Imperial College London

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

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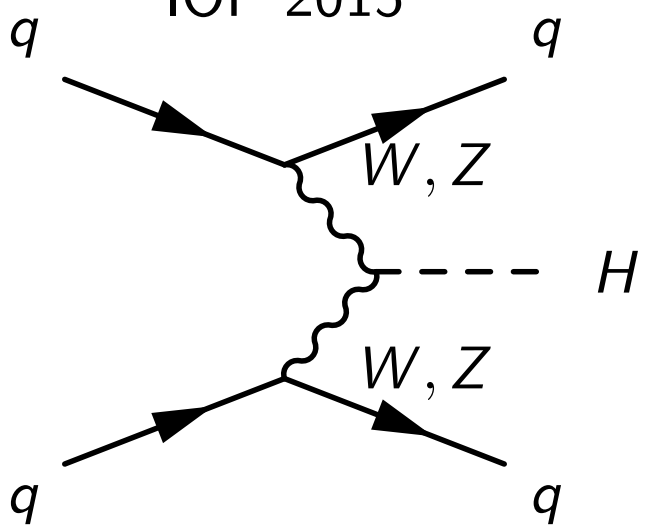
on behalf of the CMS Collaboration

IOP 2015

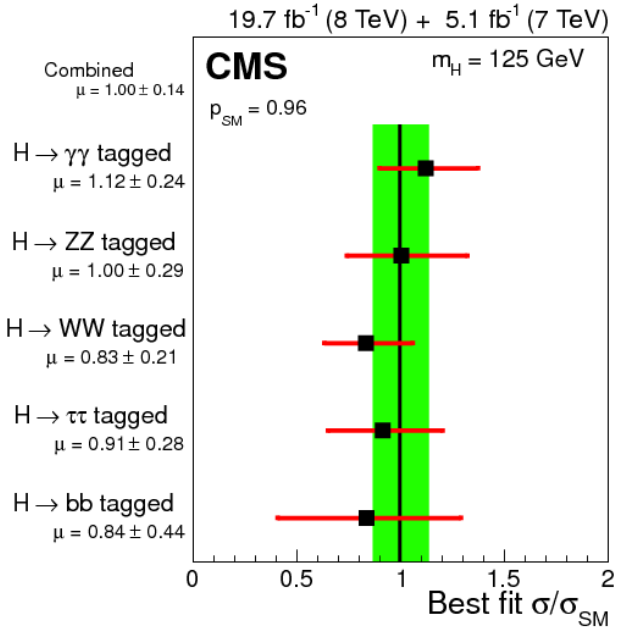


Outline

- Why look for invisibly decaying Higgs bosons?
- Higgs to invisible at CMS
- The vector boson fusion (VBF) channel search
- Results

