Searches for invisible decays of the Higgs boson with the CMS detector

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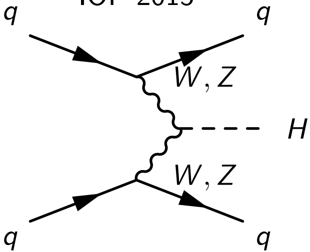
on behalf of the CMS Collaboration

IOP 2015

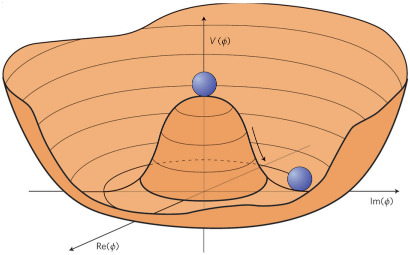


My thesis outline

- Theory
- Detector & physics objects
- Statistics
- CMS Prompt Higgs to invisible search
- CMS Parked Higgs to invisible search
- Combination with other searches
- Dark matter interpretations
- Run II

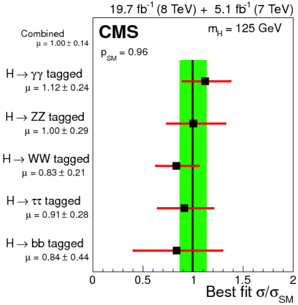
Theory: Why look for invisibly decaying Higgs bosons?

- Introduce Standard Model Higgs mechanism
- Introduce Dark Matter
- Discuss why Higgs is a good place to look for dark matter
  - Give model examples e.g. EFT, simplified models
- Discuss Higgs production and why VBF



Why look for invisibly decaying Higgs bosons?

- SM compatible 125 GeV Higgs boson observed by ATLAS and CMS
  - SM compatible does not mean BSM incompatible

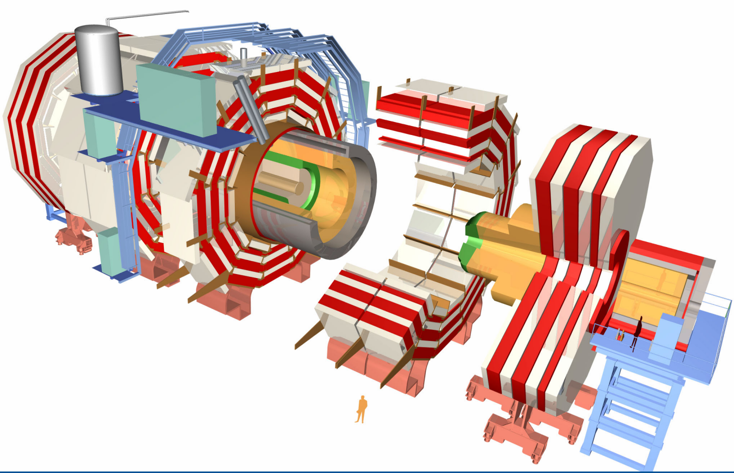


CMS-HIG-14-009

- Many BSM theories predict Higgs to invisible, e.g. SUSY
  - Often provide good DM candidates

Detector & physics objects

- LHC overview, introduction to CMS subsystems and objects



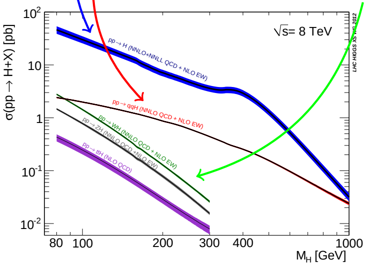
Invisible signatures at CMS

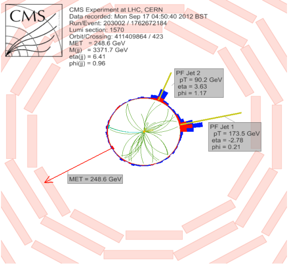
- Which signatures do we see at CMS?
- Indirect: Look for effect of BSM Higgs decays on Higgs total width
- Direct: Use channels where the Higgs recoils against a visible system

  ggH: high rate, no visible products (unless ISR/FSR, i.e. mono-X)

