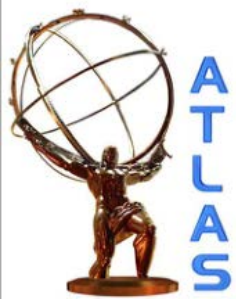

Search for invisible decays of the Higgs Boson at the LHC

Andy White
University of Texas at Arlington

for the ATLAS and CMS Collaborations

LHCP2015 THE THIRD ANNUAL CONFERENCE ON LARGE HADRON COLLIDER PHYSICS
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St. Petersburg, Russia

Introduction and Motivation

- Results on Higgs boson couplings to date indicate that the discovered particle at M_H = 125 GeV is consistent with the Standard Model expectations.

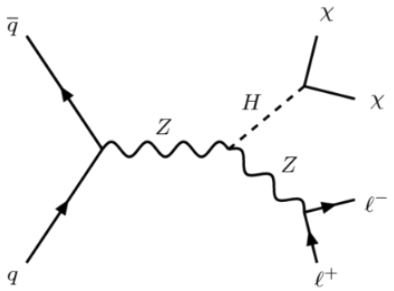
- But, the total branching ratio of BSM Higgs decays could be at the 30-40% level
  (ATLAS-CONF-2015-004,
  CMS - Eur. Phys. J. C. (2014) 74:2980)

- A natural question is whether the Higgs, which is assumed to be ubiquitous in our universe, could be coupled to as yet undiscovered particles, such as those making up the Dark Matter.

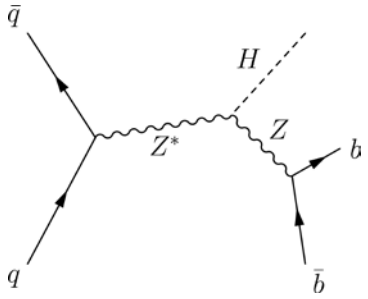
- If indeed the Higgs does couple to Dark Matter, then the limit on the associated branching fraction can be used to set a limit on the Dark Matter- nucleon interaction – mediated by the Higgs.

Search channels for Higgs to Invisible

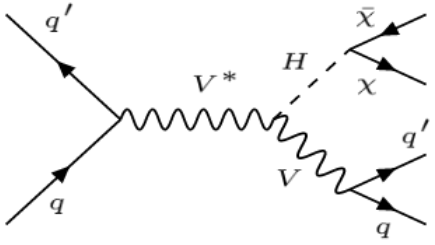
Zll + MEt

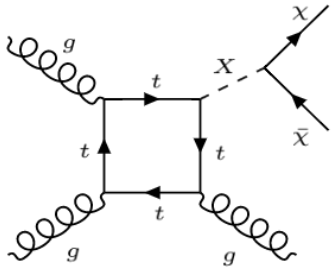


Zbb + MEt

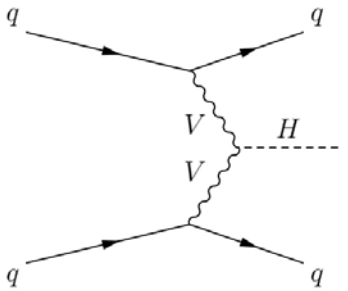


V/jet + Met modes

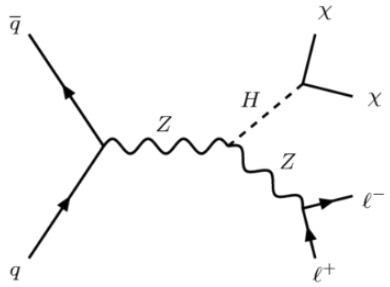




Vector Boson Fusion



p p -> Z(-> ll) + H(-> invisible)



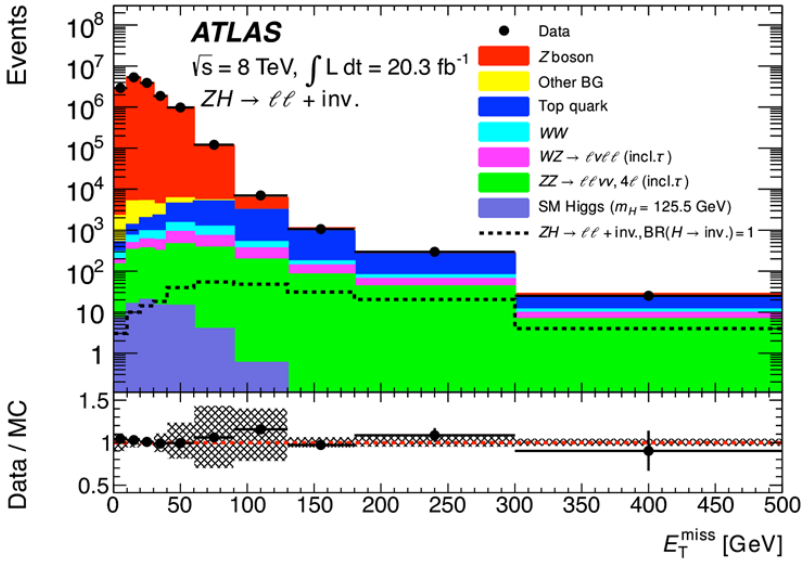
Trigger: single or di-lepton

First selection: 76 < m_{ll} <106 GeV

Steeply falling Z background -> require E_T^{miss} > 90 GeV

Reject events with fake E_T^{miss} from mis-recon energy: $\Delta\phi(E_T^{miss}, \; p_T^{miss}) < 0.2$

E_T^{miss} distribution before suppression of Z+jets background:



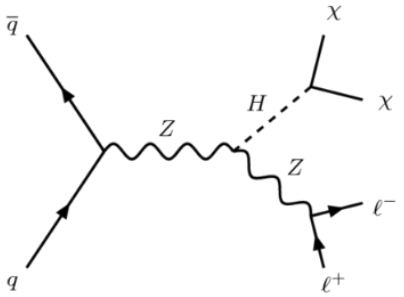
Cuts to select events with expected signal characteristics:

- Invisibly decaying Higgs ~ opposite Z: $\Delta\phi(p_T^{ll}, E_T^{miss})$ > 2.6
- Boost of Z -> small ll opening angle: $\Delta\phi$(l,l) < 1.7
- p_T^{ll} and E_T^{miss} should be similar: $|E_T^{miss} - p_T^{ll}|/p_T^{ll}$ < 0.2
- No reconstructed jets p_T > 25 GeV and $|\eta|$ < 2.5

Backgrounds

- Dominant backgrounds: SM ZZ, SM WZ from simulation
- Other backgrounds, with genuine isolated lepton pair, (ttbar, WW, Wt, Z->$\tau\tau$) estimated from data eμ.
- Z(ll)+jets background estimated using data-driven method, and (small) background from W(lν)+jets, multijet estimated from data with one failing lepton.

