Search for invisible Higgs bosons produced via vector boson fusion at the LHC using ATLAS detector

Mohamed Zaazoua [1], Farida Fassi [1], Kétévi Adiklè Assamagan [2], Loan Truong

[1] University Mohammed V in Rabat
[2] Brookhaven National Laboratory

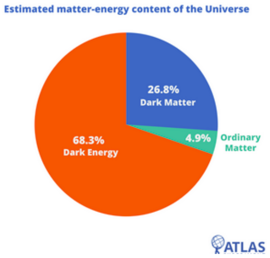
Université Mohammed V
Faculté des Sciences
Rabat

BROOKHAVEN NATIONAL LABORATORY

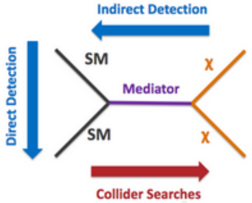
ATLAS EXPERIMENT

Motivation

- Strong evidence that dark matter (DM) exists.
- LHC searches complement evidence from direct and indirect detection.
  - Can actually produce DM mediators.
- Invisible decays of the Higgs boson, are good way of searching for new physics.



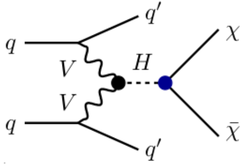
- Higgs boson could be a mediator between SM particles and ones that belong to the DM sector.



data sample: L=139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV

Invisible decays of the Higgs boson:

$B^{SM}_{H\to inv}$: 0.1% vs. $B^{BSM}_{H\to inv}$: 10%



(e.i: H → WIMPs)

- powerful topology: VBF + MET
- signal: VBF, ggF
- main background: V+j, QCD

The experimental signature:

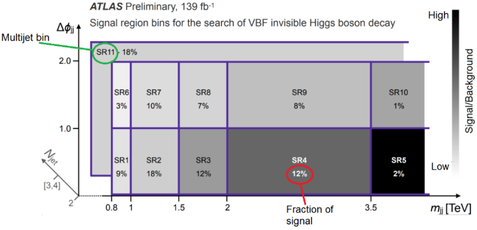
- pair of energetic jets
- wide gap in η_{jj}
- large invariant massess m_{jj}

Previous analysis result: (link)

- Limit on $B_{H\to inv}$: 0.37 at 95% CL.

Changes and improvements:

- Relaxed selection criteria on m_{jj}, $\Delta\eta_{jj} > 3.8$ and $\Delta\Phi_{jj}$
- $E_T^{miss} > 200$ GeV slightly increased



Improvements efficiency:
Better S/B ratio for selections with larger m_{jj} and smaller $\Delta\Phi_{jj}$

Signal and control region definitions

SR definitions:

Lepton/photon vet

$p_T(j_1) > 80$ GeV

$p_T(j_2) > 50$ GeV

$\eta_{j_1} * \eta_{j_2} < 0$

$p_T(j) > 25$ GeV

$E_T^{miss} > 200$ GeV

$H_T^{miss} > 180$ GeV

$E_{T,soft}^{miss} < 20$ GeV

$2 <= Njet <= 4$

$\Delta\Phi_{jj} < 2.0$

$\Delta\eta_{jj} > 3.8$

$mjj > 0.8$ TeV

$Nbjet < 2$

$p_T(j_{3,4}) > 20$ GeV

JVT or fJVT$(j_{3,4})$

$C_{j3,4} < 0.6$

$m_{j3,4}^{rel} < 0.05$

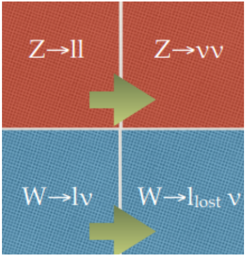
CR definitions:
to estimate V+jets background

$Z \rightarrow ll$

- $N_{lep} = 2$
- $p_T(l1) > 30$ GeV
- $|mll - mZ| < 25$ GeV
- $E_T^{miss} < 70$ GeV

$W \rightarrow l\nu$

- $N_{lep} = 1$
- $p_T(l1) > 30$ GeV
- MET sign. (e)$> 4\sqrt{GeV}$

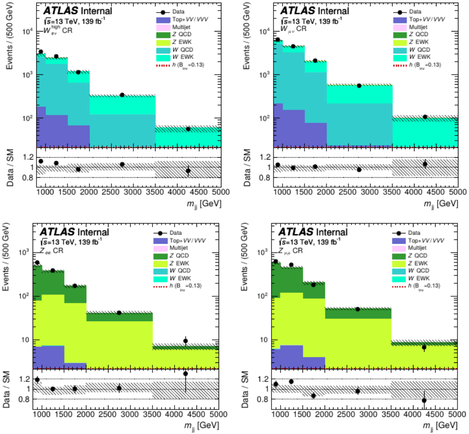


Background estimation

V+jets: about 95%

data driven technique uses CRs to constrain this Background.
CRs binned similarly to SR.

