ATLAS Higgs to invisible: plans and summary

Diallo Boye

Roadmap of Dark Matter models for Run 3 (CERN)

May 14, 2024

Outline

The Higgs boson exists and then...

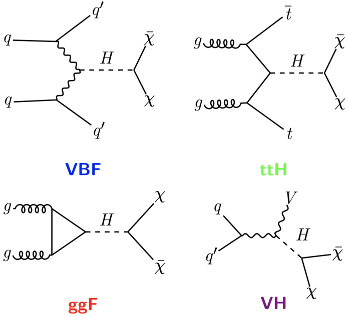
- **The Higgs boson exists and it's discovered in 2012 → scrutinize its properties and the Higgs sector nature.**
- Recent search set a 95% CL upper limit of 21% on the branching ratio for H boson decays via undetected modes. ▸ arXiv:1909.02845
  - ⇒ **Exotic decays of the Higgs boson remain a high priority.**

- Even with its excellent successes in providing experimental predictions, the SM leaves some phenomena unexplained.
  - hierarchy problem, baryon asymmetry, **Dark Matter**/energy etc...
- **Many Beyond Standard Model (BSM) theories predict the Higgs as mediator between SM particles and dark matter** ▸ PhysRevD.82.055026, ▸ doi.org/10.1016/, ▸ Phys. Rev. Lett. 112, 201802

Higgs to invisible search at the LHC

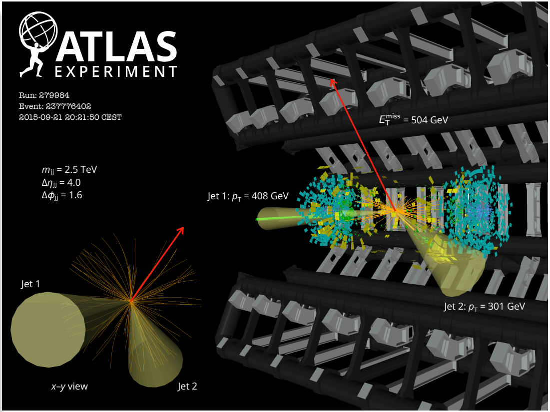
- **Invisible Higgs carries off momentum, characterised by large missing transverse momentum in the events**

- **Four different channels for the Higgs to invisible search**
- **Very unlikely process in Standard Model; branching ratio** $\mathcal{B}_{H \to inv} \sim 1.05 \times 10^{-3}$ **from** $H \to ZZ^* \to 4\nu$
- **Can be significantly enhanced in various BSM scenarios, including Higgs coupling to dark matter ("Higgs portal").**

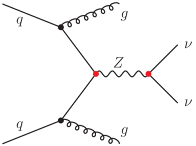


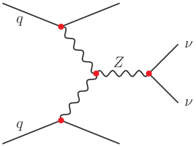
Vector Boson Fusion: VBF

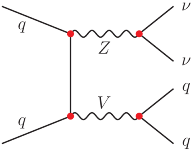
- Strong background rejection due to its distinct event topology.
- The most sensitive mode for invisible decays of a Higgs boson at hadron colliders
- Three mains backgrounds: Z strong, Z electroweak and di-boson production.



arXiv:2202.07953





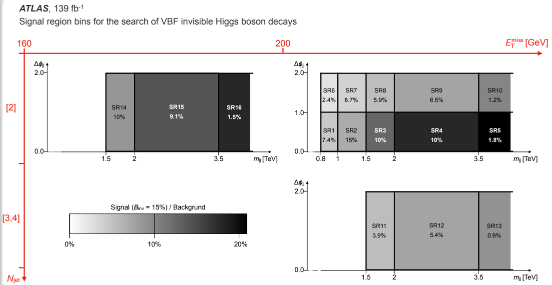


VBF search in ATLAS: Analysis strategy

arXiv:2202.07953

Event selection

- **Two jets with $p_T(j_1/j_2) > 80/50$ GeV.**
- **Small add. jet activity: $p_T(j_3) < 25$ GeV.**
- **Jets in opposite hemispheres.**
- $\Delta\eta_{jj} > 3.8$.
- $m_{jj} > 0.8$ TeV
- **Veto on e and μ**
- **A 3D $m_{jj}, \Delta\phi_{jj}$ and N_{jets} binning used.**