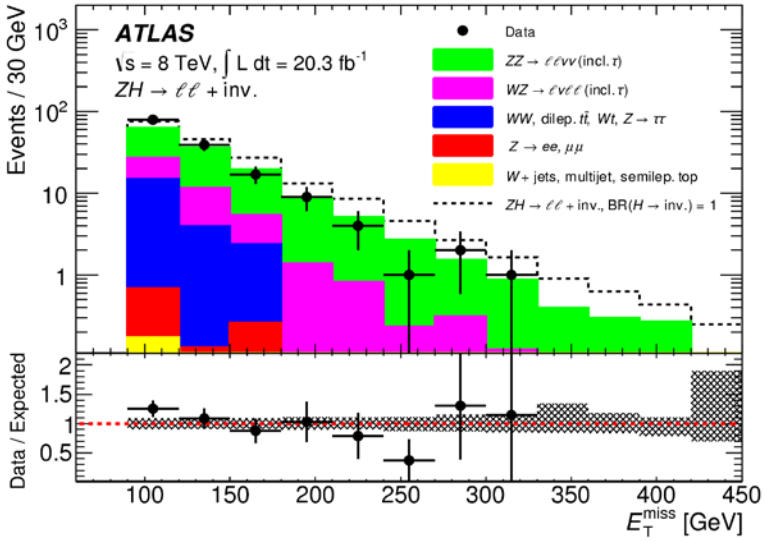
p p -> Z(-> ll) + H(-> invisible)

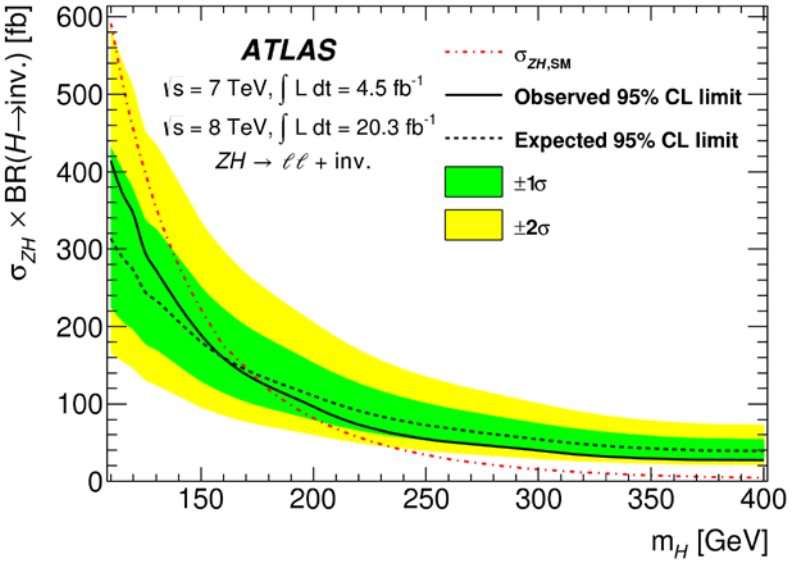


Main systematics:
- SM ZZ theory 8%
- Signal theory (ZH) 3.5 - 5.7%
- JES, JER 3-6 %

8 TeV:
Total background $138 \pm 4 \pm 9$
Signal (125 GeV, SM,BR = 1) 44 $\pm 1 \pm 3$
Observed 152

E_T^{miss} after full selection

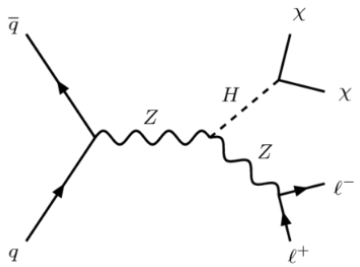




Results of maximum likelihood fit to E_T^{miss}:
upper limit on BR(H-> Inv):
75% (62% expected) limit for M_H = 125 GeV to invisible

PRL 112, 201802 (2014)

p p -> Z(-> ll) + H(-> invisible)



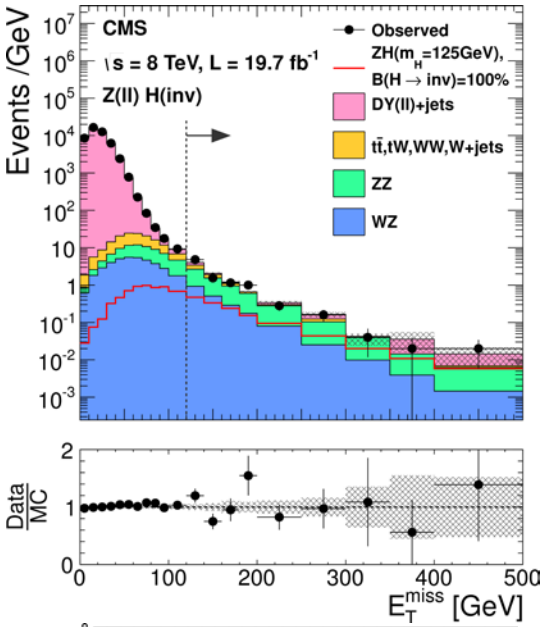
Trigger: dilepton (e,μ) p_T(leading) >17 GeV, p_T(subleading) > 8 GeV; single μ.

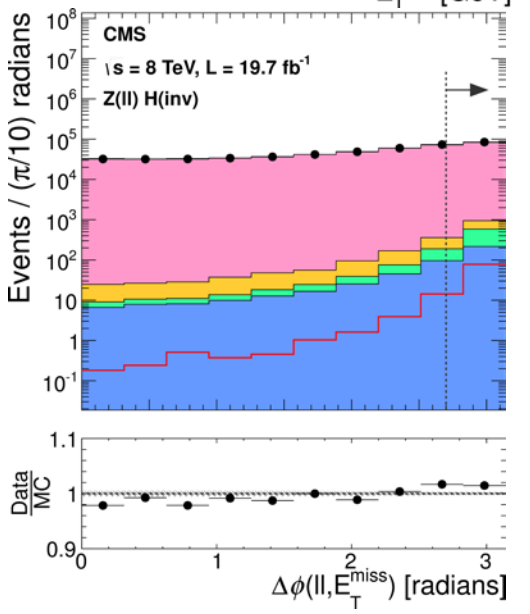
Event selection: e^+e^-, $\mu^+\mu^-$ each $p_T > 20$ GeV, $|M_{ll} - M_Z| < 15$ GeV
Accept events with 0 or 1 jet -> treat separately (S/B's differ)
(*cf. ATLAS jet suppression*)
Reject events with ≥ 2jets with pT > 30 GeV (DY+jets suppression)

- Dominant backgrounds: ZZ, WZ – from simulation
- DY+jets, ttbar , WW, W+jets – from CR's in data.

