Invisible Higgs decays with the ATLAS and CMS experiments

Precision theory for precise measurements at LHC and future colliders
Quy Nhon, Vietnam (25 Sept-01 Oct 2016)

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Outline

- Higgs portal to Dark Sector.
- ATLAS and CMS results in invisible decays of the 125 GeV Higgs boson:
  - Using jet tagging.
  - Using lepton tagging.
  - Combination
- Summary

Why Higgs Portal to Dark Sector?

- Physics Beyond Standard Model (BSM) needed to explain naturalness, hierachy, dark matter, etc.
- Dark Sector includes dark matter candidates and other dark particles. This talk is mainly concerned about dark matter with weakly interacting massive particles (WIMPs) as the candidates.
- The Higgs portal (more on Dr. Myeonghun Park's talk) is simple with two free parameters: dark matter mass and coupling between the Higgs boson and dark matter. Higgs as the mediator between SM particles and dark matter.
- WIMPs-nucleon scattering cross section exclusion limit can be constrained by the LHC experiments by searching for invisible decay of the Higgs boson, in various production modes.

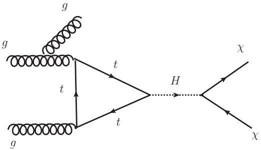
Search for invisible Higgs decay with tagged jets

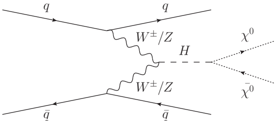
Strategies

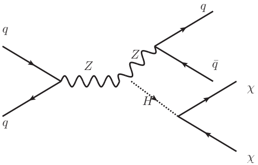
- Select events with large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) + jet(s).
- Assume productions (& acceptance) as in the SM $BR(H \rightarrow ZZ^* \rightarrow 4\nu) = 1.2 \times 10^{-3} \longrightarrow$ result not sensitive to this but rather BSM physics.
- Main backgrounds:
  - QCD multijets with fake $E_{\mathrm{T}}^{\mathrm{miss}}$ can be reduced by large $E_{\mathrm{T}}^{\mathrm{miss}}$ threshold.
  - W/Z+jets with real $E_{\mathrm{T}}^{\mathrm{miss}}$ can be estimated using control regions (CR) with visible decay products where one sees the p_{T} spectrum.
- Use statistical method to get upper limit on BR(H→ invisible), use the limit to make dark matter Interpretation.

Analysis	$\sqrt{s}$(TeV)	Luminosity (fb^{-1})	Publication number
		ATLAS	
Mono-jet	8	20.3	Eur. Phys. J. C (2015) 75:299
VBF H	8	20.3	JHEP 01 (2016) 172
Z/W (→ qq)H	8	20.3	Eur. Phys. J. C (2015) 75:337
Z(→ $\ell\ell$)H	8, 13	20.3, 13.3	ATLAS-CONF-2016-056
Combination	8	20.8	JHEP11(2015)206
		CMS	
Mono-jet	8, 13	19.7, 2.3	CMS-PAS-HIG-16-016
VBF H	8, 13	19.2, 2.3	CMS-PAS-HIG-16-009
Z/W (→ jj)H	8, 13	19.7, 2.3	CMS-PAS-EXO-16-013
Z(→ $\ell\ell$)H	8, 13	19.7, 2.3, 12.9	CMS-PAS-EXO-16-038
Combination mono-jet+VH	13	12.9	CMS-PAS-EXO-16-037
Combination VBF+VH+ggF	7+8+13	4.9+19.7+2.3	CMS-PAS-HIG-16-016

Search for invisible Higgs decay with tagged jets







Mono-jet topology

- High p_{T}, central jet(s).
- Large $E_{\mathrm{T}}^{\mathrm{miss}}$.

VBF topology

- Two high p_{T} well separated forward jets, in opposite hemisphere, large m_{jj}.
- Large separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and jets.
- Central jet veto.
- Large $E_{\mathrm{T}}^{\mathrm{miss}}$.