  VBF: medium rate, jets+MET final state

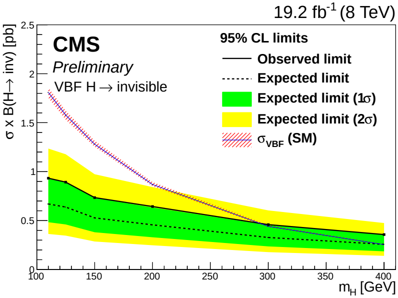
  ZH: low rate, leptons/b jets+MET final state





Statistics

- A lot of my work has involved limit setting
  - Short chapter with theory of CLs, nuisance parameter treatment etc.

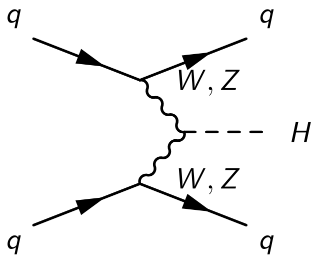


CMS VBF History

- CMS ran two sets of triggers in 2012:
  - prompt: reconstructed immediately
  - parked: looser thresholds, reconstructed in long shutdown
- CMS published result using full run I prompt dataset
  - I did the limit setting and worked on the cross-check
- A CMS PAS was produced using the full run I parked dataset
  - I was the main analysis contact
  - This will be the main piece of work in my thesis

Prompt VBF

- Introduce analysis focusing on my work
  - Background estimation, systematics, limits



Parked data VBF analysis

- I was the main contact for this analysis and it will be the main piece of work in my thesis
- Analysis reoptimised using new variables
  - Target significant MET away from jets
- Trigger efficiency remeasured
  - 3D characterisation to enable trigger turn on to be used
- Systematics and background estimations improved

Parked Triggers

- Parked triggers present for runs B, C and D
  - Parked trigger cuts are looser so prompt trigger not used where parked trigger is available
  - Two different triggers, one in runs B and C one in run D
- Looser thresholds allowed us to look at new regions of phase space and different analysis techniques

HLT

Run period	MET cut	dijet p_T cut	dijet mass cut
A	METnoMuons>65 GeV	DiPFJet40	MJJ800
B&C	N/A	DiJet35	MJJ700
D	N/A	DiJet30	MJJ700

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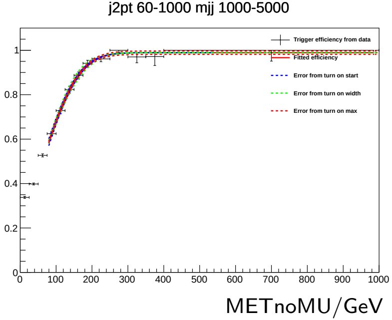
Trigger efficiency

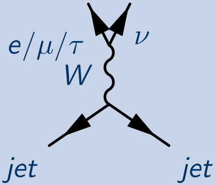
- Variables used in triggers are highly correlated
- In prompt analysis correlations neglected
  - cut tighter to ensure trigger is efficient
- For the parked analysis fit trigger turn on in each bin of a 2D grid
  - Cuts can then be looser



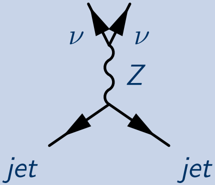
VBF: selection

- Select events with two VBF jets + MET:
  - no colour connection between jets means large η gap
- QCD background difficult to model:
  - use tight selection to remove
- Main backgrounds: $W \to \ell\nu / Z \to \nu\nu$+jets, QCD, top
  - Veto events with leptons present