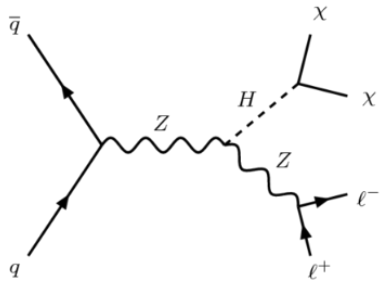
Background reduction:
- Top – b-tag or soft muon rejection
- WZ – reject events with additional (≥ 2) leptons

Remaining selection (after optimization for M_H = 125 GeV):
$E_T^{miss} > 120$ GeV, $\Delta\phi(p_T^{ll}, E_T^{miss}) > 2.7$, $|E_T^{miss} - p_T^{ll}|/p_T^{ll} < 0.25$





p p -> Z(-> ll) + H(-> invisible)

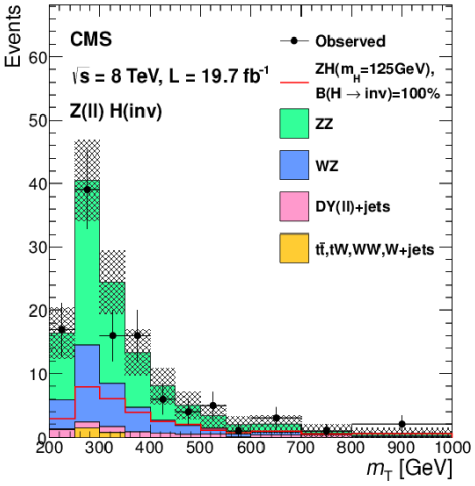


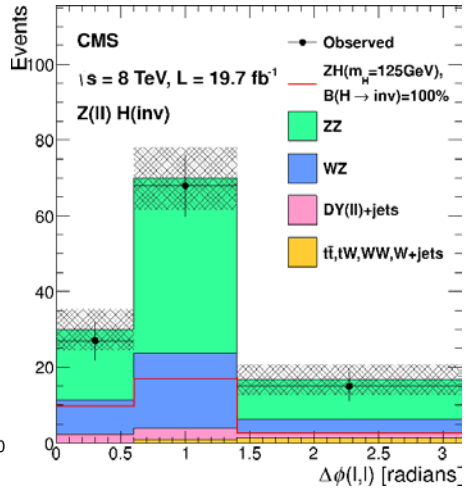
Background(s) estimation:

- WZ, ZZ: from σ(NLO) using MCFM
- DY + jets: from a γ+jets sample with event weight normalization to Zll + jets
- Other (ttbar, tW, WW, W+jets, Zττ): use control sample of ($e^{\pm}$, $\mu^{\pm}$) with scale factors to estimate e^+e^-, $\mu^+\mu^-$

Process	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	
	ee	μμ	ee	μμ
	0 jet selection			
$Z/\gamma^* \to \ell^+\ell^-$	0.1 ± 0.1	0.2 ± 0.2	0.2 ± 0.3	0.9 ± 1.4
$WZ \to 3\ell\nu$	1.7 ± 0.2	2.0 ± 0.3	10.4 ± 1.6	14.1 ± 1.7
$ZZ \to 2\ell 2\nu$	5.8 ± 0.7	7.8 ± 0.9	26.4 ± 3.0	35.9 ± 3.6
$t\bar{t}$, Wt, WW & W+jets	1.1 ± 6.4	1.0 ± 3.1	0.4 ± 1.5	0.7 ± 2.1
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(%)	26	28	28	24
	1 jet selection			
$Z/\gamma^* \to \ell^+\ell^-$	0.2 ± 0.2	$0.0 \pm {}^{1.3}_{0.0}$	2.0 ± 3.8	3.0 ± 5.6
$WZ \to 3\ell\nu$	0.8 ± 0.1	0.9 ± 0.2	3.3 ± 0.4	3.8 ± 0.5
$ZZ \to 2\ell 2\nu$	1.1 ± 0.2	1.4 ± 0.2	4.8 ± 0.5	6.3 ± 0.7
$t\bar{t}$, Wt, WW & W+jets	0.5 ± 0.6	0.5 ± 0.8	0.4 ± 1.7	0.7 ± 1.3
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 (%)	15	18	15	18

Main systematics:
Signal theory 9%
Background theory 8%





Limits determined from profile likelihood fit to 2-D distributions $\Delta\phi_{ll}$ and m_T of di-lepton-E_T^{miss} system (*cf. ATLAS fit to* E_T^{miss})

For m_H = 125 GeV: Observed (expected) limit on $\sigma.B(H \to inv)/\sigma_{SM}$ is 0.83 (0.86)

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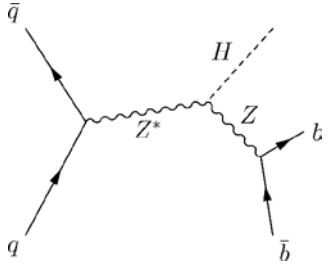
p p -> Z(-> bbar) + H(-> invisible)



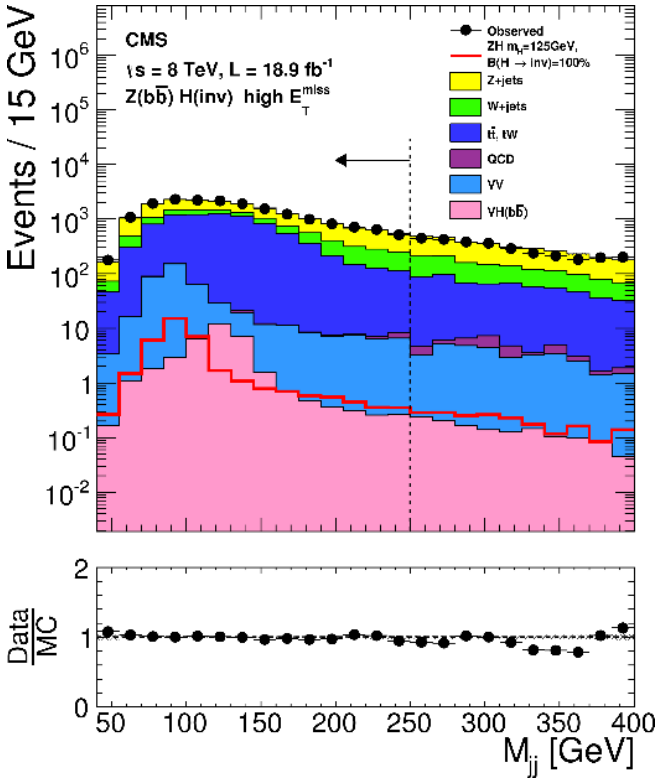
Triggers: E_T^{miss}> 150 GeV and several E_T^{miss}+jets (luminosity dependent) combinations.