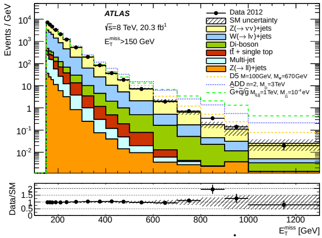
VH topology

- High p_{T} vector boson decaying to jets forming a single "fat-jet" in highly boosted regime (13 TeV), or 2 very close jets in 8 TeV.
- Large $E_{\mathrm{T}}^{\mathrm{miss}}$.

Event Selection

- E_T^{miss} trigger 80 GeV threshold.
- Leading jet $p_T > 120$ GeV, $|\eta| < 2.0$.
- $E_T^{miss} > 250$ GeV for SR1.
- $\Delta\Phi(jet, E_T^{miss}) > 1.0$.
- More signal regions (SRs) in E_T^{miss} .

Dominant systematic uncertainties: jet energy scale & resolution ~10%.

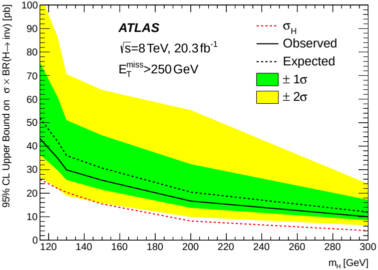


Measured distributions of E_T^{miss} for the SR1 selection compared to the SM expectations.

Background estimation

- $Z(\to)\nu\bar{\nu} + jets$ & $W(\to \ell\nu) + jets$ estimated using CRs.
- Diboson, Z($\to \ell\ell$)+jets (MC-only)
- Multijets and non-collision backgrounds (Data-driven)

Results: @95% CL obs (exp) upper limit on $\sigma \times BR$: 1.51 (1.91) $\times SM$. (from SR3 with $E_T^{miss} > 250$ GeV)

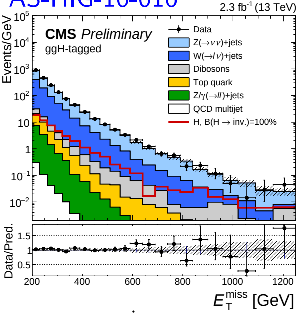


With 2.3 fb^{-1} (2015 CMS-PAS-16-013) & 12.9 fb^{-1} (2016 CMS-PAS-16-037) data.

Event Selection

- E_T^{miss} trigger 90 GeV threshold
- Leading jet $p_T > 100$ GeV, $|\eta| < 2.5$
- $E_T^{miss} > 200$ GeV

CMS-PAS-HIG-16-016



Distributions of E_T^{miss} in data and predicted background contributions.

Background estimation

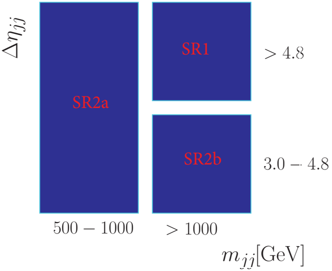
- High rate in ggH but large QCD multijets background (data-driven).
- Using ℓ/γ+jets CRs where emulated $E_T^{miss} = |\overrightarrow{E_T^{miss}} + \sum \vec{p}_T^{\,\ell\ell/\gamma}|$ to constrain $Z(\to \nu\bar{\nu})/W(\to \ell\nu)$ +jets

Fitting method

- Fit to E_T^{miss} distributions in all regions, affected by a sizeable theory systematics on ggH p_T spectrum. The uncertainty in the modelling of E_T^{miss} $\sim 2\%$ to 5%.

Results: Upper limits on $\frac{\sigma \times BR}{\sigma_{SM}}$ @95% CL.

Luminosity [fb^{-1}]	Expected	Observed
2.3	1.14	1.46
12.9	0.85	0.48



Event Selection

- Define 3 orthogonal SRs, see the graph.
- $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers (60, 80 GeV threshold), $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ *GeV* for SR1 (high sensitivity)
- Lepton veto.
- VBF topologies on two jets, central jet veto, $\Delta\Phi(jx, E_{\mathrm{T}}^{\mathrm{miss}}) > 1$ rad.