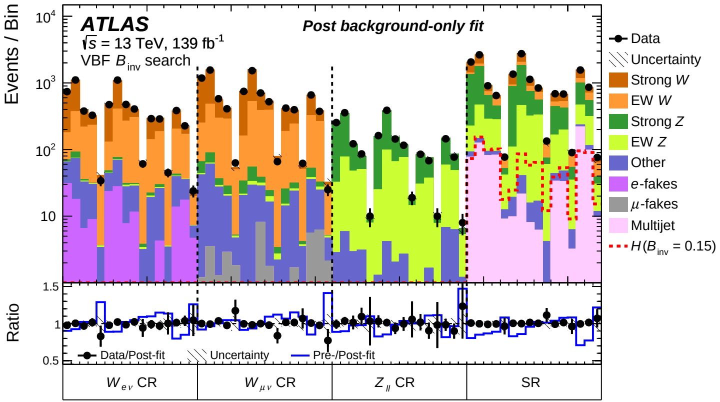


Bkg estimates

- The V+jets (95% bkgs) estimates by data-driven technique.

Systematics uncertainties

- Lepton and JER (32% and 40%)
- theoretical uncertainties on V+Jets bkg $\sim$ 28%.



Process	SR	$Z_{\ell\ell}$ CR	$W_{e\nu}$ CR	$W_{\mu\nu}$ CR	Fake-e CR	Fake-μ CR	Pile-up CR
Total bkg.	14 990 ± 2990	1880 ± 510	6210 ± 1260	9150 ± 1890	4560 ± 760	2110 ± 390	2030 ± 110
H (VBF)	886 ± 81	Predicted signal for $\mathcal{B}_{\text{inv}} = 15\%$					3.9 ± 1.3
H (ggF)	106 ± 41						$1.0 \pm ^{1.5}_{1.0}$
H (VH)	0.9 ± 0.2						-
Data	16 490	2051	6361	9294	4563	2110	2033

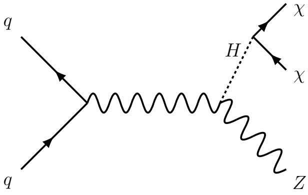
- **CMS: Obs (Exp) $\mathcal{B}$(Hinv) $<$ 0.18(0.12) @95%C.L**

‣ CMS

- The analysis considers 3 signal models with Z(ll)+MET final state:
    - **Higgs invisible**, vector/axial-vector simplified and 2HDM+a.

Analysis overview: H to inv

- SR selection:
    - SFOS dilepton pairs.
    - $p_T(\ell) > 30,\ 20$ GeV.
    - $76\,\text{GeV} < m_{\ell\ell} < 106$ GeV.
    - $E_T^{\text{miss}} > 90$ GeV.
    - vetoed $p_T^{\ell_3} > 7$ GeV.
    - $S_{E_T^{\text{miss}}} > 9$
    - $\Delta R(\ell\ell) < 1.8$.



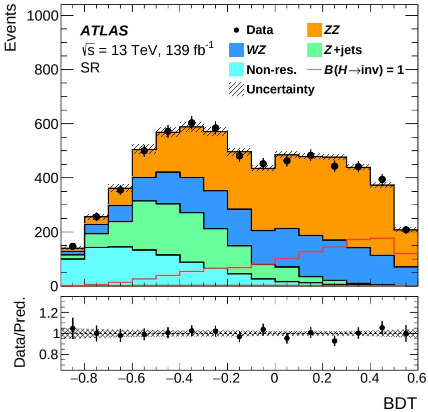
Bkg estimation

bkg	CR in smult. fit	Contribution
ZZ	4ℓ CR	44%
WZ	3ℓ CR	26%
Z+jets	–	14%
Non resonant $\ell^+\ell^-$	$e\mu$ CR	15%
W+jets	–	<1%
$ttV, ttVV, VVV$	–	<1%

Uncertainties

- Statistics → 5.1%
- Systematics → 7.1%
    - Theory → 4.9% (ZZ modelling → highest impact)
    - Experimental → 4.2% (Jet/MET highest impact)

ZH + MET results ‣ arXiv:2111.08372



Full Run2 results

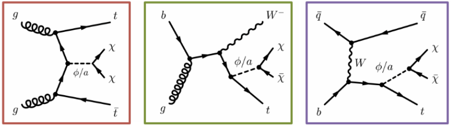
- Fit SR and CRs simultaneously.
- BDT is used in SR and $e\mu$ CR.
- Use MET in 3l CR and 4l CR.
- **Obs (Exp) $\mathcal{B}$(Hinv) < 0.19(0.19) vs 0.29(0.25) for CMS @95%C.L** ‣ CMS
- Table below: Summary of SR and CRs yields after the simultaneous fit for the $ZH \to \ell\ell + \text{inv}$ signal.

