Searches for Higgs boson decays to invisible particles in ATLAS and CMS

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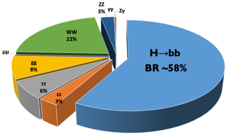
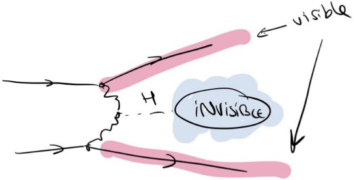
on behalf of the ATLAS and CMS collaborations

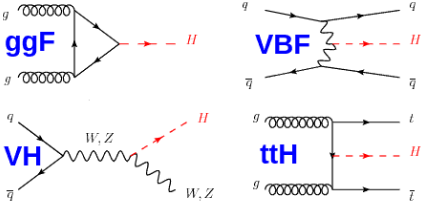
LHCP 2022

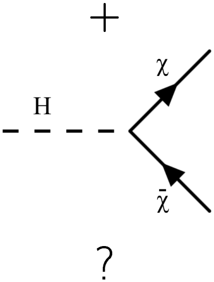
- In the Standard Model $\mathcal{BR}(H \to ZZ \to 4\nu)$: 0.1%
- Many dark matter scenarios consider a DM candidate coupling to the Higgs.
  - If $m_{DM} < \frac{m_H}{2}$: direct contribution to the H decay.
  - $\mathcal{BR}$ O(10%) are possible.
- At colliders, need for visible particles recoiling against the invisible Higgs.
  - **Common signature: significant missing transverse momentum (MET).**
- ATLAS and CMS probing all production modes.
  - Will review their latest results based on the full Run 2 dataset in the next slides.

Higgs branching ratios in Standard Model

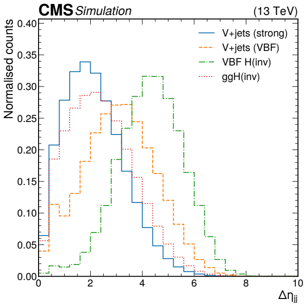


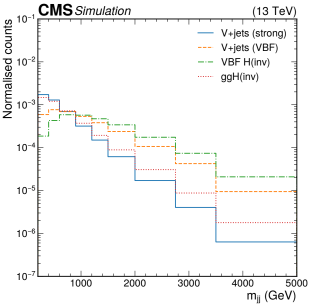


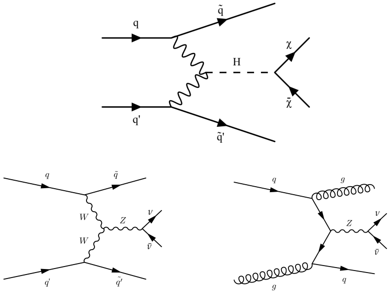




- Select events with a pair of jets with large angular separation ($\Delta\eta_{jj}$) and large invariant mass m_{jj}
- Lepton/photon veto.
- High MET ($\gtrsim$ 200 GeV) due to trigger constraint and to reject QCD events with mismeasured jets.
- Low $|\Delta\phi(jj)|$ cut to reduce QCD background further.
- Main remaining backgrounds: $Z(\nu\nu)$+jets (strong and electroweak production), $W(l\nu)$+jets with lost lepton.

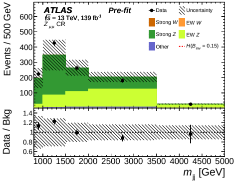


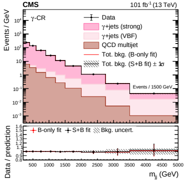


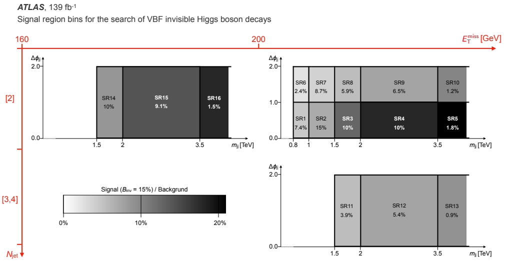


Similar strategy in ATLAS/CMS:

- Simultaneous fit on m_{jj} distribution in both the signal region (SR, no lepton) and control regions (CR, 1 or 2 e/μ, enriched in $W(l\nu)/Z(ll)$)
- CMS also includes a γ+jets CR to improve stat. at high m_{jj}
- ATLAS uses several bins in number of extra jets
- Both separate between medium and high MET.







