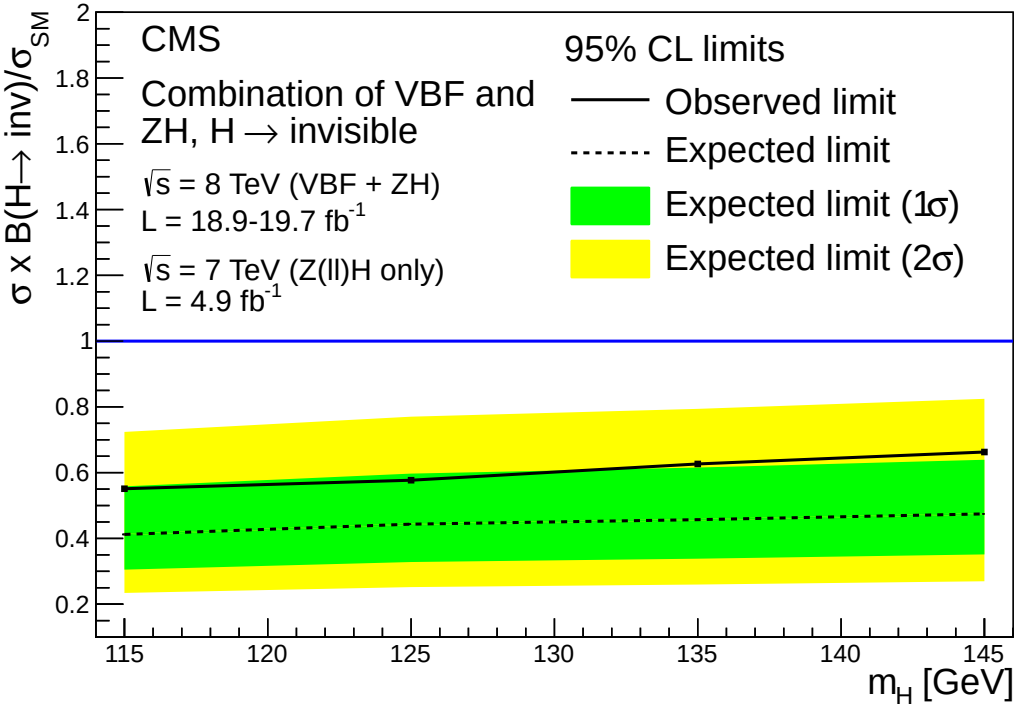
- Multivariate analysis (BDT):
  - performed for each mass hypothesis and boost region
- Limits from a fit to the BDT output distribution
- Assuming SM Higgs production cross-section and acceptance:
  - observed(expected) 95% C.L. limit on $B(H \to inv)$ for m_H=125 GeV is 182(199)%



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

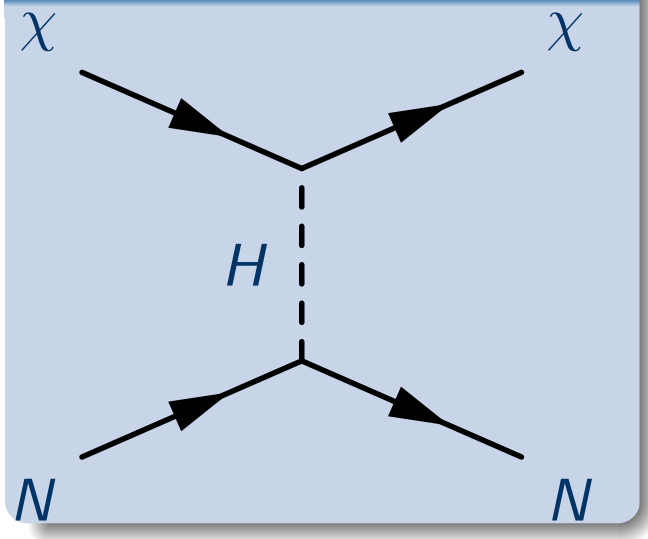
Observed (expected) limits on B(H→inv) at 95% C.L. for m_H=125 GeV