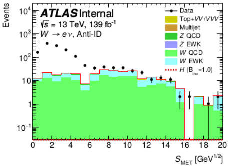
observed yield Vs expectation from simulation

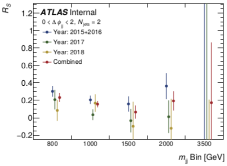


W CR can have small contribution from events with fake e^- originating from multijet jet.

estimated with W_e^{low} **CR:**

- enriched by fake electrons.
- loose identification requirement (e-).





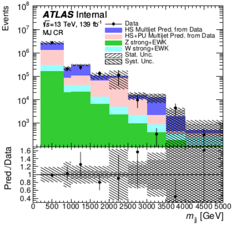
- data Vs MC plotted inclusively in $\Delta\Phi_{jj}$ and m_{jj} (left).
- $R_s = \frac{S_{MET}^{high}}{S_{MET}^{low}}$ used to scale the $W_{e\nu}^{low}$ CR, to obtain the contribution in $W_{e\nu}^{high}$.

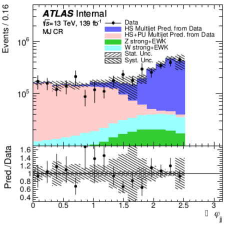
Other Background: Multijet, diboson, ttbar.

ttbar, diboson: predicted directly from simulation.

Multijet:

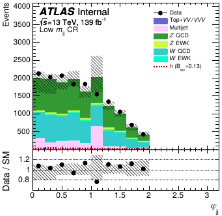
- large $\Delta\Phi_{jj}$ and little E_T^{miss}
- estimated from data using Rebalance and Smear technique.

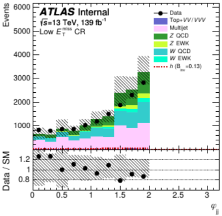




- Add correction to account for the ineficiency of the E_T^{miss} triggers.

agreement of predictions and data





- (HS, blue) and (HS+PU, red) templates are normalised to fit the $\Delta\Phi_{jj}$ distribution.

Systematic uncertainties

Theoretical uncertainties

V+jets:
high-order matrix element effects and parton shower matching unc: ren, fac, qsf, ckkw. Sherpa MC samples

- ren and fact:
  strong V+jets downward: 18 to 26%
  strong V+jets upward: 27% to 43%
  EWK V+jets downward 9% to 20%
  EWK V+jets upward: 11% to 29%.
- qsf: 4% to 8%
- ckkw: 4% to 6%
- PDF: 1% to 2%

Signal uncertainties:

- VBF:
  - p_T dependent NLO corr: 2%.
  - ren, fac: 1-3%.
  - parton shower: 2% to 4%.
  - PDF from NNPDF : 1-2%.
- ggF:

  ren and fac: 45% unc in the 2-jet bin and a 41% in the 3- and 4-jet bin

Experimental uncertainties

Luminosity: 1.7%

- impacts only the signal yield.
- effect cancel on the backgrounds.

Triggers efficiency: 2%

- To account for possible trigger efficiency differences between data and simulation.

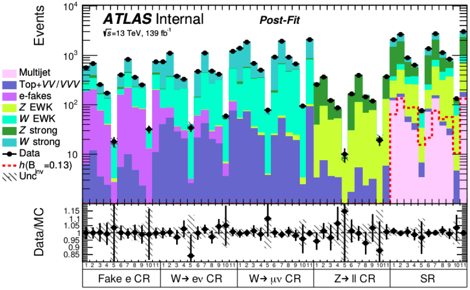
physics objects:

- propagated to the calculation of E_T^{miss}

Results

Results:

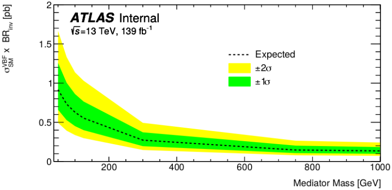
Postfit results of all SR and CR bins.



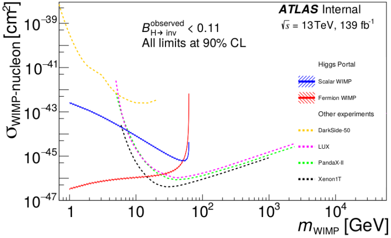
- good agreement of expected background yields and observed data
- set an upper limit on the $B_{H\to inv}$ of 13%.