ATLAS search regions

$$\mathcal{L}(\mu,\kappa^{\nu\bar{\nu}},\boldsymbol{\theta}) = \prod_i \mathrm{P}\left(d_i \middle| B_i(\boldsymbol{\theta}) + \mathrm{Z}_i(\kappa_i^{\nu\bar{\nu}}) + \mathrm{W}_i(\kappa_i^{\nu\bar{\nu}},\boldsymbol{\theta}) + \mu S_i(\boldsymbol{\theta})\right)$$
$$\prod_{\mathrm{CR}} \left(\prod_i \mathrm{P}\left(d_i^{\mathrm{CR}} \middle| B_i^{\mathrm{CR}}(\boldsymbol{\theta}) + \mathrm{V}_i^{\mathrm{CR,strong}}(\kappa_i^{\nu\bar{\nu}},\boldsymbol{\theta}) + \mathrm{V}_i^{\mathrm{CR,VBF}}(\kappa_i^{\nu\bar{\nu}},\boldsymbol{\theta})\right)\right)$$
$$\prod_j \mathrm{P}(\theta_j),$$

EWK and/or VBF W/γ/Z contributions, expressed as Z→νν (strong) yields times transfer factors taken from simulations

$$\mathrm{Z}_i(\kappa_i^{\nu\bar{\nu}}) = (1 + Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}})\kappa_i^{\nu\bar{\nu}},$$
$$\mathrm{W}_i(\kappa_i^{\nu\bar{\nu}},\boldsymbol{\theta}) = (f_i^{\mathrm{W/Z,strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}} f_i^{\mathrm{W/Z,VBF}}(\boldsymbol{\theta}))\kappa_i^{\nu\bar{\nu}},$$
$$\mathrm{V}_i^{\mathrm{CR,strong}}(\kappa_i^{\nu\bar{\nu}},\boldsymbol{\theta}) = \mathrm{C}_i^{\mathrm{CR,strong}}(\boldsymbol{\theta}) R_i^{\mathrm{CR,strong}}(\boldsymbol{\theta})\kappa_i^{\nu\bar{\nu}},$$
$$\mathrm{V}_i^{\mathrm{CR,VBF}}(\kappa_i^{\nu\bar{\nu}},\boldsymbol{\theta}) = \mathrm{C}_i^{\mathrm{CR,VBF}}(\boldsymbol{\theta}) Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}} R_i^{\mathrm{CR,VBF}}(\boldsymbol{\theta})\kappa_i^{\nu\bar{\nu}},$$

Z→νν (VBF) /Z→νν (strong) contribution

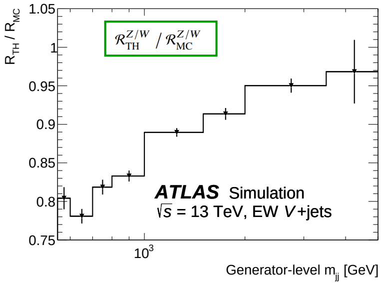
Z→W transfer factor

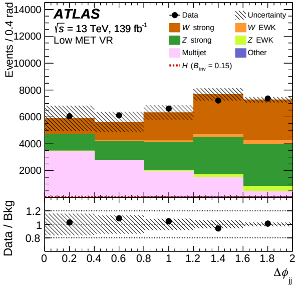
CR→SR transfer factor

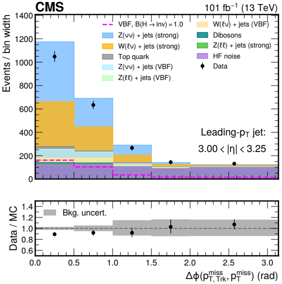
Channel dependent factors (1 for ee/μμ)