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

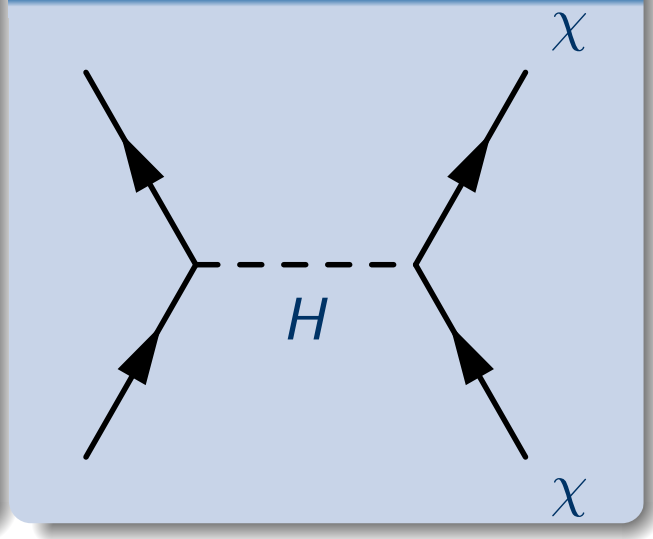
Signatures of Dark Matter (DM)

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

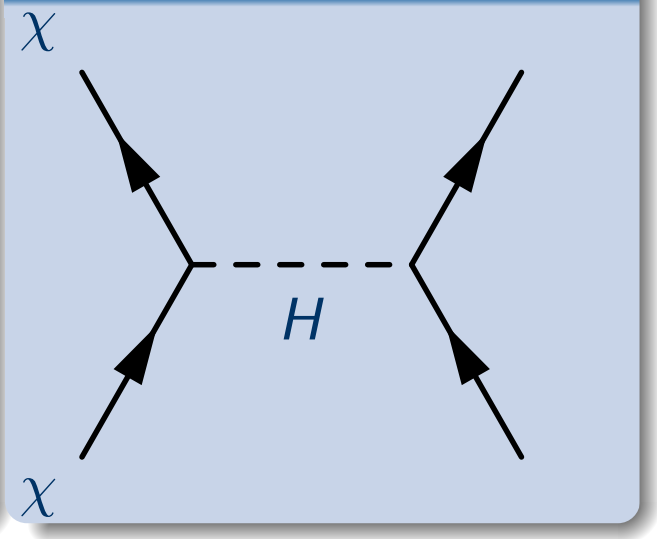
Direct Detection - e.g. LUX



Invisible Higgs - LHC



Annihilation - e.g. WMAP

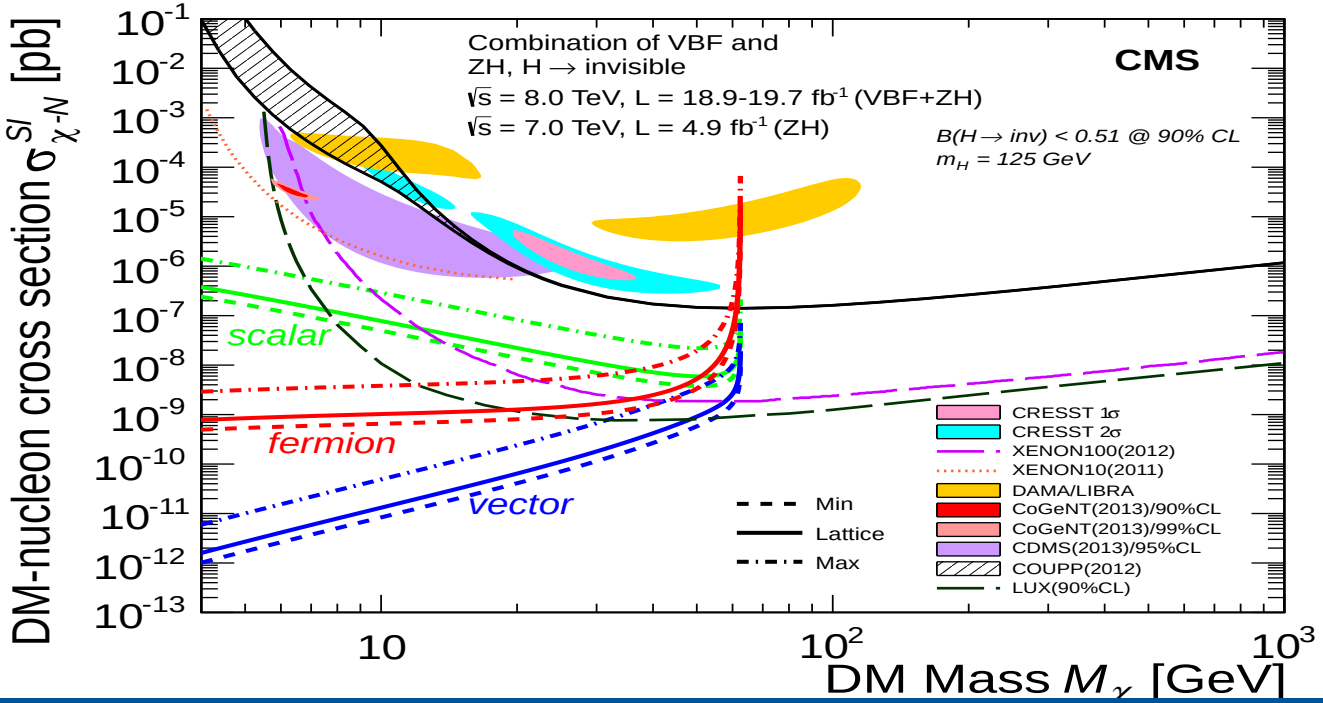


- Limits on $\mathcal{B}$(H→inv) therefore constrain Higgs Portal DM models
  - These constraints are directly comparable to those from other experiments