Event selection – large E_T^{miss} and jet pair consistent with Z -> bbar:

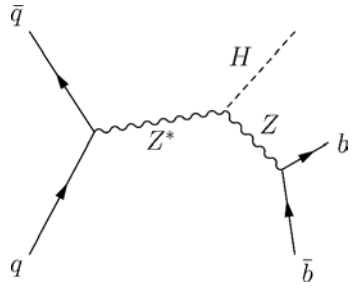
- Large E_T^{miss}
- Large Z/H azimuthal separation
- False E_T^{miss} suppression
- ttbar, WZ reduction: no isolated lepton pT > 15 GeV
- Z formed from jet pair with greatest vector p_T^{jj} and jets tagged by CSV b-tagging algorithm
- M_{jj} below 250 GeV

-> Selection optimized for m_H = 125 GeV, BR(H -> inv)=100%

Define three regions in E_T^{miss}:
Low 100 – 130 GeV
Intermediate 130 – 170 GeV
High > 170 GeV



p p -> Z(-> bbar) + H(-> invisible)



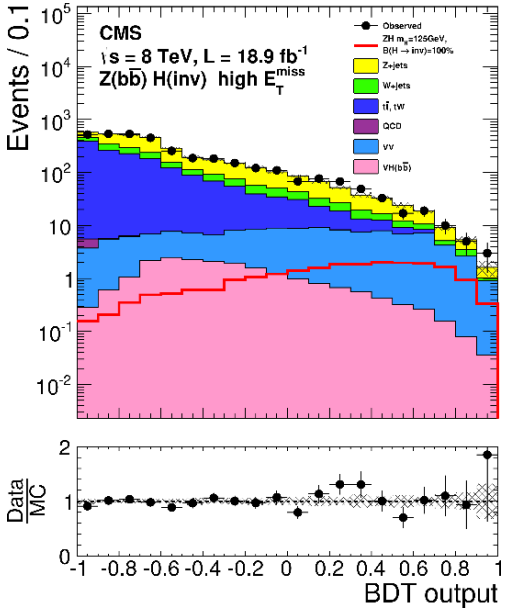
BDT used to enhance heavy flavor production and high boost Higgs boson

- Control regions for BDT input validation and for pre-fit normalizations of dominant backgrounds (W/Z+jets, ttbar)
- Scale factors obtained from fits to b-tag variable distributions

Background estimates, signal predictions

Process	High E_T^{miss}	Intermediate E_T^{miss}	Low E_T^{miss}
$Z(\nu\bar{\nu})H(b\bar{b})$(SM)	2.0 ± 0.3	0.4 ± 0.1	0.1 ± 0.0
$W(\ell\nu)H(b\bar{b})$(SM)	0.5 ± 0.1	0.1 ± 0.0	0.1 ± 0.0
ZZ(bb)	27.7 ± 3.1	11.6 ± 1.3	5.5 ± 0.7
WZ(bb)	10.2 ± 1.6	7.3 ± 0.9	3.1 ± 0.5
VV(udscg)	5.3 ± 1.1	0.3 ± 0.2	0.1 ± 0.1
$Z+b\bar{b}$	61.8 ± 7.1	21.1 ± 2.4	13.2 ± 1.6
Z+b	16.7 ± 1.7	3.2 ± 1.4	0.7 ± 0.9
Z+udscg	7.1 ± 0.3	0.6 ± 0.4	3.1 ± 2.5
$W+b\bar{b}$	15.8 ± 2.2	5.8 ± 0.8	3.0 ± 1.4
W+b	4.7 ± 1.2	0.2 ± 0.3	0.0 ± 0.0
W+udscg	4.9 ± 0.2	1.1 ± 0.3	0.2 ± 0.3
$t\bar{t}$	20.4 ± 1.8	9.6 ± 1.0	8.9 ± 1.1
Single-top-quark	4.1 ± 2.4	3.5 ± 2.0	2.5 ± 0.7
QCD	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
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	48
S/B	6.9%	5.6%	3.9%

Main systematics: signal theory 9%
Background 11%



Limits determined from fit to BDT output.

For mH = 125 GeV: Observed (expected) limit on $\sigma.B(H \to inv)/\sigma_{SM}$ is 1.82 (1.99)
…used in combination with Z(ll) H(inv) to give limit on BR(H -> inv) = 0.81 (0.83) for m_H =125 GeV

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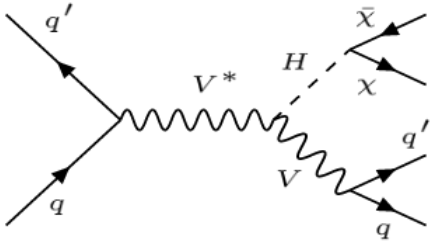
p p -> V(W,Z -> jets) + H(-> invisible)



Trigger (HLT): $E_T^{miss} > 80\ GeV$

Analysis selection:

Require M_{jj} consistent with W/Z + ΔR_{jj} restricted for boosted W/Z.
VBF Higgs production strongly suppressed by M_{jj} cut.
SR's defined with 0, 1, or 2 b-tags

- E_T^{miss} > 120 GeV, p_T^{miss} > 30 GeV, No "loose" leptons, two/three jets |η| < 2.5, p_T > 20 GeV, $p_T^{leading\ jet}$ > 45 GeV
- H_T > 120 (150) GeV for events with two (three) jets
- No additional jets p_T > 20 (30) GeV and |η| < 2.5 (2.5 <|η| < 4.5)

Back-to-back topology:
Strong correlation $E_T^{miss} \leftrightarrow p_T^V$: optimize in four E_T^{miss} ranges:

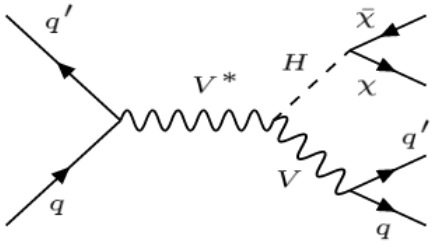
E_T^{miss} range [GeV]	120–160	160–200	200–300	> 300
Variable	Selection			
ΔR_{jj}, 2- and 3-jet events	0.7–2.0	0.7–1.5	< 1.0	< 0.9
m_{jj}, 2-jet events [GeV]	70–100	70–100	70–100	75–100
m_{jj}, 3-jet events [GeV]	50–100	55–100	60–100	70–100

Main backgrounds: V+jets, ttbar

Multi-jet events suppressed by azimuthal cuts between E_T^{miss}, p_T^{miss}, ϕ_{jet}, and ϕ_{dijet} .

V+jets backgrounds estimated from control regions enhanced in W+jets, Z+jets, with simulated events reweighted according to $\Delta\phi$(jet1, jet2) and p_T^V to match data.