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

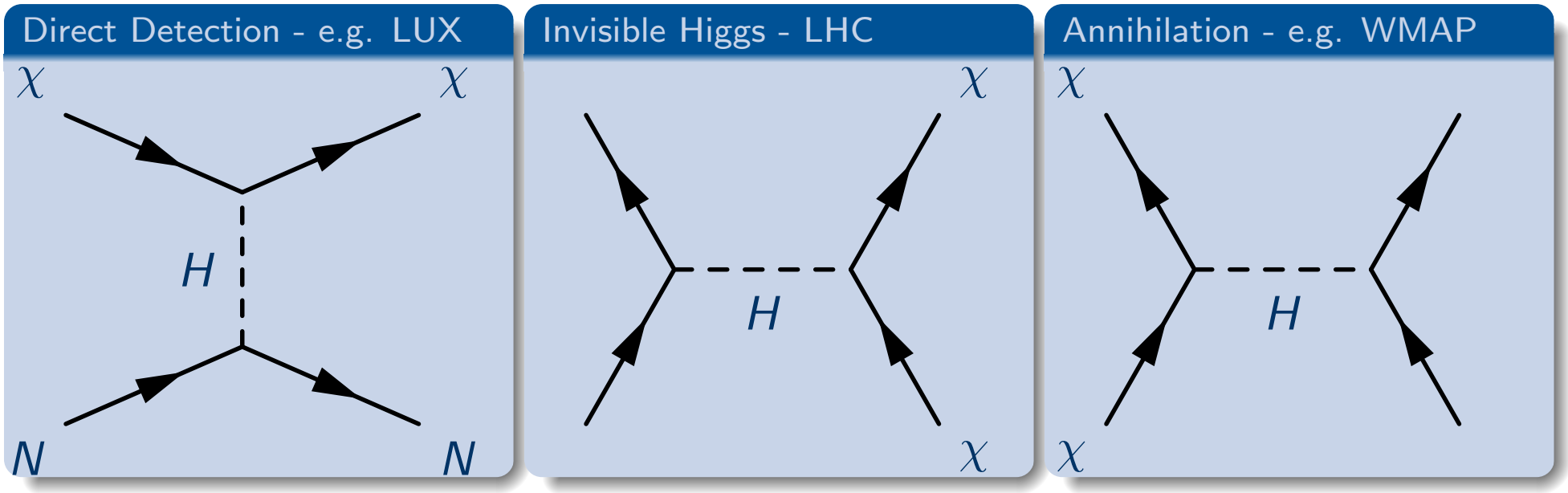


CMS-HIG-14-009

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

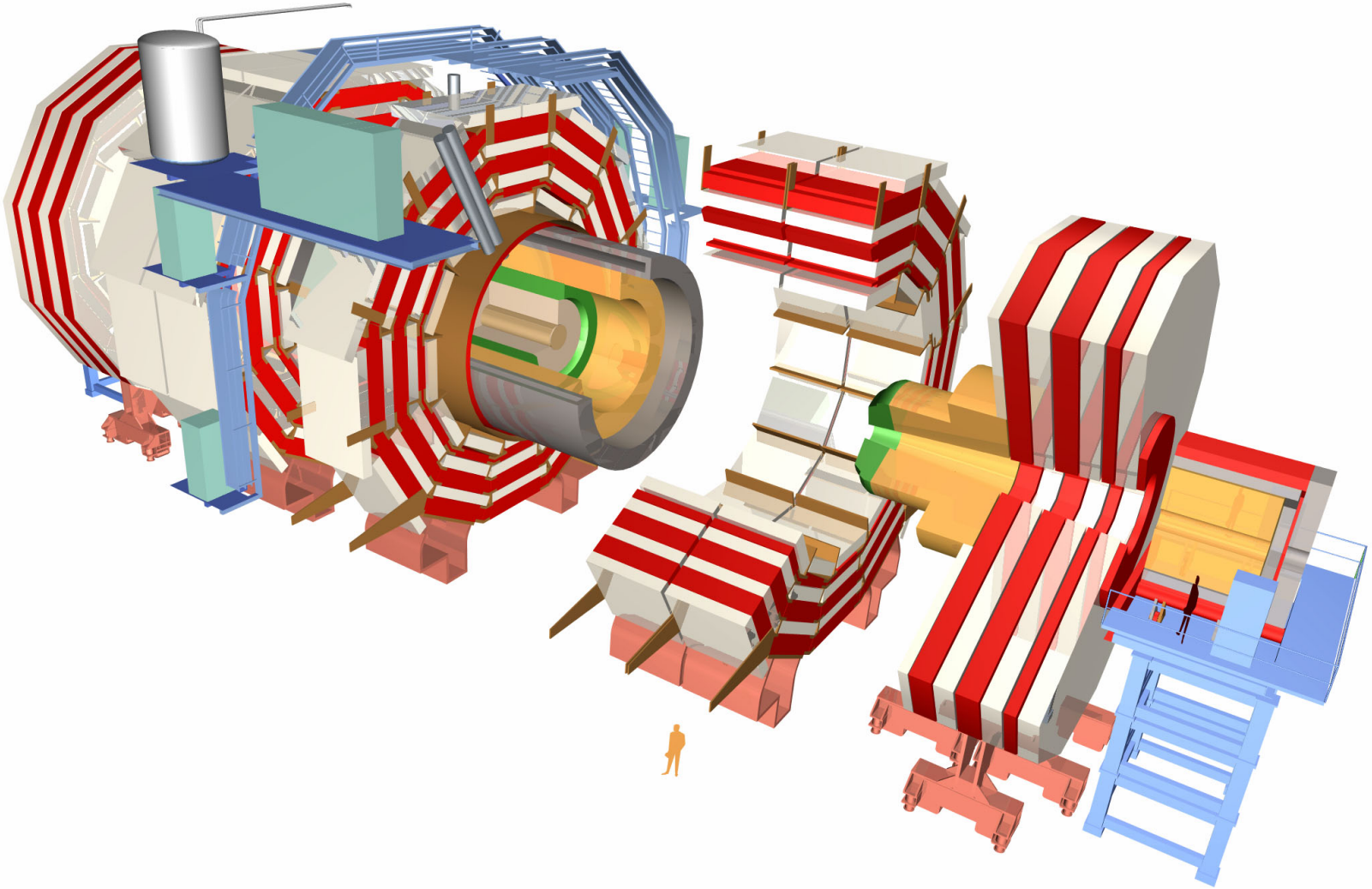
Signatures of Dark Matter (DM)

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



- Limits on $\mathcal{B}$(H→inv) complement/are complemented by other experiments