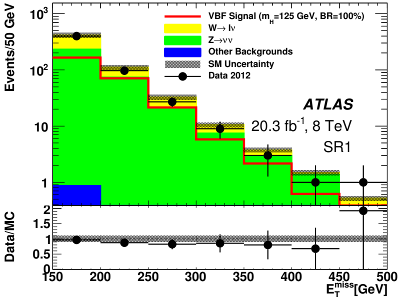
Background Estimation

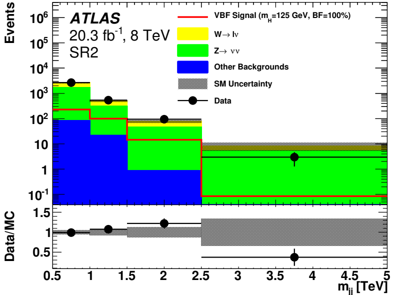
- Use W/Z+jets CRs to estimate $Z \rightarrow \nu\nu + jets$ and $W \rightarrow \ell\nu$+jets (lepton is not reconstructed) in the SR.
- Large $E_{\mathrm{T}}^{\mathrm{miss}}$ cut reduces QCD multijets background, estimated by data-driven method.
- The rest estimated by MC.

VBF ATLAS @8TeV JHEP 01 (2016) 172

- Fit simultaneously all the signal and CRs for each SR then combine.
- Dominant uncertainties: jet energy scale and resolution ($\sim 16\%$ for signal), Q^2 variation for W,Z production ($\sim$ 7-12% on W/Z ratio). .

Results:@95%CL upper limit of BR: obs (exp) 0.28 (0.31).





W/Z ($\rightarrow qq$) CMS @13 TeV

Event Selection:

- E_T^{miss} (H_T^{miss}) triggers > 90 GeV
- $p_T^j > 250$ GeV, $E_T^{miss} > 250$ GeV
- $\Delta\Phi(j, E_T^{miss}) > 0.5$ rad.
- Using jet substructure techniques to identify jets from V-boson decay:
  - Fat-jet with m_j close to $m_{W/Z}$: $65 < m_j < 105$ GeV
  - Likelihood for N-daughter hypotheses τ_N: $\frac{\tau_2}{\tau_1} < 0.6$

Backgrounds: Main ones are Z($\rightarrow \nu\nu$)+jets, Z($\rightarrow \nu\nu$)/Z($\rightarrow jj$)+jets

- Using W/Z and γ +jets CRs to estimate W+jets and Z+jets with independent scale factor per bin.

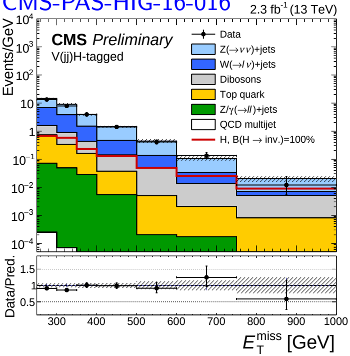
Fitting E_T^{miss} distribution all SR and CRs simultaneously.

Dominant systematic uncertainties affect γ/Z and W/Z ratios coming from higher order EW and QCD corrections.