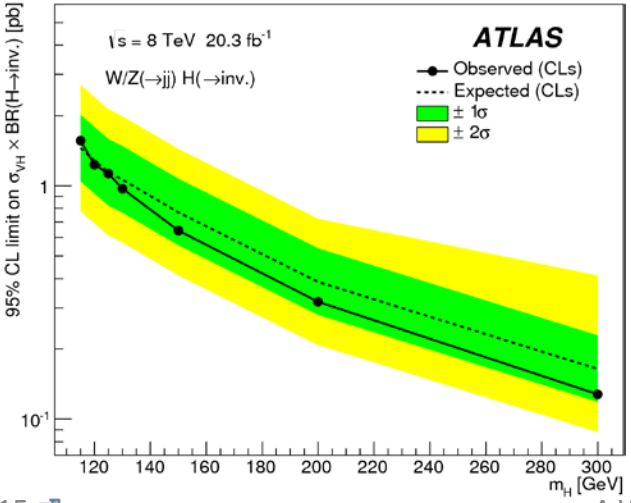
p p -> V(W,Z -> jets) + H(-> invisible)



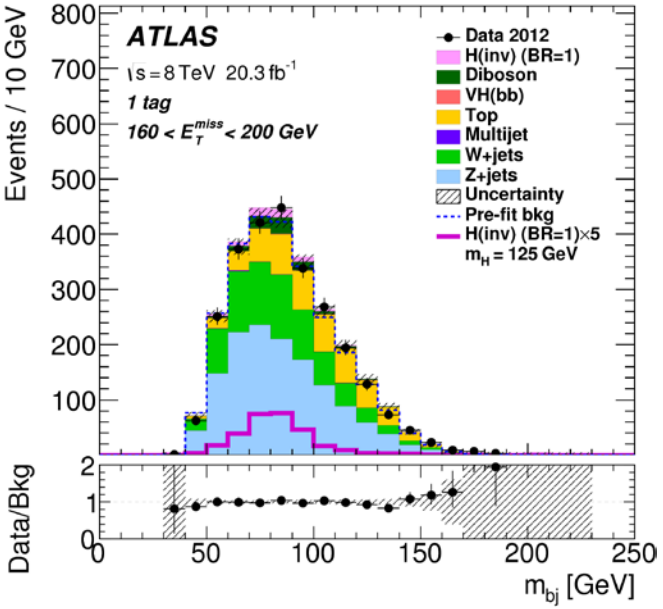
Best fit signal strength extracted from fit to observed E_T^{miss} distributions for signal and sidebands (events failing M_{jj} requirement), and p_T^V distributions for control regions.

Event yields (after profile likelihood fit):

	b-tag category	0-tag			1-tag			2-tag		
	Process	2-jet events								
Background	Z+jets	24400	±	1100	1960	±	200	164	±	13
	W+jets	20900	±	770	1160	±	130	47	±	7
	$t\bar{t}$	403	±	74	343	±	65	57	±	10
	Single top	149	±	16	107	±	14	11	±	2
	Diboson	1670	±	180	227	±	25	64	±	7
	SM VH($b\bar{b}$)	1.5	±	0.5	6	±	2	3	±	1
	Multijet	26	±	43	8	±	7	0.7	±	0.9
Total		47560	±	490	3804	±	64	347	±	15
Signal	$gg \to H$	403	±	95	25	±	6	2.1	±	0.5
	$W(\to jj)H$	425	±	45	44	±	6	0.6	±	0.1
	$Z(\to jj)H$	217	±	19	42	±	4	26	±	2
Data		47404			3831			344		



Post-fit example:

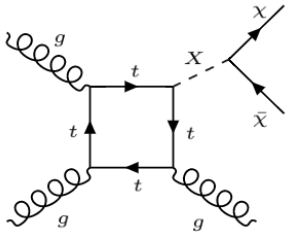


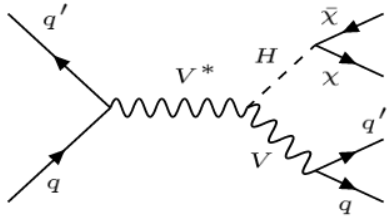
Set BR for H -> Invisible:

Upper limit of 78% (86%) at 95% CL for Higgs -> Invisible at M_H = 125 GeV

EPJC (2015) 75:337

p p -> V/Jet + E_T^{miss}





Search for new physics in mono-jet and mono-V states -> interpret for BR(H-> invisible)

Trigger: E_T^{miss} > 120 GeV; $E_T^{miss\prime}$ (Pflow) > 95/105 GeV +$p_T^{jet} > 80$ GeV

Event selection: large E_T^{miss} , ≥ 1 jet, $\Delta\phi(E_T^{miss}$, jet) > 2, no well identified, isolated e, μ, γ, p_T > 10; τ p_T > 15 GeV.

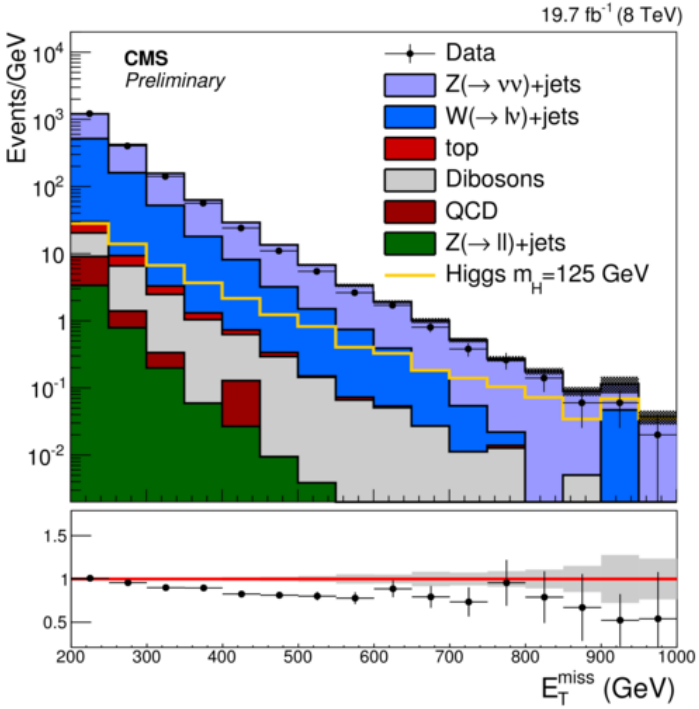
Three categories of events:
Using multivariate V-tagging technique

1) *Unresolved* (boosted) V-tagged:
Single "fat" jet, with 60 < M < 110 GeV

2) *Resolved* V-tagged:
Two high p_T jets passing a multivariate tagger, and with 60 < M < 110 GeV; E_T^{miss} > 250 GeV.

3) *Monojet*: no V-tag, high p_T lead jet, large E_T^{miss}

Three categories combined, after signal selection



p p -> V/Jet + E_T^{miss}

Backgrounds: W(missed charged lepton)/Z(νν) + jets
Control regions used to determine shape and normalization for the V+jets backgrounds in signal region.