CMS



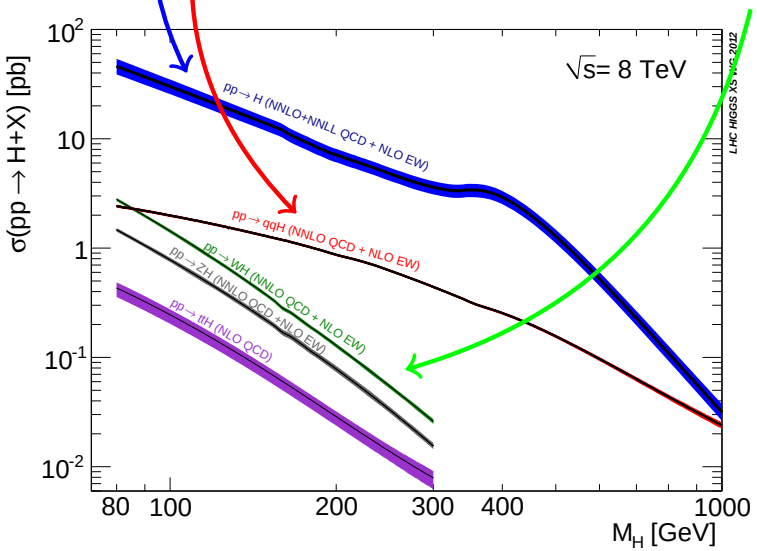
Higgs to invisible at CMS

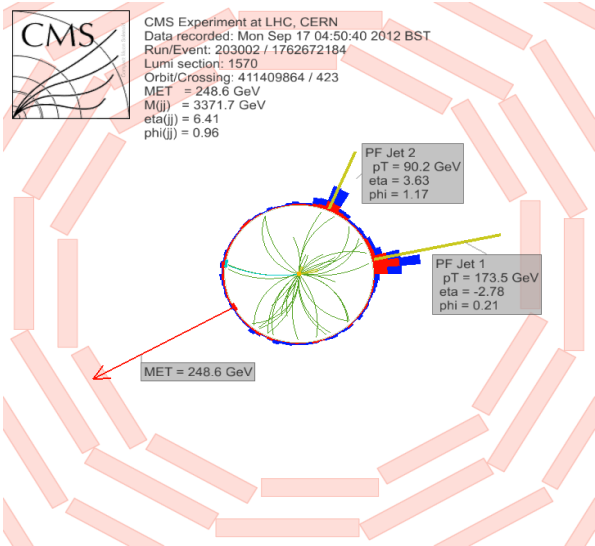
- Indirect: Look for effect of BSM Higgs decays on Higgs total width
- Direct: Use channels where the Higgs recoils against a visible system

  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



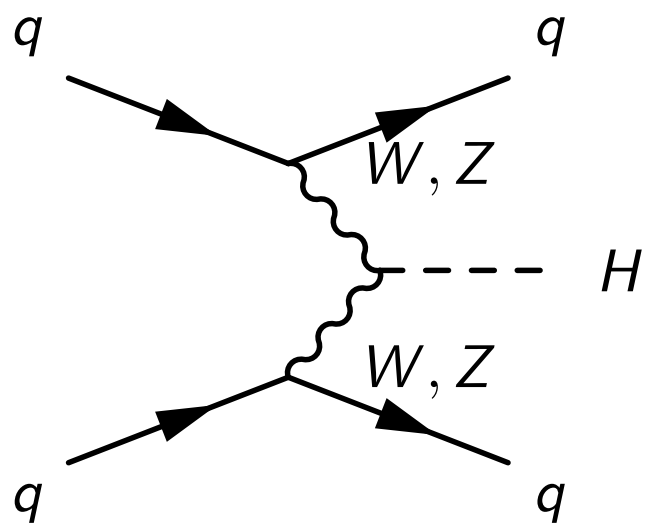


CMS VBF History

- CMS ran two sets of triggers in 2012:
  - prompt: reconstructed immediately
  - parked: looser thresholds, reconstructed in long shutdown
- Current CMS published result using full run I prompt dataset
  - VBF only observed(expected) 95% C.L. limit on $B(H \rightarrow inv)$ for m_H=125 GeV is 0.65 (0.49)
- New analysis presented today uses full run I parked dataset

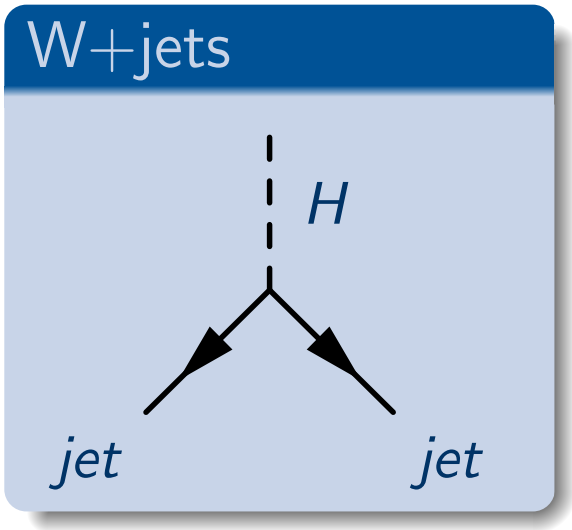
VBF: strategy

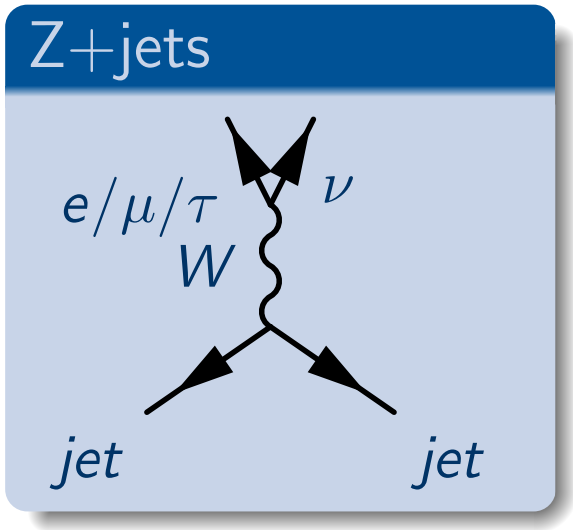
- Select events with two VBF jets + MET:
  - no colour connection between jets means large η gap
- QCD background difficult to model:
  - use tight selection to remove
- Restricted phase space necessitates data driven background estimation