Results: @95% CL Upper limits on $\frac{\sigma \times BR}{\sigma_{SM}}$:

Luminosity (fb^{-1})	Expected	Observed
2.3	1.43	1.04
12.9	1.17	0.72

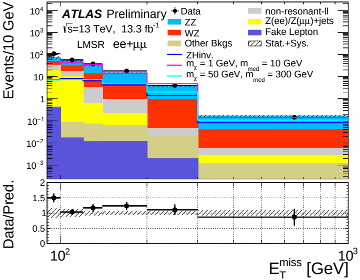
CMS-PAS-HIG-16-016



Using 2015+2016 integrated luminosity of 13.3 fb^{-1}

Event Selection:

- Single lepton trigger.
- Exactly one e^+e- or $\mu+\mu-$ pair.
- $|m_{\ell\ell} - m_Z| < 15$ GeV.
- $E_T^{\text{miss}} > 90$ GeV.
- $\Delta R_{\ell\ell}$ (boosted Z-boson).
- $\Delta\Phi(Z, E_T^{\text{miss}}) > 2.7$ (back-to-back)



Backgrounds:

- ZZ continuum bkg (50% qqZZ, 3% ggZZ) estimated by MC-only.
- WZ, W($\ell\nu$), Z($\ell\ell$) ($\sim$24%) estimated from a 3-lepton CR.
- $t\bar{t}$/WW/Wt/Z($\tau\tau$) estimated in different flavour $e\mu$ events.
- Drell-Yan Z($\ell\ell$)+jets ($\sim$8-10%) estimated with ABCD method.

Dominant uncertainties lepton and jet energy scale and resolution propagated to the uncertainty on the E_T^{miss}.

Fitting with maximum likelihood fit of the E_T^{miss} distribution.

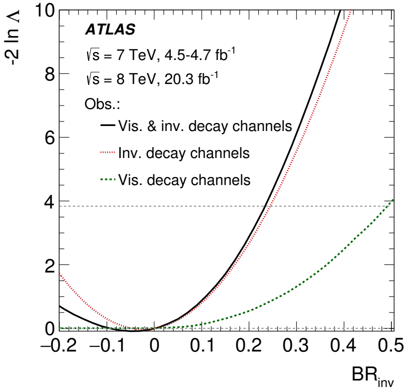
Results: @95% CL Upper limits on BR: obs (exp) 0.98 (0.65).

Combine direct limit on BR($h \to inv$) @8 TeV ATLAS JHEP11(2015)206

- Combine direct invisible Higgs decay search results from VBF and VH (also include $Z \to \ell\ell$, in backup)

Channel	Expected	Observed
VBF	0.31	0.28
V(jj)H	0.86	0.78
Z($\ell\ell$)H	0.62	0.75
Combine	0.27	0.25

- ATLAS brings this down further to 0.23 (0.24), and removes the assumptions of SM production rates (couplings), by including measurements of visible Higgs decay rates ($\gamma\gamma$, ZZ, WW, $\tau\tau$, bb). (see backup)



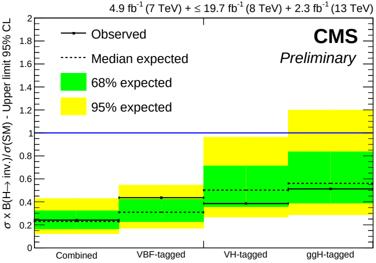
Combine direct limit on BR($H \rightarrow inv$) CMS

Combine Run I and 2015 data. CMS-PAS-HIG-16-016

Analysis Tag		$\int \mathcal{L}$ (fb^{-1})			Expected Signal Composition (%)	
		7 TeV	8 TeV	13 TeV	7 or 8 TeV	13 TeV
qqH-tagged	VBF	–	19.2 [16]	2.3	7.8 (ggH), 92.2 (qqH)	9.1 (ggH), 90.9 (qqH)
VH-tagged	$Z(l^+l^-)$	4.9 [16]	19.7 [16]	2.3	100 (ZH)	
	$Z(b\bar{b})$	–	18.9 [16]	–	100 (ZH)	
	V(jj)-tagged	–	19.7 [56]	2.3	25.1 (ggH), 5.1 (qqH), 23.0 (ZH), 46.8 (WH)	38.7 (ggH), 7.1 (qqH), 21.3 (ZH), 32.9 (WH)
ggH-tagged	monojet	–	19.7 [56]	2.3	70.4 (ggH), 20.4 (qqH), 3.5 (ZH), 5.7 (WH)	69.4 (ggH), 21.9 (qqH), 4.2 (ZH), 4.6 (WH)

- VH includes Z($\ell\ell$), Z(bb) and V(qq).
- Upper limits on BR(H$\rightarrow$ invisible) @95% CL: obs (exp) 0.24 (0.23).