CMS likelihood

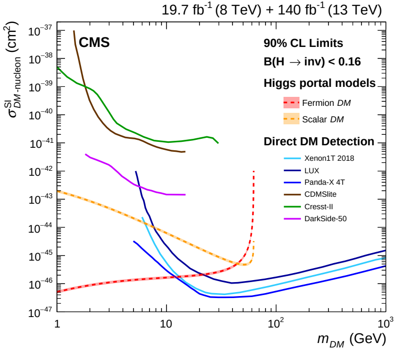
- V+jets: High order corrections applied to simulation to accurately describe the m_{jj} distribution ratios in W/Z+jets.
- Remaining QCD contribution from events with large $|\Delta\phi(jj)|$
- ATLAS: dedicated validation region defined with intermediate $|\Delta\phi(jj)|$ condition
- CMS: noise in the forward calorimeter (HF) reduced and estimated by the use of dedicated jet shower shape variables.

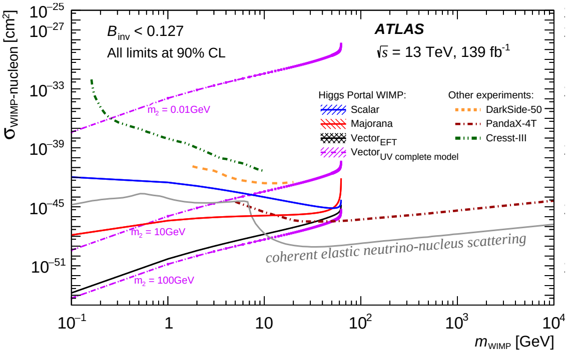


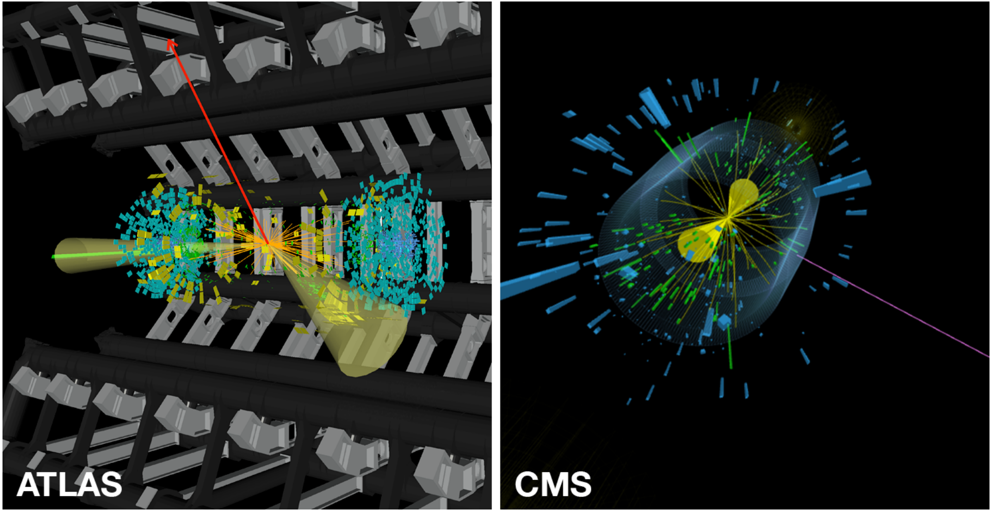




- Data compatible with SM expectation
- Observed 95% CL limit: $\mathcal{BR}(H \to \text{invisible}) < 0.145$ (ATLAS), 0.18 (CMS)
- Similar exp. limit at 0.10.
- By far the most sensitive production mode for $H \to \text{invisible}$
- Interpretations in terms of DM candidate mass m_{DM}.
  - Outperforms direct searches experiments for $m_{DM} \lesssim 10$ GeV.