Interpretation:

invisible decays of heavy scalar particles (med of DM)

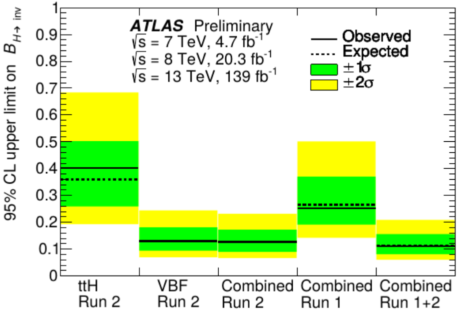


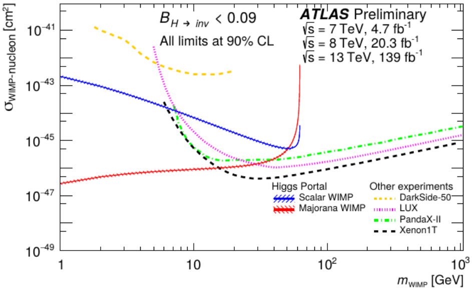
Upper limits on the SI $\sigma_{WIMP-nucleon}$ using Higgs portal interpretations



ATLAS-CONF-2020-052

- The upper limits on $B_{H\to inv}$ at the 95% CL from direct searches for invisible decays of the 125 GeV Higgs boson and their statistical combinations in Run 1 and 2.





- Comparison of the upper limits at 90% CL from direct detection experiments on the $\sigma^{SI}_{Wimp-nucleon}$ to the observed exclusion limits from combination analysis.

Conclusion

- Search using VBF channel.
  - No excess over the Standard Model background to be interpreted as DM particle candidates.
  - Set up a limit on $B_{H \to inv}$: 0.13 at 95% CL.
- Search using combinned invisible Higgs decays.
  - No excess over the Standard Model background to be interpreted as DM particle candidates.
  - Set up a limit on $B_{H \to inv}$: 0.11 at 95% CL.

Backup

VBF Analysis Results

Table 4: Inclusive yields of signal and major backgrounds in signal and control regions after the likelihood fit. Minor backgrounds from $t\bar{t}$, VV, VVV, and VBF $H \rightarrow W^{+}W- / \tau^{+}\tau^{-}$ are summed up as "Others". The signal yields (VBF, ggF, and VH) are normalised to a branching ratio of the Higgs boson into invisible final states of 13%.

Process	SR	$Z_{\ell\ell}$	$W_{e\nu}^{\text{high}}$	$W_{\mu\nu}$	$W_{\ell\nu}$	$W_{e\nu}^{\text{low}}$
Z strong	6,809 ± 304	1,394 ± 66	48 ± 14	195 ± 13	243 ± 19	156 ± 41
Z EWK	2,652 ± 236	634 ± 56	12 ± 1	41 ± 2	53 ± 2	26 ± 2
W strong	3,744 ± 239	0 ± 0	3,573 ± 185	6,741 ± 310	10,314 ± 361	1,769 ± 105
W EWK	1,371 ± 100	0 ± 0	2,149 ± 160	3,768 ± 273	5,917 ± 316	1,128 ± 89
Fake e	0 ± 0	0 ± 0	174 ± 24	0 ± 0	174 ± 24	1,161 ± 115
Multijet	744 ± 115	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Others	154 ± 12	36 ± 5	325 ± 21	395 ± 24	720 ± 32	57 ± 4
Tot. bg.	15,474 ± 478	2,065 ± 87	6,281 ± 247	11,140 ± 414	17,421 ± 482	4,298 ± 184
H (VBF)	647 ± 118	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
H (ggF)	90 ± 20	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
H (VH)	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Data	15,511	2,050	6,323	11,095	17,418	4,293

Table 4: Inclusive yields of signal and major backgrounds in signal and control regions after the likelihood fit. Minor backgrounds from $t\bar{t}$, VV, VVV, and VBF $H \rightarrow W^{+}W- / \tau^{+}\tau^{-}$ are summed up as "Others". The signal yields (VBF, ggF, and VH) are normalised to a branching ratio of the Higgs boson into invisible final states of 13%.