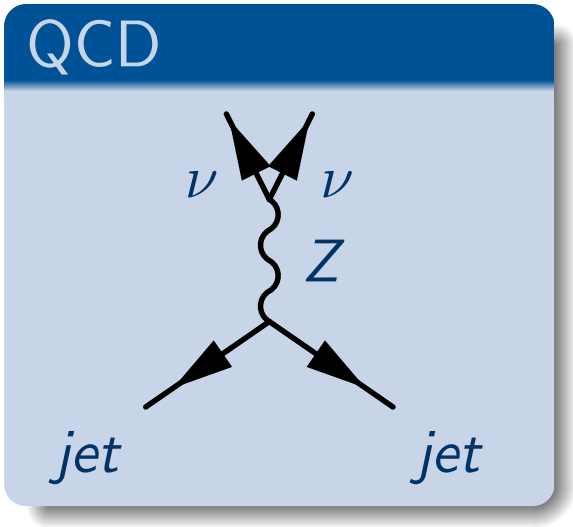


VBF: selection

- Main backgrounds: $W \to \ell\nu / Z \to \nu\nu$+jets, QCD, top
  - Veto events with leptons present
  - Require MET to be well separated from any jets
  - Require MET to be significant compared to event activity





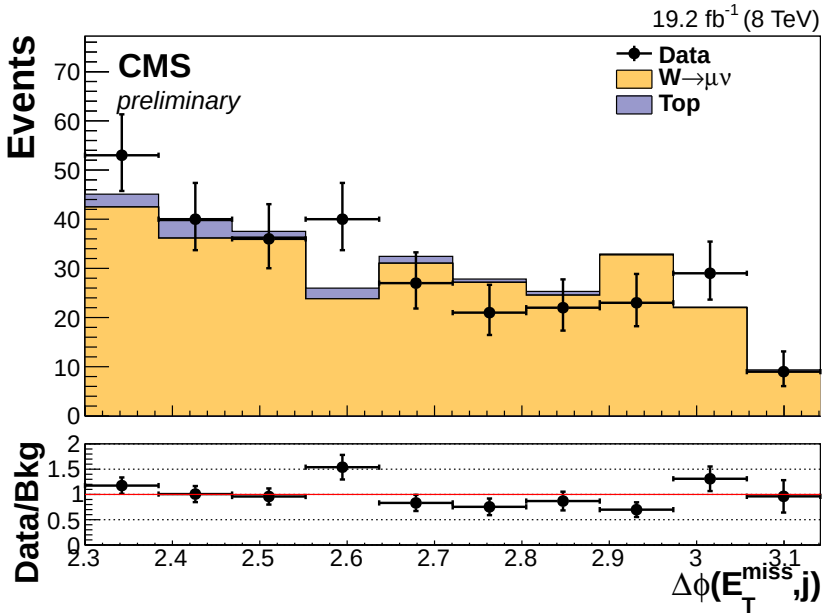


VBF: background estimation

- All major backgrounds have data driven normalisation
- Most backgrounds from missed lepton or misreconstructed jet
  - use control region where object is reconstructed

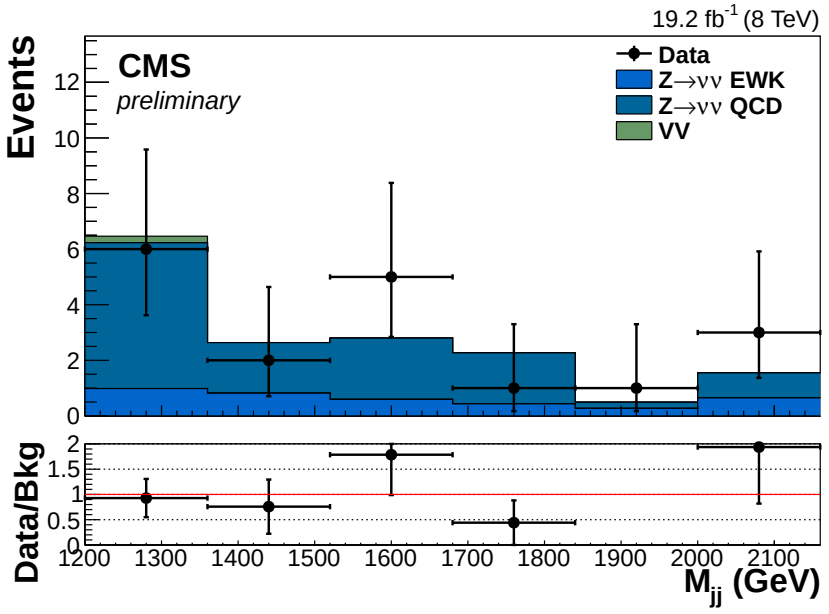
$$N^{sig}_{bkg} = (N^{control}_{obs} - N^{control}_{other\ bkgs}) \cdot \frac{N^{sig}_{MC}}{N^{control}_{MC}}$$