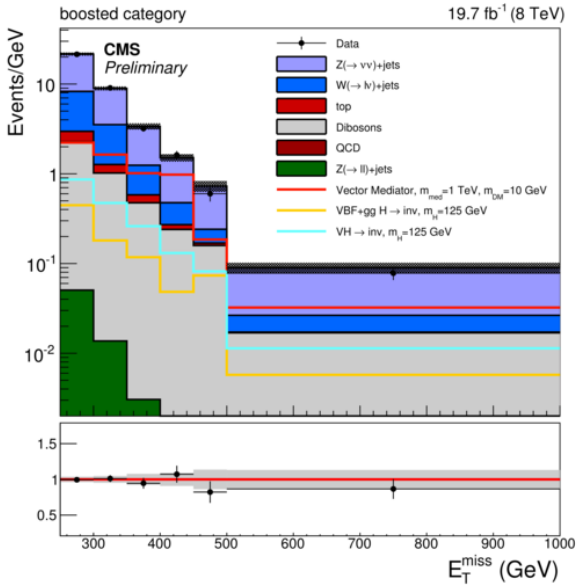
Z -> μμ and γ+jets control regions used to estimate Z(->νν)+jets

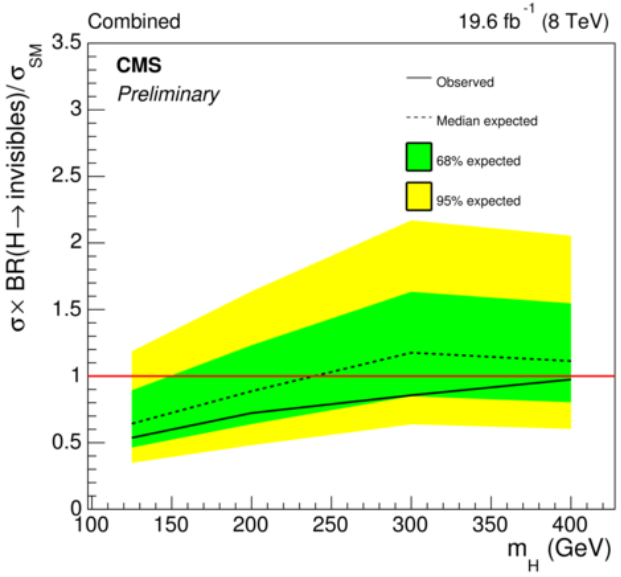
W -> μν + jets control region used to estimate W + jets

E_T^{miss} spectra for V +jets backgrounds corrected by simultaneous likelihood fit across all three CR's.
Resulting reweighted events used to give E_T^{miss} templates in SR.
Signal extraction is from a template fit to E_T^{miss}

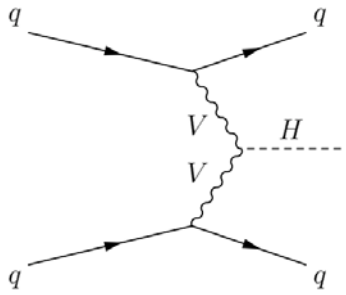
For m_H = 125 GeV: Observed (expected) limit on σ.B(H -> inv)/σ_{SM} from combined categories is 0.53 (0.62)

CMS Preliminary CMS-PAS-EXO-12-055





VBF Higgs -> Invisible



Updated result using triggers from "parked" data stream

Trigger: Level 1 E_T^{miss} > 40 GeV plus Particle Flow jet pair with requirements on p_T, M_{jj}, and $\Delta\eta_{jj}$ varying with data taking period

Event selection: reduce multijet backgrounds from fake and genuine E_T^{miss}

$\eta_{j1}.\eta_{j2} < 0$, $\eta_{j1} < 4.7$, $\eta_{j2} < 4.7$

$p_T^{j1} > 50$ GeV, $p_T^{j2} > 40$ GeV

$\Delta\eta_{jj} > 3.6$, $M_{jj} > 1000$ GeV

$E_T^{miss} > 90$ GeV

$\Delta\phi(E_T^{miss}, j) > 2.0$, $\sigma(E_T^{miss})/E_T^{miss}$

After optimization for best 95% C.L. expected limit for B(H -> inv) for m_H = 125 GeV, impose additional cuts:

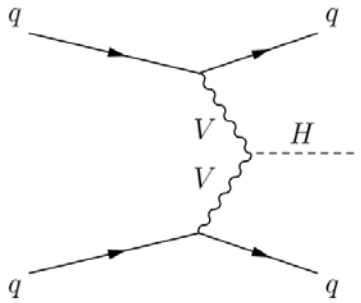
$\Delta\phi(E_T^{miss}, j) > 2.3$, $p_T^{j2} > 45$ GeV, $M_{jj} > 1200$ GeV

Backgrounds:

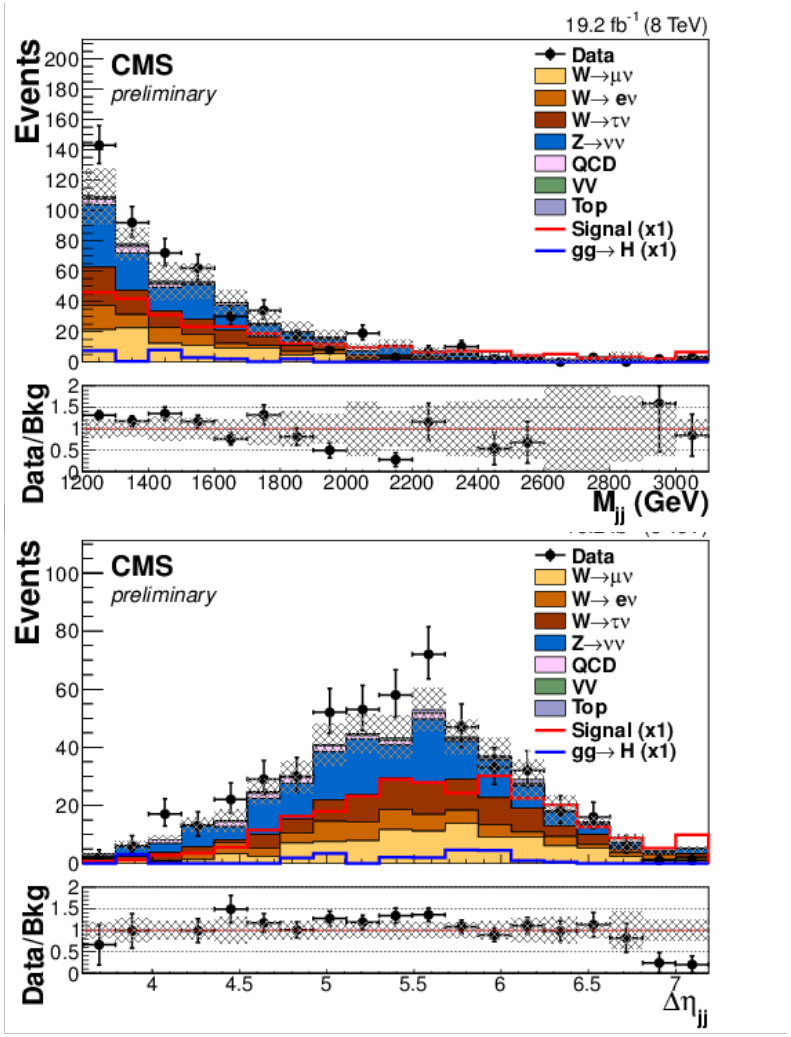
- W, Z estimated from Monte Carlo, normalized to data in independent control regions with inverted lepton requirements
- QCD – estimated from data using non-isolated E_T^{miss} region, (verified by 3-jet region), with normalization from a sideband region