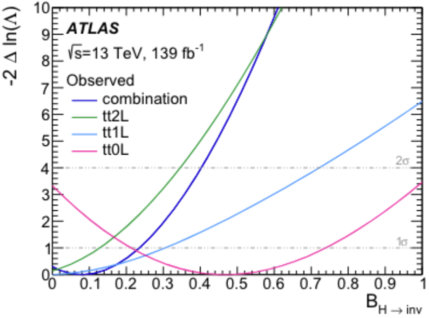
	SR	$e\mu$ CR	3ℓ CR	4ℓ CR
Observed events	6382	891	11622	314
Expected yields after fit	6385 ± 81	895 ± 29	11620 ± 110	296 ± 11
$ZH \to \ell\ell + \text{inv}$	4 ± 110	-	-	-
$ZZ \to \ell\ell\nu\nu$	2681 ± 110	0.763 ± 0.064	2.61 ± 0.18	-
WZ	1595 ± 34	11.6 ± 1.1	10623 ± 150	-
$Z + \text{jets}$	1111 ± 100	0.79 ± 0.30	235 ± 89	-
Non-resonant	881 ± 39	876 ± 29	220 ± 31	-
$ZZ \to 4\ell$	85.8 ± 5.5	0.621 ± 0.056	443 ± 40	295 ± 11
$t\bar{t} + V$	12.7 ± 2.8	1.76 ± 0.41	53 ± 12	-
Triboson	13.0 ± 6.2	3.1 ± 1.4	44 ± 20	0.48 ± 0.23

3 analyses channels

- tt0L (tt0L-high and tt0L-low) → no leptons
- tt1L → only 1 lepton.
- tt2L → only 2 leptons.
- Invisible Higgs decays
  - Special case: $ttH(125)$ production ∼ DM+tt, $m_\phi = 125$ GeV

Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.08^{+0.20}_{-0.19}$	0.36	$0.40^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$





- **Obs (Exp) $\mathcal{B}$(Hinv) 0.38 (0.30) vs 0.51(0.53) for CMS @95%C.L** ▸ CMS

VBF+MET+photon

Event selection

- $p_T(j_1/j_2) > 60/50$ GeV.
- $E_T^{\text{miss}} > 150$ GeV.
- $\left|\Delta\phi(E_T^{\text{miss}} - \gamma)\right| > 1.8$
- $|\Delta\phi(j_1, j_2)| < 2.5$
- $|\Delta\eta(j_1, j_2)| > 3.0$
- $m_{jj} > 0.25$ TeV
- Veto on e and μ, $n_\gamma = 1$
- $p_T(\gamma) < 110$ GeV
- $C_\gamma(C_3) < 0.4(< 0.7)$
- $\left|\Delta\phi(j_i, E_T^{\text{miss}})\right| > 1.$
- DNN used in 4 regions

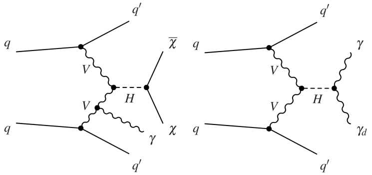


Figure 1: Signal

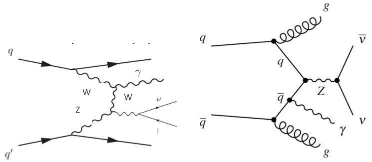


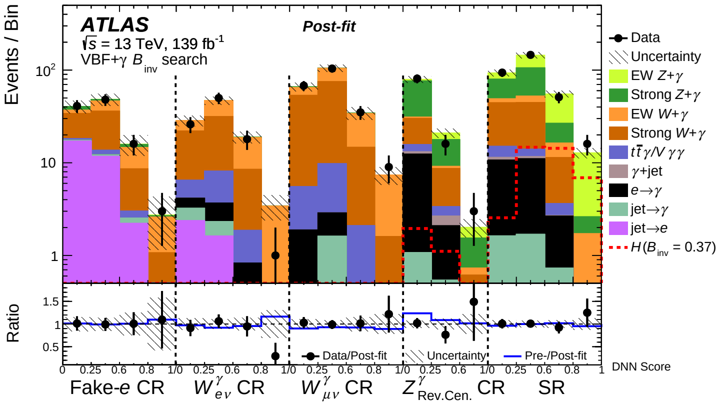
Figure 2: Dominant bkg

Bkg estimates

- CRs used to estimate the bkgs:
  - $W^\gamma_{e\nu}$, $W^\gamma_{\mu\nu}$, Fake-e, $Z^\gamma_{\text{rev.cent.}}$