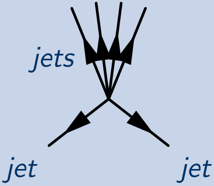
W+jets



Z+jets



QCD



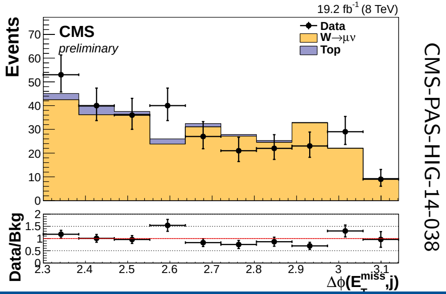
VBF: background estimation

- All major backgrounds have data driven normalisation

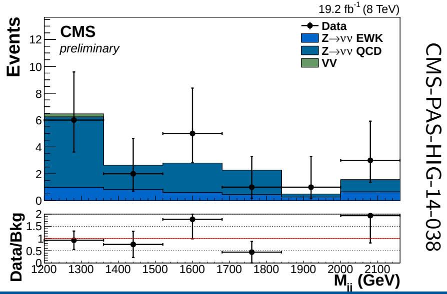
$$N^{sig}_{bkg} = \frac{(N^{control}_{obs} - N^{control}_{other\ bkgs})}{N^{control}_{MC}} \cdot N^{sig}_{MC}$$

- Most backgrounds from missed lepton or misreconstructed jet
  - use control region where object is reconstructed

$W \to \mu\nu$ control region



$Z \to \nu\nu$ control region

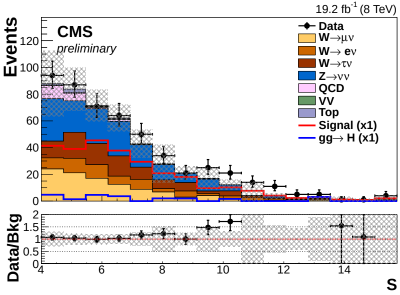


VBF results

Total background	$439.7 \pm 41.0(stat.) \pm 55.8(syst.)$
VBF H(inv.) assuming B(H→inv)=100%	$273.4 \pm 31.2(syst.)$
ggF H(inv.) assuming B(H→inv)=100%	$22.6 \pm 15.6(syst.)$
Observed data	508

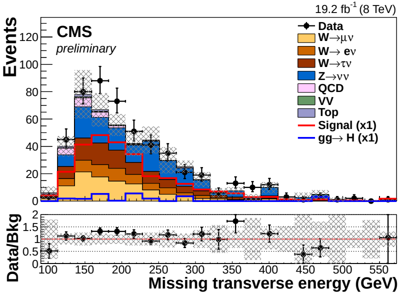
- Compatible with the background hypothesis

Signal region



CMS-PAS-HIG-14-038

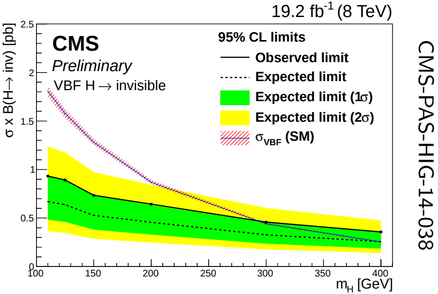
Signal region

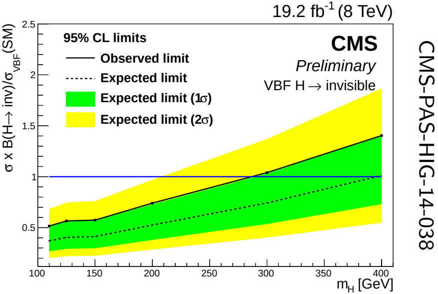


CMS-PAS-HIG-14-038

VBF limits

- Perform a single bin counting experiment using CL_S method
- Observed(expected) 95% C.L. limit on $B(H \rightarrow inv)$ for m_H=125 GeV is 57(40)%





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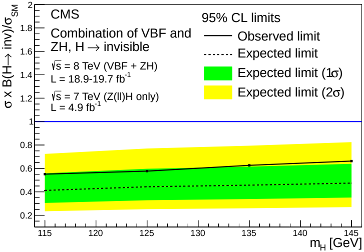
Combined Results

- I was responsible for combining the VBF search results with those in the ZH channels
- Separate limits on $\sigma \times B(H \to inv)$ are combined at 125 GeV
- Assume SM production cross-sections to interpret as a limit on B(H→inv)