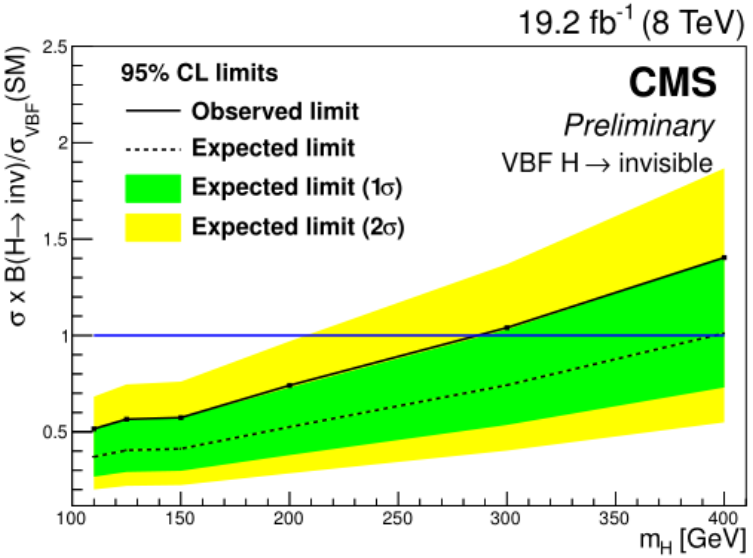
Process	Event yields
$Z \to \nu\nu$	$158.1 \pm 37.3 \pm 21.2$
$W \to \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \to e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \to \tau\nu$	$94.6 \pm 13.1 \pm 23.8$
top	5.5 ± 1.8
VV	3.9 ± 0.7
QCD multijet	17 ± 14
Total Background	$439.4 \pm 40.7 \pm 43.5$
Signal(VBF)	273.1 ± 31.2
Signal(ggH)	23.1 ± 15.9
Observed data	508

VBF Higgs -> Invisible



Results after full selection

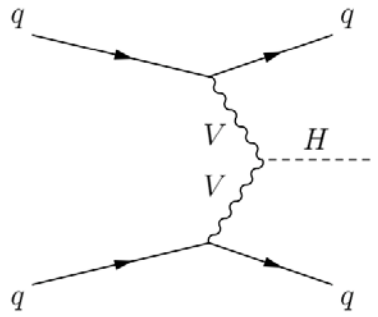




Upper limit of 57% (40%) at 95% CL for Higgs -Invisible at M_H = 125 GeV

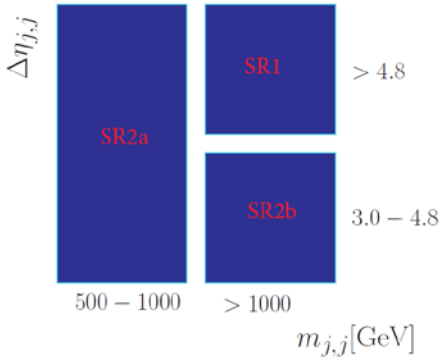
CMS Preliminary: CMS-PAS-HIG-14-038

VBF Higgs -> Invisible



Trigger: $E_T^{miss} > 80\ GeV$

Event selection: 3 orthogonal signal regions



SR1: E_T^{miss} > 150 GeV

- 2 Jets, p_T^{j1} > 75 GeV, p_T^{j2} > 50 GeV in opposite hemispheres, plus central jet veto, pT > 30 GeV
- Veto on jets from b-decay or τ-lepton
- VBF enhancement: $|\Delta\eta| > 4.8$, $M_{jj} > 1$ TeV
- Multijet suppression: $\Delta\phi_{jj} < 2.5$, $|\Delta\phi_{j1}, E_T^{miss}| >$ 1.6 radians, $|\Delta\phi_{j2}, E_T^{miss}| > 1.0$ radians
- Veto on e (p_T^e > 10 GeV), μ (p_T^{μ} > 5 GeV), τ (p_T^{τ} > 20 GeV)

SR2: selections motivated by search with jet + E_T^{miss}

Backgrounds:

Z(->νν) + jets: from Z(->ee/μμ)+jets, and W(->eν/μν) +jets control regions (cf. CMS use of only Zll+jets)

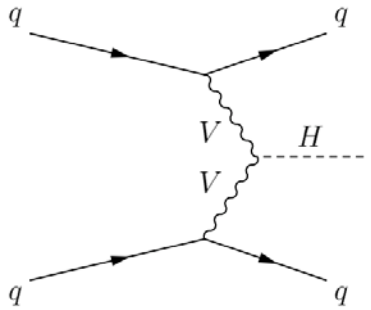
W + jets: from W(->eν/μν)+jets control region

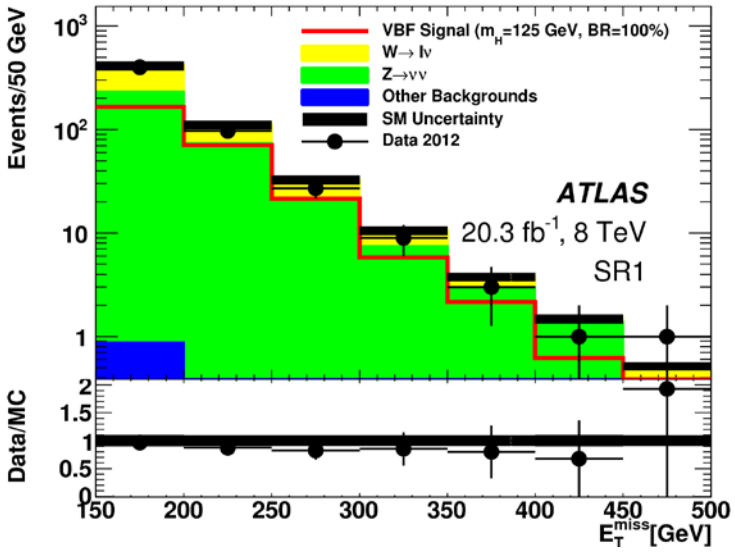
Multijet: from control region with $\Delta\phi$(j, E_T^{miss}) requirement inverted; efficiencies of cuts from control region then applied to signal region