$W \to \mu\nu$ control region



CMS-PAS-HIG-14-038

$Z \to \nu\nu$ control region



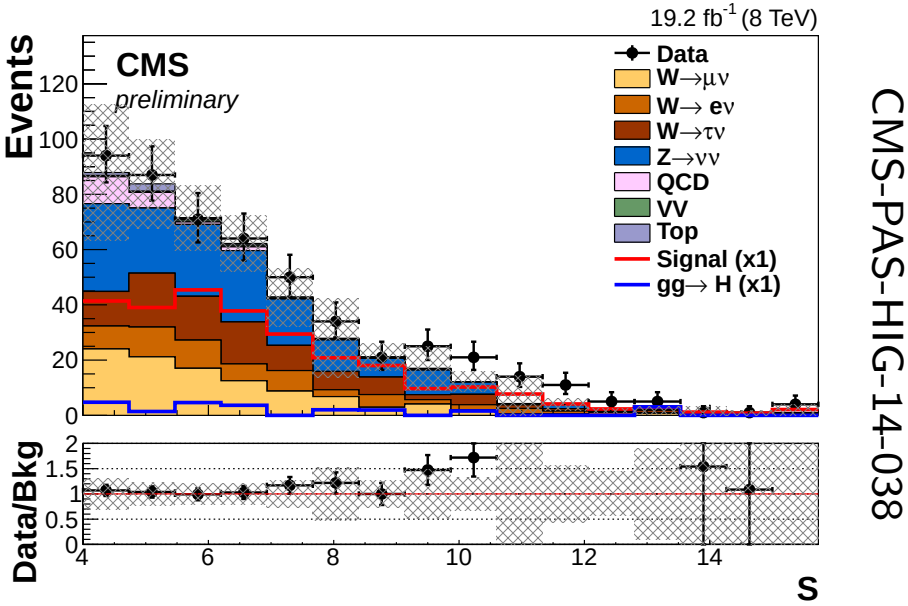
CMS-PAS-HIG-14-038

VBF results

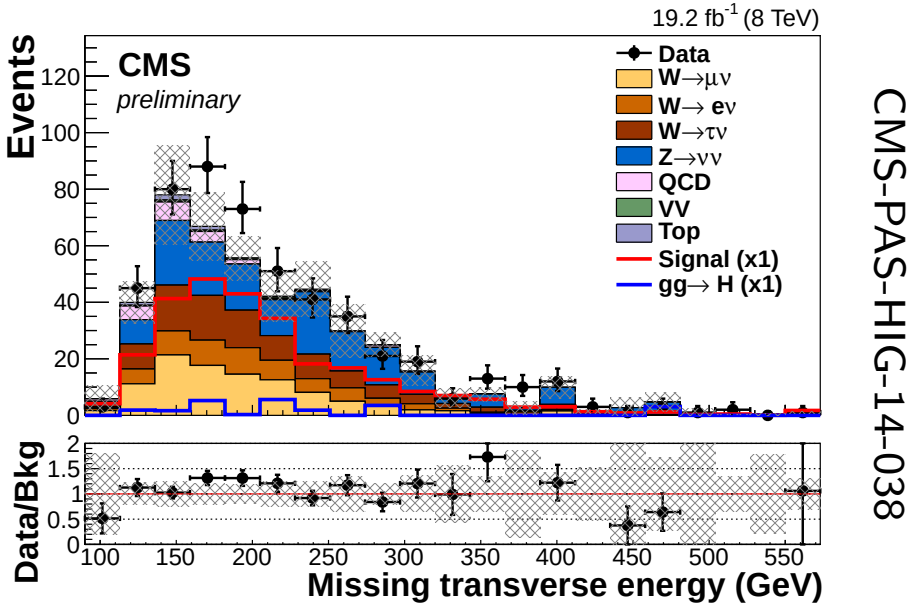
Total background	$439.7 \pm 41.0(stat.) \pm 55.8(syst.)$
VBF H(inv.) assuming B(H→inv)=100%	$273.4 \pm 31.2(syst.)$
ggF H(inv.) assuming B(H→inv)=100%	$22.6 \pm 15.6(syst.)$
Observed data	508