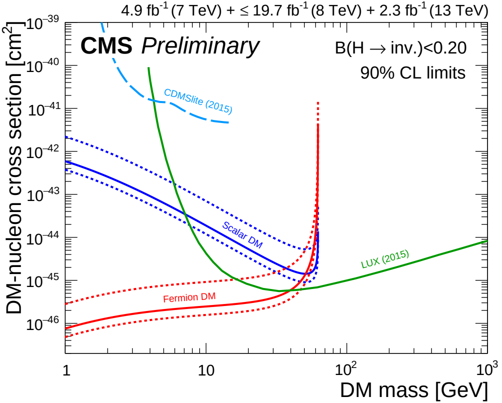
[16] Eur.Phys.J.C 74(2014)
[56] arXiv:1607.05764 (submitted to JHEP)



LHC results on Higgs portal to dark matter interpretation

- Use limit @90% CL of 0.20 of $BR(H \to inv)$ to make consistent interpretation with other astro-experiments.
- Use Higgs portal models (Higgs as the only mediator) assuming scalar/fermion DM.
- Sensitive for WIMP's mass $< m_H/2$, more sensitive results in low m_{WIMPs}.

- Form factor of Higgs-nucleon coupling $f_N = 0.33^{+0.30}_{-0.07}$ causes a band on ATLAS/CMS exclusion lines.
- Similar exclusion plot from ATLAS for 7-8 TeV in JHEP 11 (2015) 206



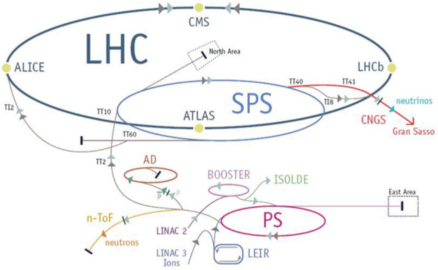
Summary

- No significant excess in any of the direct Higgs to invisible searches.
- Strong limits on the BR($H \to$ invisible) are set.
- Results for 13 TeV data are available from the CMS Collaboration. Because of limited statistics, so far nothing has gone beyond the Run I results except the mono-jet one is much improved.
- ATLAS is working on the same analyses for Run II.
- The limit on the BR gives compatible exclusion limits comparing with direct detections at low WIMP mass.

THANKS!