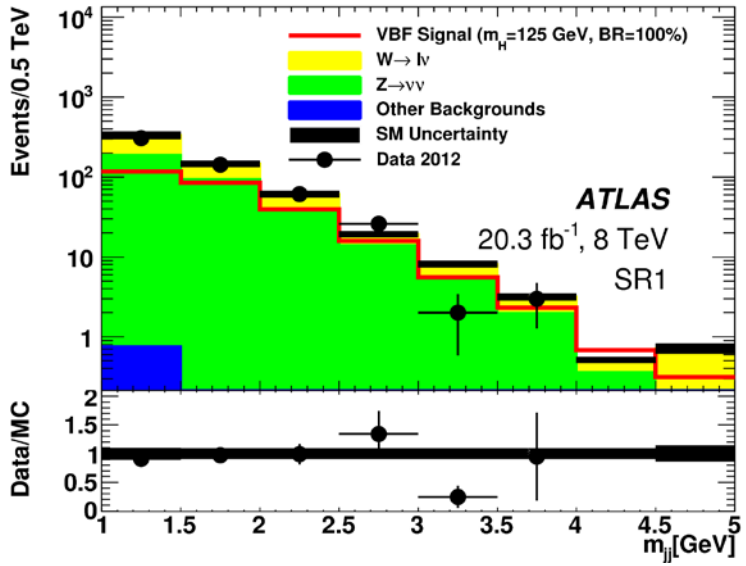
SR1/2 Yields and uncertainties

Signal region Process	SR1	SR2a	SR2b
ggF signal	20± 15	58± 22	19± 8
VBF signal	286± 57	182± 19	105±15
$Z(\rightarrow \nu\nu)$+jets	339± 37	1580± 90	335±23
$W(\rightarrow \ell\nu)$+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

VBF Higgs -> Invisible







Limit on BR(H-> Invisible) computed using maximum likelihood fit to yields in the signal regions and the Z(->ee/μμ)+jets, and W(->eν/μν)+jets control regions.

Upper limit set at 95% CL on BF(H -> Invisible) at 0.28 (0.31), assuming SM production, acceptance and efficiency of 125 GeV Higgs Boson.

ATLAS arXiv: 1508.07869

Summary of limits on BR (Higgs -> Invisible)

Process	Experiment	Observed limit	Expected limit
Z(-> ll) H	ATLAS	75%	62%
Z(-> ll) H	CMS	83%	86%
Z(-> bbar) H	CMS	182%	199%
V(W/Z -> jets) H	ATLAS	78%	86%
V/jet + E_T^{miss}	CMS	53%	62%
VBF H -> inv	CMS	57%	40%
VBF H -> inv	ATLAS	28%	31%

Combined limits on BR (Higgs -> Invisible)

ATLAS – limit from combining VBF + ZH + VH results: BR(H -> invisible) < 25% (27% expected)
(ATLAS HIGG-2015-03)

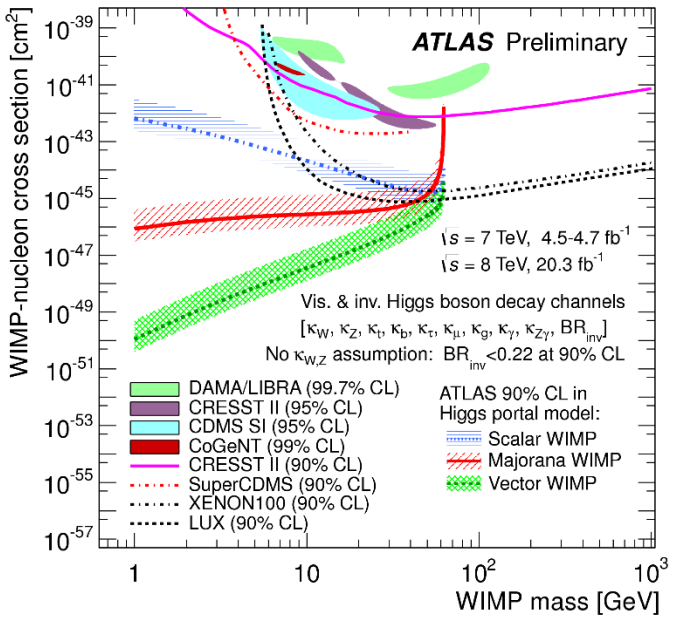
ATLAS – limit from visible* + invisible: BR(H->Invisible) < 23% (24% expected)
(ATLAS HIGG-2015-03)

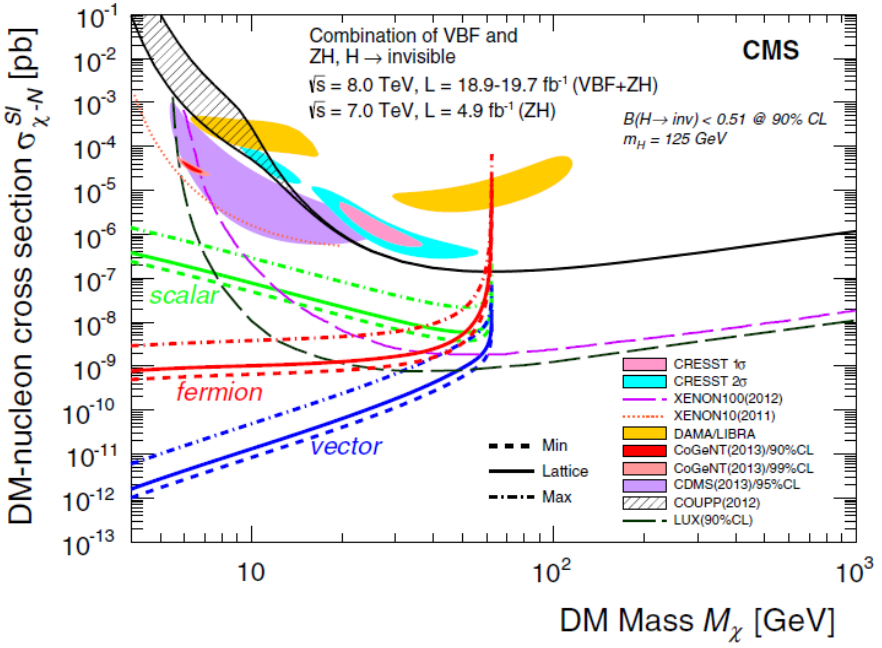
CMS – limit from combining VBF + ZH results: BR(H -> invisible) < 47% (35% expected)
(CMS PAS HIG-14-038)

[CMS – limit from visible + invisible: BR(H -> Invisible) < 49% (32% expected)
but this result used as input the VBF + ZH limit BR(H -> Invisible) < 58% (44% expected)]

* visible decay modes include those to photons, charged leptons and b-quarks and vector bosons. The limit on invisible decays from the measurements of visible decays is 49% (48%) (arXiv: 1507.04548 [hep-ex])

Higgs Portal Dark Matter - Interpretation of limits





Note: vertical scale difference between the ATLAS and CMS results

- Limits on BR(H -> Invisible) interpreted in terms of upper limits on spin-independent DM-nucleon cross-section.
- Results are given for three forms of DM: scalar, Majorana fermion, vector boson.
- Results from direct DM search experiments are shown for comparison.
- Only sensitive up to $M_{DM} < M_H/2$.

CONCLUSIONS

- Searches by the ATLAS and CMS Collaborations have so far shown no evidence of invisible decays of the Higgs Boson.

- Combined limits on the invisible decay of the Higgs Boson with a mass of 125 GeV have been set:

ATLAS: BR(H -> invisible) < 25% (27% expected) (invisible only)
< 23% (24% expected) (visible + invisible)

CMS: BR(H -> invisible) < 47% (35% expected)

- Results have been used to set constraints on spin-independent DM-nucleon cross-sections for $M_{DM} < M_H/2$.