Prompt



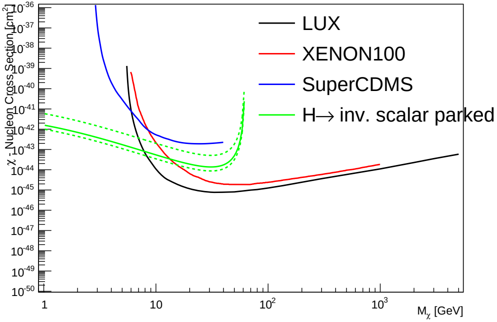
Parked

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

Channel	Limit/%
VBF	57(40)
ZH($\ell\ell$+bb)	81(83)
VBF + ZH	47(35)

Dark matter interpretations

- Completed: Parked result has been interpreted in a scalar EFT
- In progress: Replicating analysis in Delphes framework for phenomenology paper with other models



Run II

- Currently working on VBF Higgs to invisible Run II analysis
- Contribution to the thesis will depend on progress
- Plans:
  - Add γ+jets control region to improve Z estimation
  - Reoptimise analysis for new kinematics and trigger

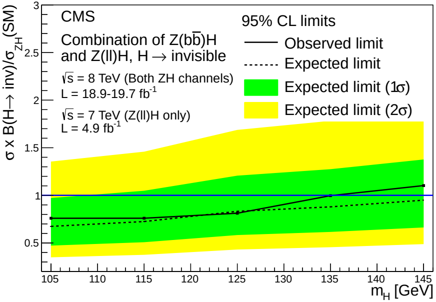
Conclusions

- The thesis will focus on the parked data VBF Higgs to invisible analysis
- The majority of work is complete
- Items still in progress are:
  - Further work on interpretations
    - Aiming for a phenomenology paper by end of year
  - Run II
    - Dependent on progress
- On track to submit before funding runs out in March 2016

Backup

ZH: summary

- Search also performed in $ZH \to \ell\ell inv$ and $ZH \to b\bar{b}inv$ channels at CMS
- Observed(expected) 95% C.L. limit on $B(H \to inv)$ for m_H=125 GeV is 81(83)%



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

References

- CMS Higgs combination - CMS–HIG-14-009
- CMS VBF Higgs to invisible parked data PAS - CMS-PAS-HIG-14-038
- CMS Higgs to invisible paper - Eur. Phys. J. C 74 (2014) 2980

Comparison to recent ATLAS result

- We see an excess where ATLAS see a deficit:
  - observed can move the post-fit expected limit
  - were we to see a similar deficit our expected limit improves by $\sim$10%
- ATLAS use a single data driven normalisation factor for all V+jets backgrounds
  - statistical uncertainty on the factor is therefore lower
  - reducing our $Z \to \nu\nu$ statistical uncertainty to the level we see in $W \to \mu\nu$ our expected limit improves by $\sim$10%

W+jets

- $W \rightarrow e/\mu\nu$ control region formed by swapping lepton veto for e/μ requirement
- $W \rightarrow \tau\nu$ control region formed by requiring a hadronic tau
  - not many events with hadronic taus, need to loosen requirements
  - assign a 20% systematic to $W \rightarrow \tau\nu$ to compensate

$$N^{sig}_{bkg} = (N^{control}_{obs} - N^{control}_{other\ bkgs}) \cdot \frac{N^{sig}_{MC}}{N^{control}_{MC}}$$

$W \rightarrow \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \rightarrow e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \rightarrow \tau\nu$	$94.6 \pm 13.1 \pm 23.8$

Z+jets

- Use $Z \to \mu\mu$ MC ignoring muons to emulate $Z \to \nu\nu$
- Correct for difference in cross-section
- Efficiency correction takes into account EWK vs QCD difference

$$N_S^{Z\to\nu\nu} = \left(N_C^{Data} - N_C^{bkg}\right) \cdot \frac{\sigma(Z\to\nu\nu)}{\sigma(Z\to\mu\mu)} \cdot \frac{\epsilon_S^{ZMC}}{\epsilon_C^{ZMC}}$$