BACK UP

LHC



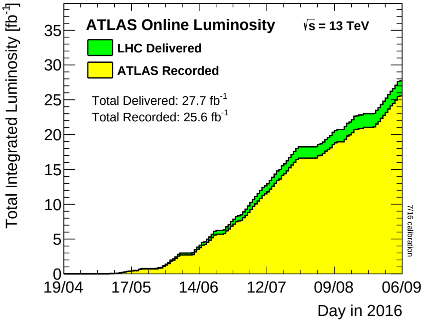
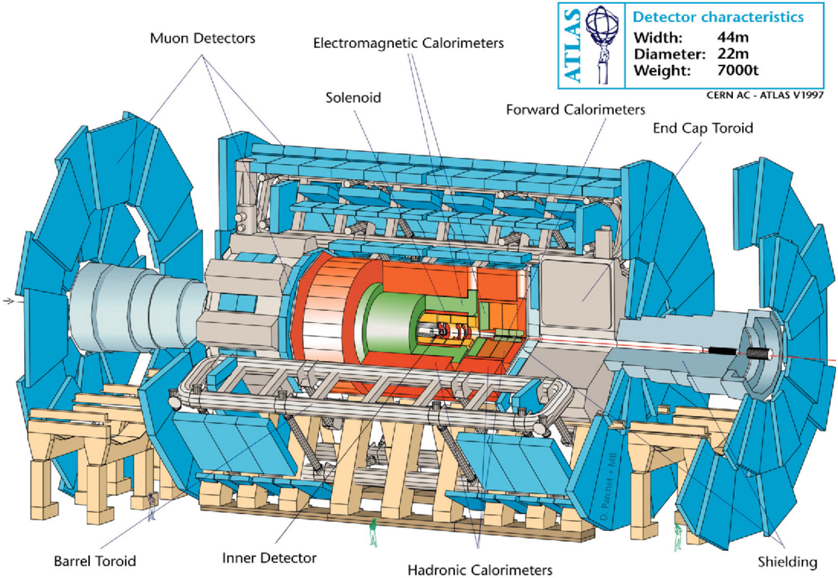
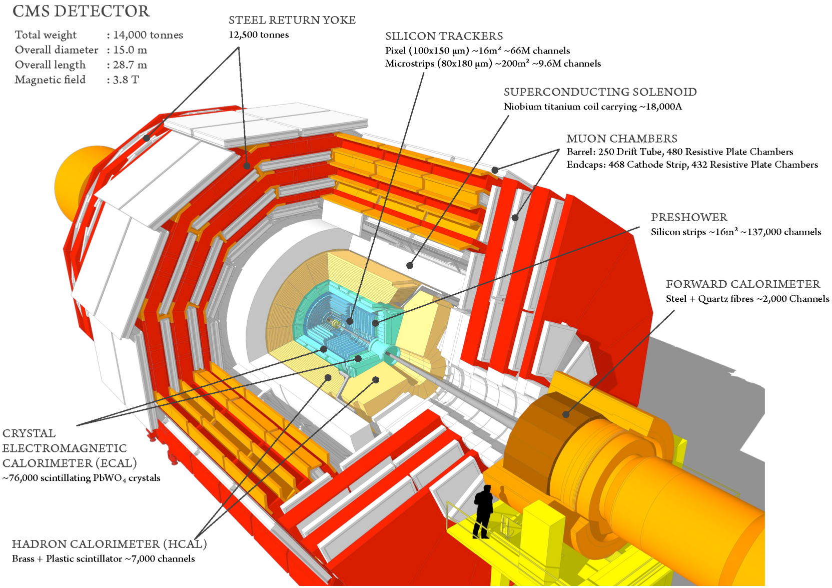


Figure : The LHC sketch out. 27km circumference

A Large Toroidal LHC ApparatuS (ATLAS) detector



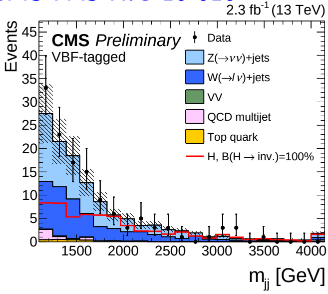
Compact Muon Solenoid (CMS) detector



Event Selection

- VBF trigger on events with 2 jets having high $|\Delta\eta(j,j)|$, large m_{jj}.
- $p_T^{j1(j2)} > 80(70)$ GeV
- $m_{jj} > 1100$ GeV
- $E_T^{miss} > 200$ GeV
- $\Delta\Phi(jet, E_T^{miss}) > 2.3$
- $\Delta\eta(j1, j2) > 3.6$

CMS-PAS-HIG-16-016



Background estimation

$Z(\to)\nu\bar{\nu}/W(\to \ell\nu) + jets$ estimated using W/Z CRs. With 30% systematic on ratio W/Z for higher order correction.

Fitting method: counting experiment, using profile maximum likelihood to fit simultaneously the SR and CRs.

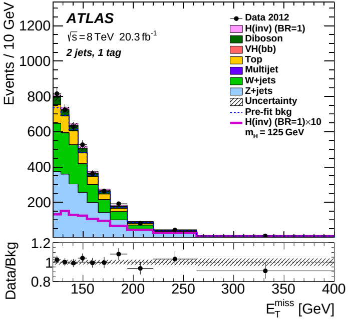
Results: @95% CL obs (exp) upper limit on *BR*: 0.69 (0.62).