- Compatible with the background hypothesis

Signal region

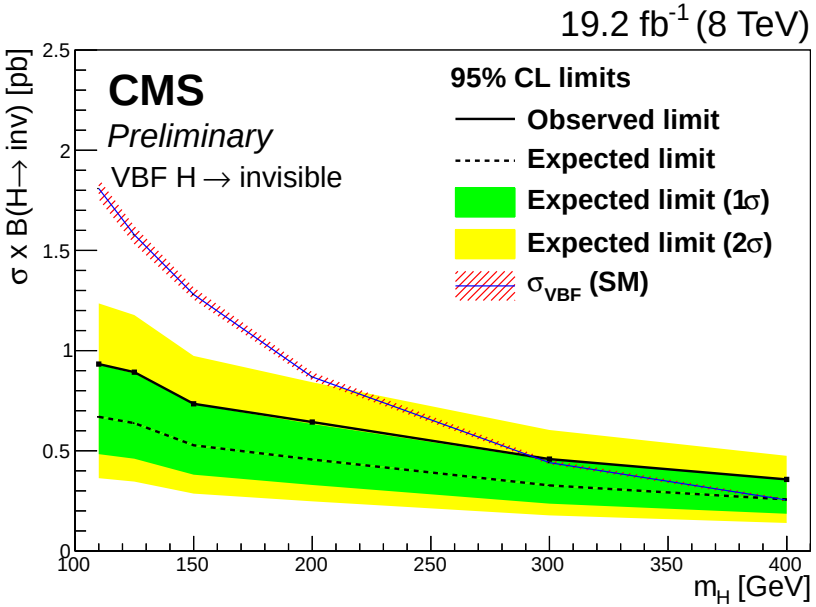


Signal region

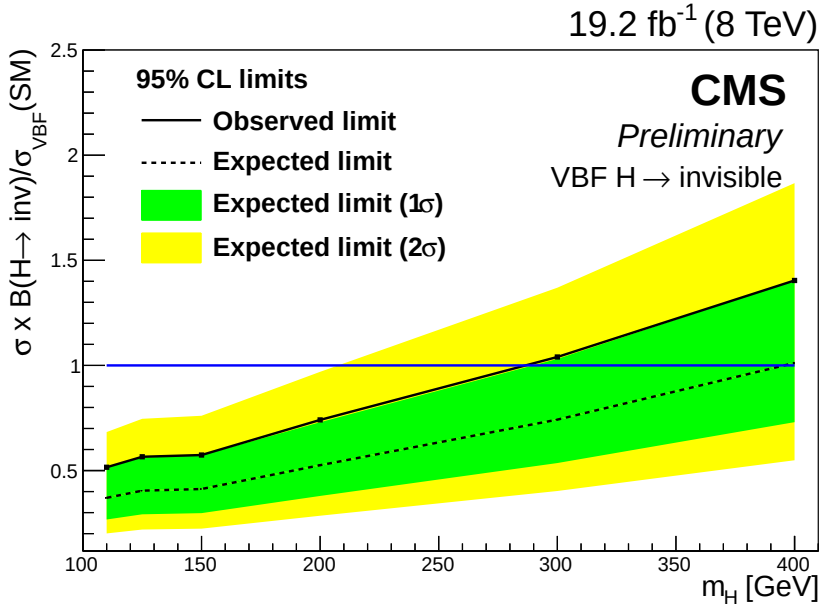


VBF limits

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



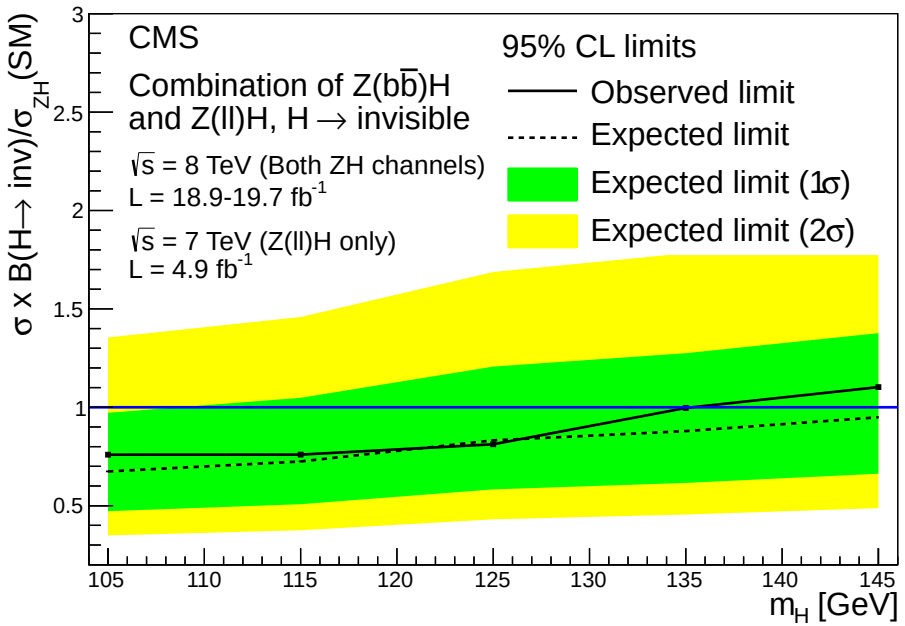
CMS-PAS-HIG-14-038



CMS-PAS-HIG-14-038

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

Combined Results

- 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)

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)

Conclusions

- A direct search for Higgs boson decays to invisible final states has been carried out in the VBF channel
  - No significant excesses are seen over the background predictions
- This has been combined with the results in the Z($\ell\ell$)H and Z(bb)H channels
- The combined limit is 47(35)% observed (expected) at 95% C.L. for $m_H = 125$GeV

Backup

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

- $W \to e/\mu\nu$ control region formed by swapping lepton veto for e/μ requirement
- $W \to \tau\nu$ control region formed by requiring a hadronic tau

- not many events with hadronic taus, need to loosen requirements
- assign a 20% systematic to $W \to \tau\nu$ to compensate