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

- Direct searches for Higgs boson decays to invisible final sates 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 $m_H = 125$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

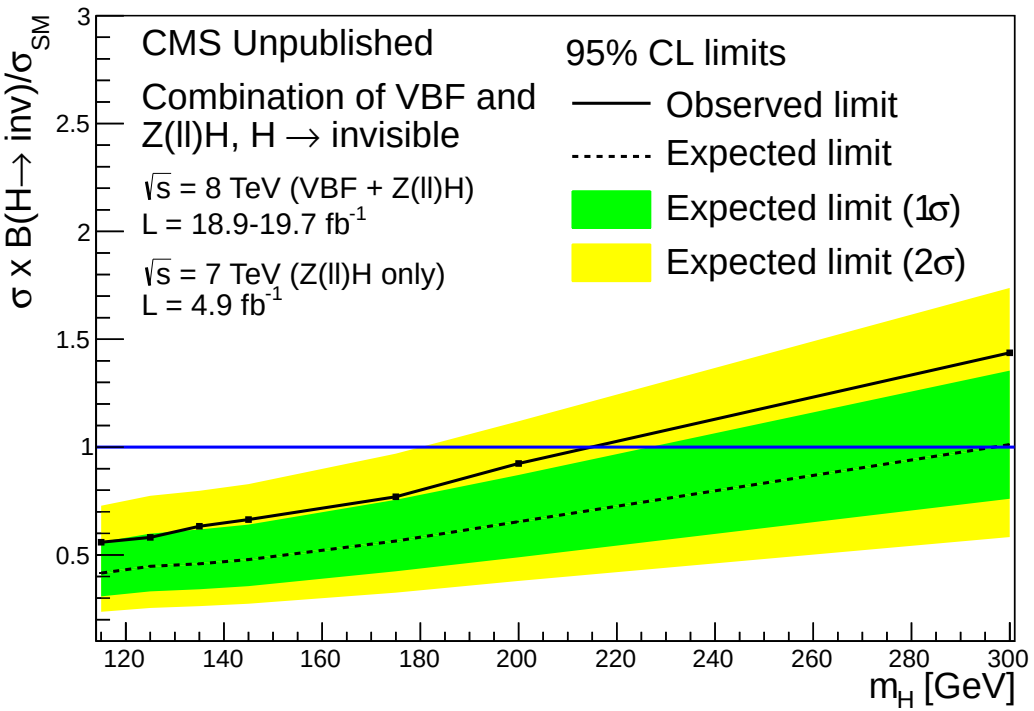
References

- 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(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
  - $\beta = \sqrt{1 - 4M_\chi^2/m_H^2}$
  - $B(H \to inv.) = \Gamma_{inv}/(\Gamma_{SM} + \Gamma_{inv})$