$Z \to \nu\nu$	$158.1 \pm 37.3 \pm 21.2$

QCD

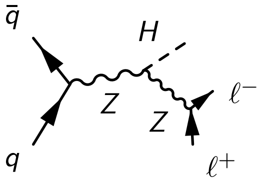
- Take shape from region with third jet near MET
- Normalise in sideband region
  - normalisation highly selection dependent
  - parameterise as function of selection and extrapolate
- Final estimate 17 ± 14

Other backgrounds

- Taken from MC

top	5.5 ± 1.8
VV	3.9 ± 0.7

$Z(\ell\ell)$H outline

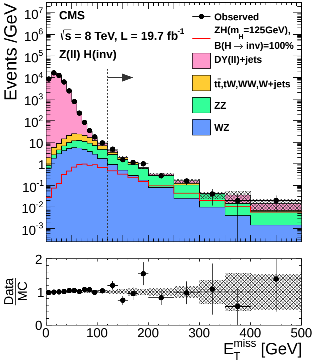


Signal Topology and Selection

- 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

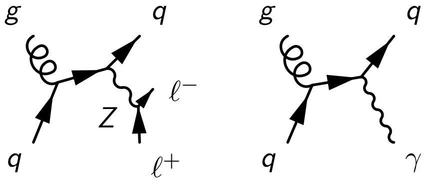
Z($\ell\ell$)H background estimation

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, $t\bar{t}$, $Z(\tau\tau)$

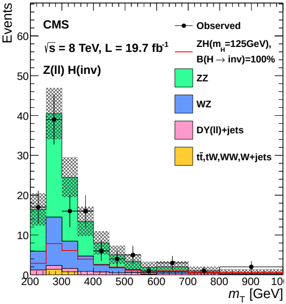
- Estimated from $e\mu$ events and Z peak sidebands:
  - $m_{\ell\ell}$ 40-70 and 110-200 GeV
  - $N_{\ell\ell}^{sig} = N_{e\mu}^{sig} \cdot N_{\ell\ell}^{SB} / N_{e\mu}^{SB}$

Z($\ell\ell$)H results

	Process	$\sqrt{s} = 7$TeV ee	$\sqrt{s} = 7$TeV $\mu\mu$	$\sqrt{s} = 8$TeV ee	$\sqrt{s} = 8$TeV $\mu\mu$
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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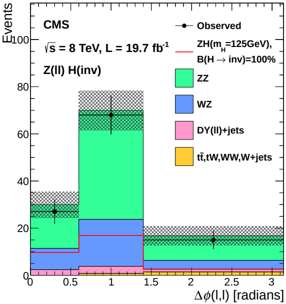


Z(bb)H outline and backgrounds

Signal Topology and Selection

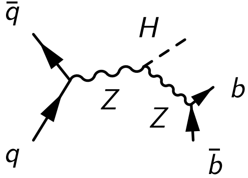
- Two b-tagged jets:
  - $p_T > 30/60$ GeV, $p_{Tjj} > 100 - 130$ GeV
- Three bins in MET
  - 100-130, 130-170, $>$ 170 GeV

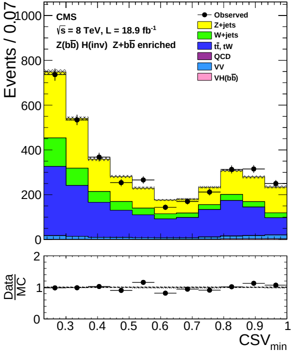
Backgrounds and Rejection Cuts

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





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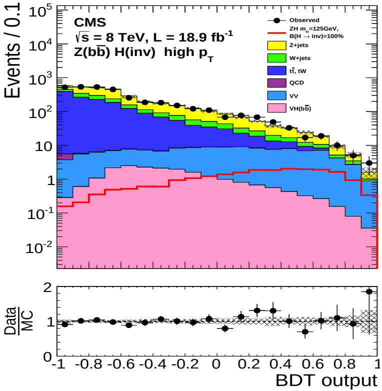
Z($b\bar{b}$)H results

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 $B(H \to inv)$ for m_H=125 GeV is 182(199)%



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