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

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

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

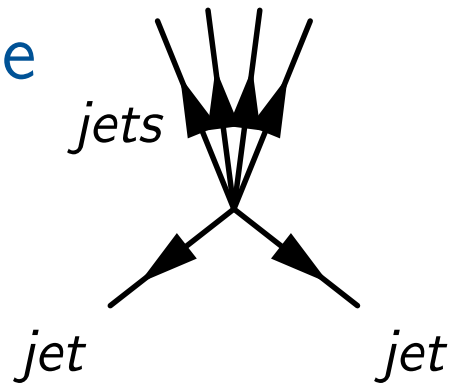
Z($\ell\ell$)H outline

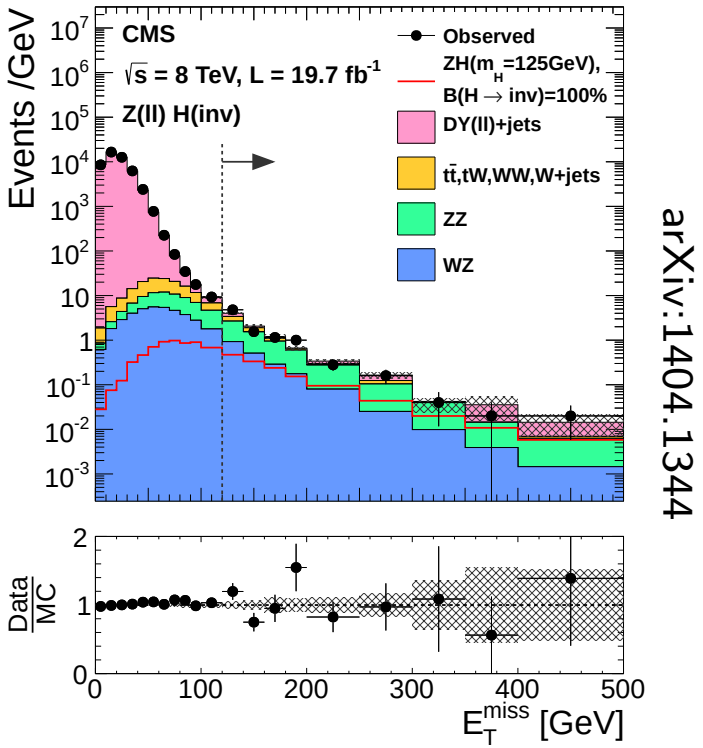
Signal Topology and Selection

- 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





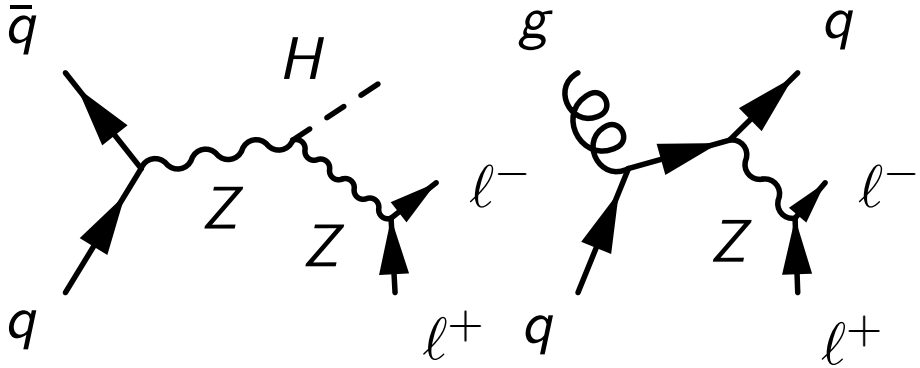
Z($\ell\ell$)H background estimation

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

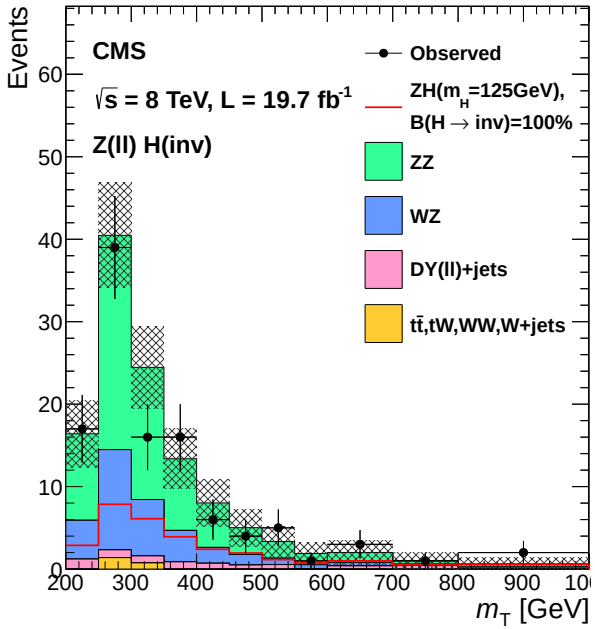
- Estimated from $e\mu$ events and Z peak sidebands:
  - $m_{\ell\ell}$ 40-70 and 110-200 GeV
  - $N^{sig}_{\ell\ell} = N^{sig}_{e\mu} \cdot N^{SB}_{\ell\ell} / N^{SB}_{e\mu}$