Uncertainties

- Data stats dominate.
- Followed by $V\gamma + jets$ theory

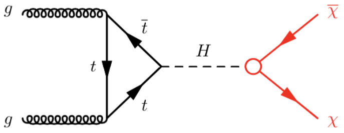


Expected	Observed	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.34	0.37	0.49	0.25	0.70	0.18

- SR and CRs are binned in DNN score.

Monojet analysis
arXiv:2102.10874

- At least a high energetic jet & large E_T^{miss} and no leptons
  - Different interpretations including **Higgs invisible**.



Analysis overview: H to inv

- SR selection:
  - no e, μ, τ & photons
  - $E_T^{\text{miss}} > 200$ GeV.
  - Leading jet $p_T > 150$ GeV
  - b-jet veto.

Bkg estimation

bkg	CR in smult. fit	Contribution
Z($\rightarrow \nu\nu$)+jets	inferred from V+jets	Dominant bkg
W($\rightarrow \ell\nu$)+jets	CR1ℓ0b	subdominant
tt single top	top CR	–
Dibosons	from MC	
Z($\rightarrow \ell\ell$)+jets	CR2ℓ0b	–
Multi jets + NCB	data-driven methods	–

- NCB: Non Collision Bkg

Different bins in E_T^{miss}

- Inclusive and Exclusive binning.

Syst. Uncertainties

- Theory: highest impact $\rightarrow$ V+jets
- Experimental: highest impact $\rightarrow e, \mu$ and jets ID.

Monotjet analysis Higgs interpretation

arXiv:2102.10874

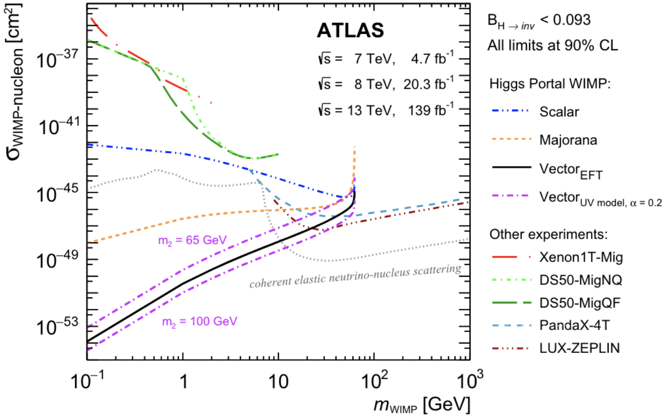
$H \rightarrow$ inv

- limits are calculated assuming SM production cross section of Higgs boson, combining all the production mechanism:
  - ggF $\sim$ 54%, VBF $\sim$ 34%, VH $\sim$ 12%, ttH negligible
- Theoretical uncertainties evaluated following LHC Higgs working group:
  - Include PDF, scale variations, PS systematics, EWK corrections to VBF cross section
- Limit on $\mathcal{B}_{H\rightarrow\text{inv}} = 0.34(0.39^{+0.16}_{-0.11})$ obs. (exp.) @ 95% CL.

Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + E_T^{miss}	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + E_T^{miss} + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + E_T^{miss}	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell)$ + E_T^{miss}	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + E_T^{miss}	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

- Statistical combination of $H \to$ inv with Run 2 data.
  - Limit on $\mathcal{B}_{H\to\text{inv}} = 0.113(0.080^{+0.031}_{-0.022})$ obs. (exp.) @ 95% CL.
- Statistical combination of $H \to$ inv with Run 2 + Run 1 data.
  - Limit on $\mathcal{B}_{H\to\text{inv}} = 0.107(0.077^{+0.030}_{-0.022})$ obs. (exp.) @ 95% CL.

$H \to$ inv combination ▸ arXiv:2301.10731



- The combined Run 1+2 result is translated into upper limits on the WIMP-nucleon scattering cross-section for Higgs portal models. The derived limits on $\sigma_{WIMP-Nucleon}$ range down to 10^{-45} cm^2 (scalar), 2×10^{-47} cm^2 (Majorana) and 10^{-54} cm^2 (vector), highlighting the complementarity of DM searches at the LHC and direct detection experiments.