Process	SR	$Z_{\ell\ell}$	$W_{e\nu}^{\text{high}}$	$W_{\mu\nu}$	$W_{\ell\nu}$	$W_{e\nu}^{\text{low}}$
Z strong	6,809 ± 304	1,394 ± 66	48 ± 14	195 ± 13	243 ± 19	156 ± 41
Z EWK	2,652 ± 236	634 ± 56	12 ± 1	41 ± 2	53 ± 2	26 ± 2
W strong	3,744 ± 239	0 ± 0	3,573 ± 185	6,741 ± 310	10,314 ± 361	1,769 ± 105
W EWK	1,371 ± 100	0 ± 0	2,149 ± 160	3,768 ± 273	5,917 ± 316	1,128 ± 89
Fake e	0 ± 0	0 ± 0	174 ± 24	0 ± 0	174 ± 24	1,161 ± 115
Multijet	744 ± 115	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Others	154 ± 12	36 ± 5	325 ± 21	395 ± 24	720 ± 32	57 ± 4
Tot. bg.	15,474 ± 478	2,065 ± 87	6,281 ± 247	11,140 ± 414	17,421 ± 482	4,298 ± 184
H (VBF)	647 ± 118	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
H (ggF)	90 ± 20	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
H (VH)	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Data	15,511	2,050	6,323	11,095	17,418	4,293

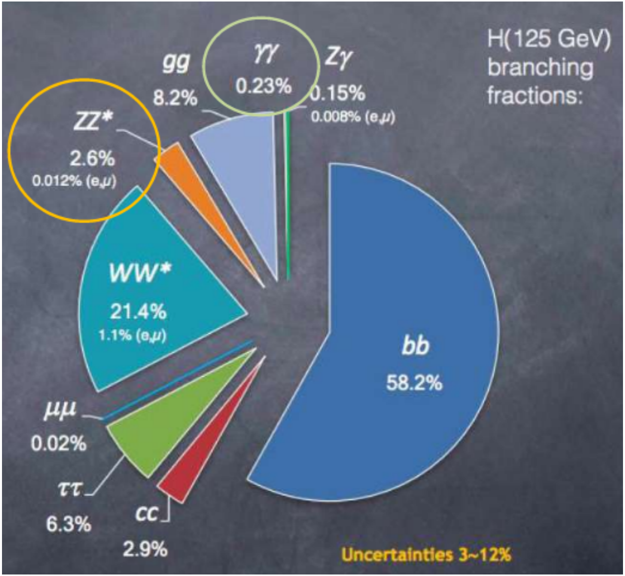
Observed	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.132	0.132	0.183	0.095	0.248	0.071

inclusive MJ prediction and assigned systematic uncertainties

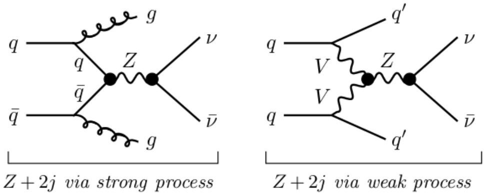
Table 3: Predicted multijet background for three data taking periods (2015-16, 2017, and 2018).

Period	Event yield	Uncertainties				
		stat.	non-closure		JER core	JER tail
			$\Delta\phi_{jj} < 1$	$1 < \Delta\phi_{jj} < 2$		
2015+16	85	10%	100%	100%	35%	18%
2017	231	8%	72%	47%	19%	3%
2018	289	9%	32%	62%	22%	5%

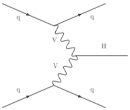
Higgs decays



CR and Production modes

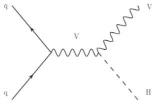


Production modes:



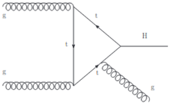
Vector Boson Fusion

E_T^{miss} + 2 jets



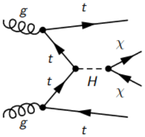
Associated VH prod.

E_T^{miss} + Z/W (ll,qq)



gluon-gluon fusion

E_T^{miss} + jet



H-combo results

Summary of results from direct searches for invisible decays of the 125 GeV Higgs boson and their statistical combinations

Analysis	$\sqrt{s}$ [TeV]	Int. luminosity [fb^{-1}]	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
Run 2 VBF	13	139	$0.00^{+0.07}_{-0.07}$	0.13	$0.13^{+0.05}_{-0.04}$
Run 2 $t\bar{t}H$	13	139	$0.04^{+0.20}_{-0.20}$	0.40	$0.36^{+0.15}_{-0.10}$
Run 2 Comb.	13	139	$0.00^{+0.06}_{-0.07}$	0.13	$0.12^{+0.05}_{-0.04}$
Run 1 Comb.	7, 8	4.7, 20.3	$-0.02^{+0.14}_{-0.13}$	0.25	$0.27^{+0.10}_{-0.08}$
Run 1+2 Comb.	7, 8, 13	4.7, 20.3, 139	$0.00^{+0.06}_{-0.06}$	0.11	$0.11^{+0.04}_{-0.03}$