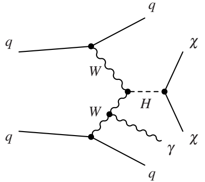


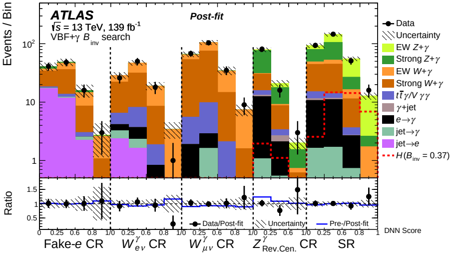


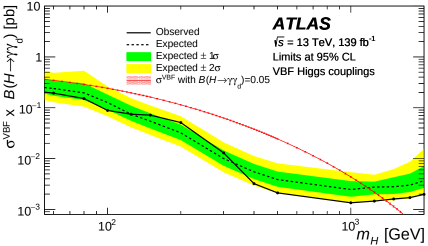


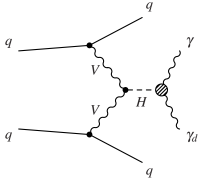
Yellow cones: jets, red/purple arrow: MET

- Similar event selection than above with the presence of an additional medium p_T photon (15-110 GeV)
- First time this signature is probed in the context of $H \to \text{invisible}$
  - Deep Neural Network trained using 8 most significant kinematic features (incl. $\Delta\eta(jj)$, MET, m_{jj})
  - 95%CL upper limit on $\mathcal{BR}(H \to \text{invisible}) < 0.37$ ($0.34^{+0.15}_{-0.10}$ exp.)
- Also searching for new Higgs boson decaying into a photon and a dark photon
  - Signal extracted from photon+MET transverse mass.

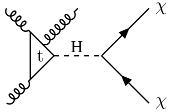




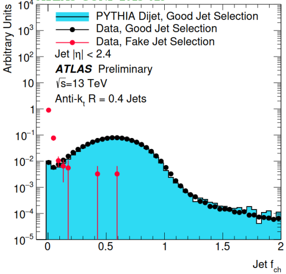


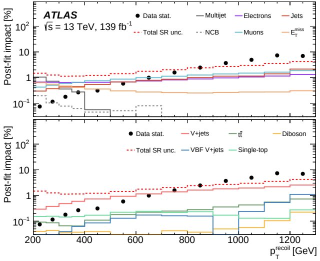


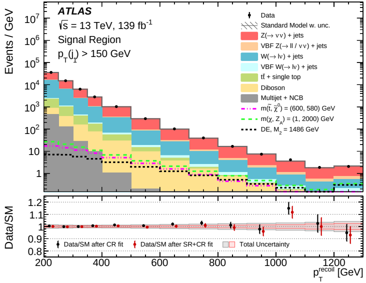
- Select events with $\geq$ 1 high p_T (> 150 GeV) central jet and p_T^{recoil} (= MET in SR) > 200 GeV
- Loose jet identification condition (e.g. on charged energy fraction) to remove fake jets from non collision backgrounds, detector noise.
- Similarly to VBF, simultaneous fit on SR (0 lepton) and CR (1 or 2 leptons) to constrain backgrounds.
- Systematic uncertainties at the same level as statistical one, up to p_T^{recoil} of 1 TeV.
- 95%CL upper limit on $\mathcal{BR}(H \to \text{invisible}) < 0.34$ ($0.39^{+0.16}_{-0.11}$ exp.)



ATLAS-CONF-2015-029



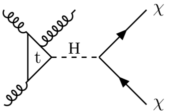


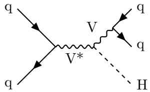


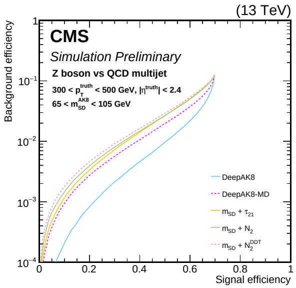
ggH (boosted) and $V(qq)+H$ (CMS)

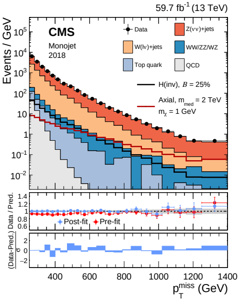
arXiv:2107.13021

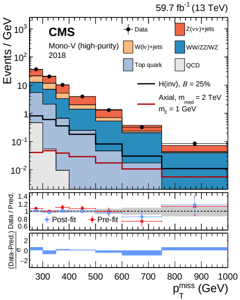
- Similar analysis performed by CMS, additionally targeting $W/Z(qq) + H$.
- Selecting high radius "AK8" jets (anti-k_T with R=0.8)
- DNN tagger "DeepAK8" to identify a two-prong substructure compatible with $W/Z \to qq$.
- Three categories based on DeepAK8 score and jet soft-drop mass ($\in/\notin$ [65,120]).
- 95%CL upper limit on $\mathcal{BR}(H \to \text{invisible}) < 0.28$ (0.25 exp.)