Run 3 plan for VBF analysis

New limit setting framework

- Transitioning from Run2 framework (HistFitter + some Higgs group packages) to pyhf.
  - Pyhf uses lite .json file → faster, flexible and more efficient.

  → Time improvement: $\mathcal{O}$(50 hrs) → $\mathcal{O}$(2 hrs)
- Previous results reproduced by Pyhf:

	Observed	Expected	+1σ	-1σ	+2σ	- 2σ
Published	0.145	0.103	0.144	0.075	0.196	0.055
Pyhf	0.146	0.105	0.146	0.077	0.197	0.059

- Next steps: integration into Run2+Run3 framework

Low-level Calo ML

- Developing a ML framework to leverage low-level calorimeter information.

MVA/ML Implementation

- Developing TMVA Classification ML framework for signal/background separation

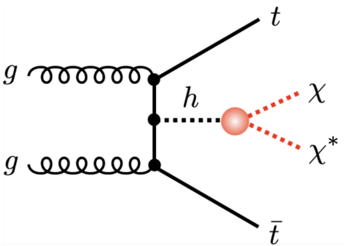
ZH + MET plan for Run 3

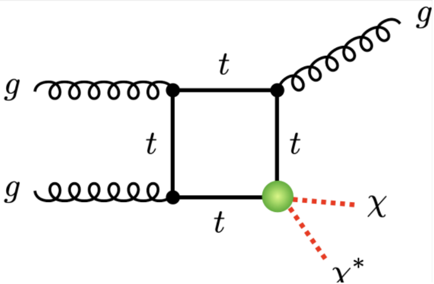
- **New implementation of tau-veto in SR is envisaged to reduce the hadronic tau decay contamination**.
  - This is expected to improve the limit significantly.
- **The leading uncertainty is the ZZ modeling**.
  - State-of-the-Art NNLO qq + NLO gg and uncertainties could be included to improve the prediction.
  - Improve the conservative EW correction uncertainty by event-weight based EW corrections in Sherpa 2.2.11+
- **Z+jets (MC-template) and non-resonant (CR fitted simultaneously) used in this round**.
  - Revisit the data-driven approach on non-resonant and V+jets processes which could benefit from the larger Run 3 dataset.
- **A better modelling of W/Z+jets could improve the sensitivity.**

- **ttH: statistically limited → will gain obviously in Run 3**.
- **An early care about the orthogonality between mono-jet and VBF+MET would help for an efficient remove of the overlap between these two analyses**.
- **VBF+MET+γ will benefit from the statistics increase of Run 3 and also from the expected improvement of VBF+MET analysis**.
- **VH(had) was missed in the legacy combination, for Run 3 we should make sure to include it given the importance of this analysis**.

Potential interpretation for Run 3 ▸ 2107.12389

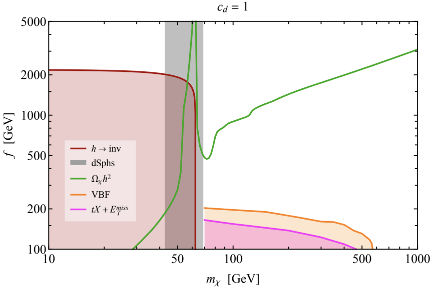
- Signal process is being studied by Run 3 searches





pNGB DM model

- Attractive DM candidates → derivative Higgs portal, with extra pNGB scalar.
- Dominant interactions are with heavy particles.
  - VBF+MET, tt/tW+MET are important signatures.



Conclusion

- **The ATLAS Higgs to invisible is reviewed by considering the most relevant channels**.
- **The limit on the branching ratio by combining Run 1 and Run 2 is** $\mathcal{B}_{H\to\mathbf{inv}} = 0.107(0.077^{+0.030}_{-0.022})$ **obs. (exp.) @ 95% CL**.
- **Most channels that are statistically limited such as VBF+MET, monoZ, tt+MET and VBF+MET+photon will benefit from Run 3 iteration**.
- **Other channels like VBF+MET which already started the Run 3 analysis has clearer plan for Run 3 improvement**.
- **For the interpretation part, the pNGB DM model for the derivative Higgs portal will be an interesting model to test**.
- **Some dark photon searches carries out Higgs to invisible interpretation (see dark photon session on Wednesday)**.