CMS-PAS-HIG-16-009

Process	Control Regions					Signal Region
	$e\nu$	$\mu\nu$	$\tau\nu$	$\mu\mu$	QCD	
QCD $Z \to \mu\mu$	–	–	–	3.7 ± 1.1	–	–
EWK $Z \to \mu\mu$	–	–	–	2.1 ± 0.7	–	–
QCD $Z \to \nu\nu$	–	–	–	–	–	40 ± 12
EWK $Z \to \nu\nu$	–	–	–	–	–	22 ± 6
QCD $W \to \mu\nu$	–	53 ± 6	0.38 ± 0.16	–	42 ± 5	13 ± 2
EWK $W \to \mu\nu$	–	27 ± 3	–	–	5.9 ± 0.9	4.4 ± 0.8
QCD $W \to e\nu$	16 ± 2	–	0.2 ± 0.3	–	37 ± 4	9.5 ± 1.5
EWK $W \to e\nu$	7.8 ± 1.3	–	0.24 ± 0.14	–	7.7 ± 1.1	5.5 ± 1.0
QCD $W \to \tau\nu$	0.05 ± 0.05	–	11 ± 2	–	70 ± 10	13 ± 2
EWK $W \to \tau\nu$	–	–	5.2 ± 1.2	–	25 ± 4	5.6 ± 1.3
Top-quark	1.4 ± 0.2	6.8 ± 0.9	7.1 ± 1.0	0.22 ± 0.06	80 ± 10	2.3 ± 0.4
QCD multijet	–	5 ± 2	0.4 ± 0.2	–	1200 ± 100	3 ± 20
Dibosons	0.4 ± 0.4	0.8 ± 0.4	–	0.02 ± 0.02	1.9 ± 0.6	0.7 ± 0.3
Total Bkg	26 ± 3	92 ± 9	25 ± 3	6.1 ± 1.3	1500 ± 100	120 ± 27
Data	29	89	24	7	1461	126
Signal (m_H = 125 GeV)						
VBF	–	–	–	–	–	53.6 ± 4.9
ggH	–	–	–	–	–	5.4 ± 3.6

Event Selection:

- E_T^{miss} trigger 80 GeV threshold.
  $E_T^{miss} > 120$ GeV, 0 lepton
- 2 or 3 central jets, forward jet veto
- $m_{jj} \sim m_{W/Z}$
- ΔR_{jj} cut for closed jets in boosted V.
- Categorising in 0, 1 and 2-tags b-jet and four E_T^{miss} ranges.



Backgrounds: Main ones are $Z(\to \nu\nu)$+jets, $Z(\to \nu\nu)/Z(\to jj)$+jets

- Using W/Z+jets CRs to estimate W+jets and Z+jets.
- Multijets estimated by ABCD method.
- Using $t\bar{t}$ CR to estimate $t\bar{t}$

Dominant uncertainties: jet energy scale (1-3%) and resolution (10-20%).
Fitting all SR and CRs simultaneously with binning E_T^{miss}/p_T^V using an automated algorithm based on expected events.

Results: @95% CL Upper limits on BR: obs (exp) 0.78 (0.86).

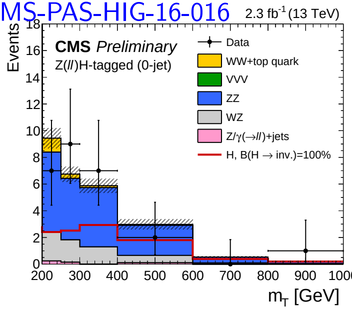
Z ($\rightarrow \ell\ell$) CMS @13 TeV CMS-PAS-EXO-16-038

2.3 fb^{-1} analysis CMS-PAS-HIG-16-008 used for the combination

Event Selection: $e^+e^-/\mu^+\mu^-$ & $E_T^{\rm miss}$

- $p_T^{\ell} > 20$ GeV, $76 < m_{\ell\ell} < 106$ GeV.
- $\Delta\Phi(Z, E_T^{\rm miss}) > 2.8$.
- $E_T^{\rm miss} > 100$ GeV, $m_T > 200$ GeV
- $\Delta\Phi(j, E_T^{\rm miss}) > 0.5$ to kill Z+jets.
- Categorising into 0 and 1 jet.