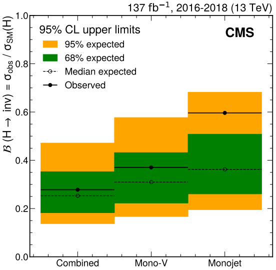




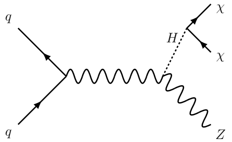


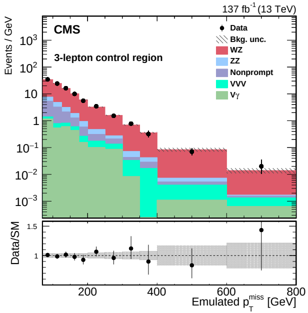


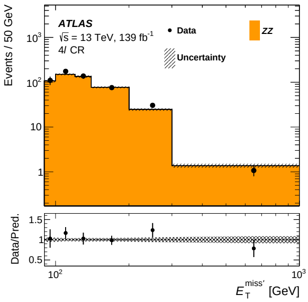




- Requires one reconstructed $Z(ee)/(\mu\mu)$.
- b-tagged jet veto (to suppress $t\bar{t}$)
- CMS: fit to the MET distribution (separately for events with 0 or 1 jet)
- ATLAS: fit to output of BDT trained with 8 variables.
- ATLAS/CMS: Simultaneous fit to SR (2 leptons) + CR with 3 or 4 leptons to constrain $ZZ(2l2\nu)$ and $WZ(1l3\nu)$ with lost lepton (ATLAS: also $e\mu$ CR)
- Main uncertainty from background (mostly ZZ) modelling at high MET.





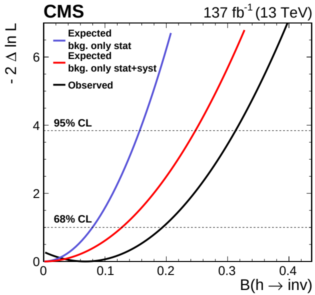


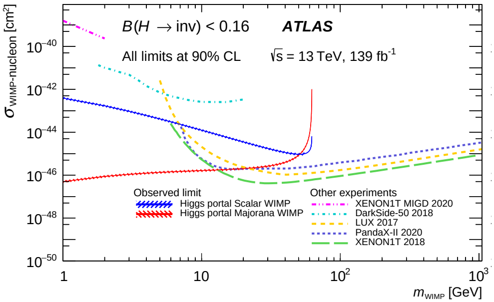
Uncertainty source	$\Delta\mathcal{B}$ [%]
Statistical uncertainty	5.1
Systematic uncertainties	7.4
Theory uncertainties	4.9
Signal modelling	0.4
ZZ modelling	4.4
Non-ZZ background modelling	2.1
Experimental uncertainties (excl. MC stat.)	4.6
Luminosity, pile-up	1.5
Jets, E_T^{miss}	4.0
Flavour tagging	0.4
Electrons, muons	1.2
MC statistical uncertainty	1.6
Total uncertainty	9.0

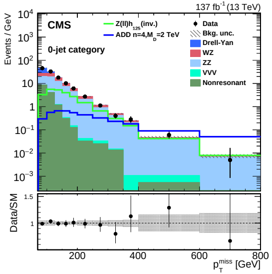
$Z(l\bar{l}) + H$ (ATLAS+CMS): results

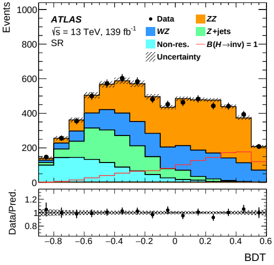
arXiv:2111.08372, arXiv:2008.04735

- $\mathcal{BR}(H \to \text{invisible}) < 0.19$ at 95%CL (0.19 exp.) by ATLAS and < 0.29 (0.25 exp.) by CMS