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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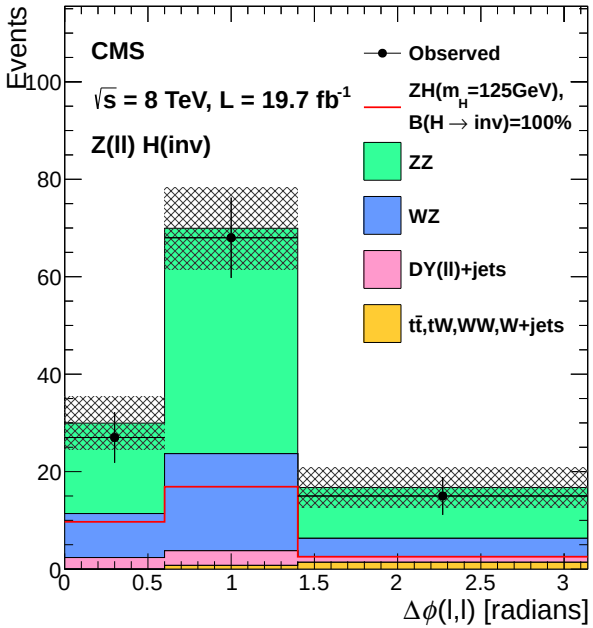


Z(bb)H outline and backgrounds

Signal Topology and Selection

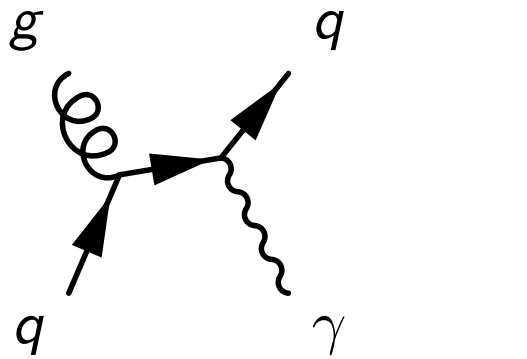
- Two b-tagged jets:
  - $p_T > 30/60$ GeV, $p_{Tjj} > 100 - 130$ GeV
- Three bins in MET
  - 100-130, 130-170, > 170 GeV

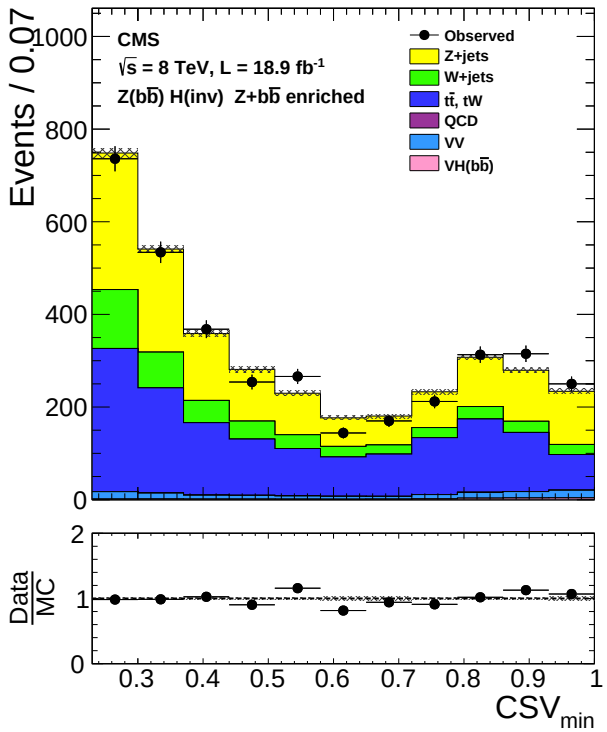
Backgrounds and Rejection Cuts

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



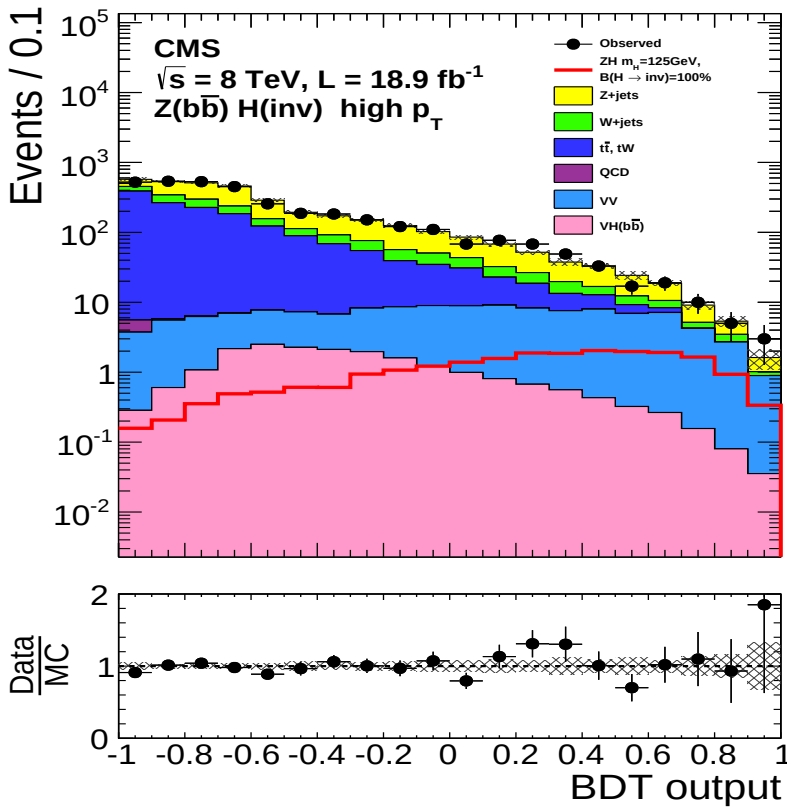


arXiv:1404.1344

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)%



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