CMS-PAS-HIG-16-016



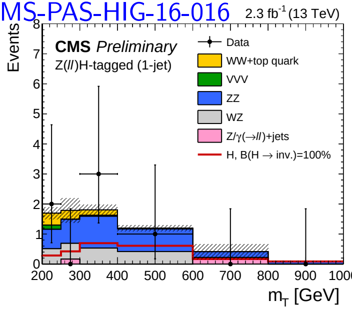
Backgrounds:

- ZZ($2\ell2\nu$)(70%), WZ($\ell\nu\ell$) (25%) estimated from MC @NLO.

Fitting m_T distributions (transverse mass of the $\ell\ell$-$E_T^{\rm miss}$ system) in e/μ channels.

Results: @95% CL Upper limit on $\sigma_{ZH} \times BR$ 1.1 pb (1.1 pb). New at 12.9 fb^{-1} on BR: obs (exp) 0.86 (0.70).

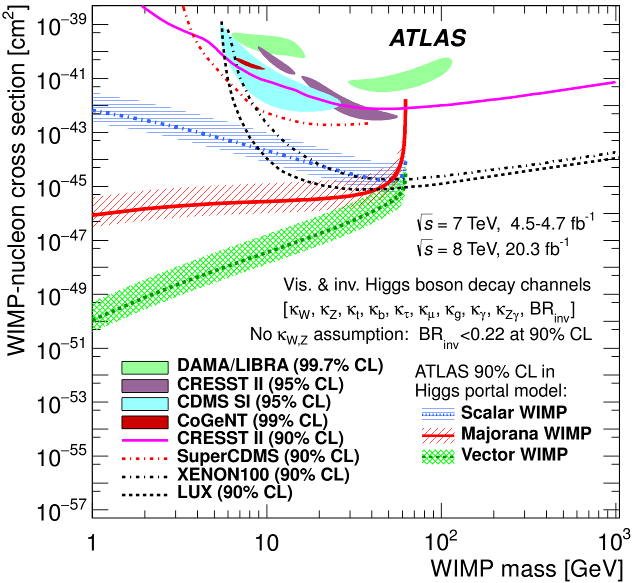
CMS-PAS-HIG-16-016



Higgs to invisible, different parametrizations

	Observed	Expected	Assumptions
Direct search	0.25	0.27	Productions as SM ($\kappa_i = 1$)
Indirect search	0.49	0.48	$\kappa_{Z,W} \leq 1$
Combination	0.23	0.24	None
Comb. 1	0.23	0.23	$\kappa_{Z,W} \leq 1$
Comb. 2	0.18	0.24	one κ_F and one κ_V
Comb. 3	0.16	0.23	one κ_F and one $\kappa_V \leq 1$

Higgs Portal Dark Matter ATLAS



Higgs Portal Dark Matter

- The hashed bands indicate the uncertainty resulting from the systematic variation of the form factor f_N
- The ATLAS limits on the WIMP-nucleon scattering cross section are proportional to those on the invisible decay branching ratio. They are weaker (stronger) at low mass for scalar (Majorana and vector) WIMPs, and degrade as m_{WIMP} approaches $m_h/2$ as expected from kinematics. The limits are shown for $m_{WIMP} \geq 1$ GeV, but extend to WIMP masses smaller than this value.
- The Higgs portal model is a special case of the spin-independent limits where the Higgs boson is taken to be the only mediator.