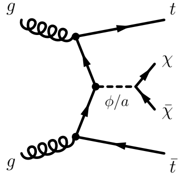


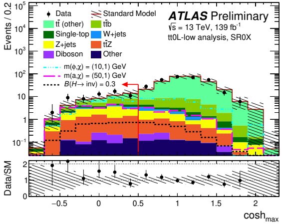


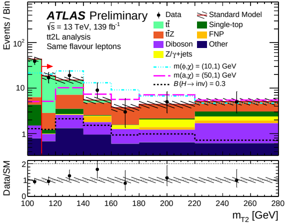




- Reinterpretation of previously published searches for new physics with a $t\bar{t}$ pair and MET in 0, 1, 2 lepton channels, primarily focusing on TeV particles.
- Each channel defines several SR based on the event content and its kinematics
- 0 lepton channel completed with a lower MET region accessible through MET+b-tagged jet triggers.
- Exclusion significantly improved with the combination.

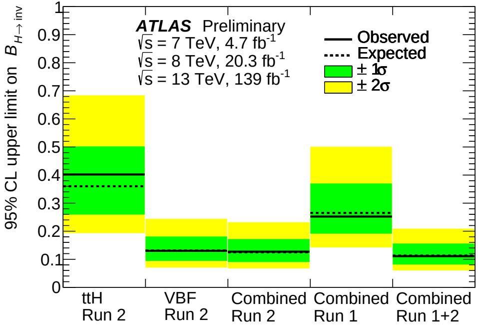






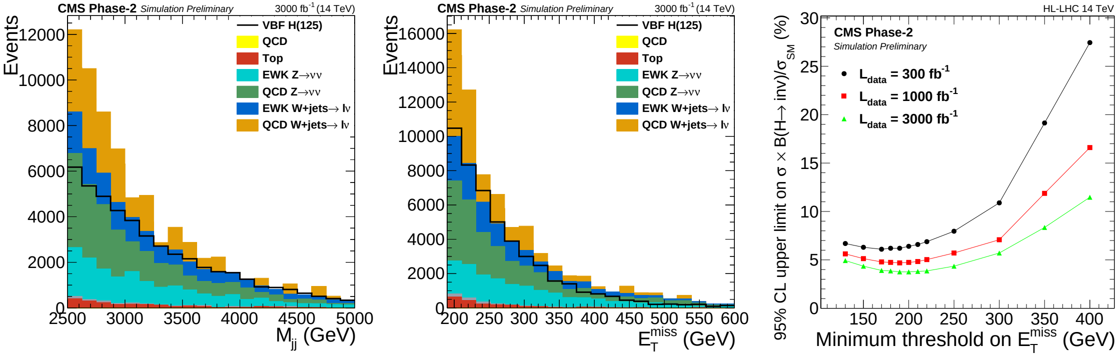
Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit	Reference
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$	[27], this document
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$	[28], this document
tt2L	$-0.09^{+0.22}_{-0.20}$	0.39	$0.42^{+0.18}_{-0.12}$	[29], this document
$t\bar{t}H$ comb.	$0.08^{+0.16}_{-0.15}$	0.40	$0.30^{+0.13}_{-0.09}$	This document

- Earlier ATLAS has also released an early combination of the VBF and $t\bar{t}$H (0 lepton, 2 leptons) channels, also combining Run 1 and Run 2
- This illustrates the interest/feasibility of combinations.
- Limits still very driven by VBF Run 2 but missing $t\bar{t}$H 1 lepton... and other production modes !



- Study of the CMS sensitivity reach to the VBF channel with HL LHC integrated luminosity
- Simplified analysis: consider events with $m_{jj} > 2.5$ TeV, MET>200 GeV
- Set limits as a function of MET threshold
- Expect to reach $\mathcal{BR}(H \to \text{invisible}) < 0.038$ at 95%CL
- ATLAS + CMS, VBF+ZH combination could reduce this down to 2.5%
- N.B. Current expected limit (VBF only, 13 TeV, $\approx$150 fb^{-1}) already at 0.1 !

  The challenge will be to deal with systematic uncertainties.



Summary

- Invisible decay of the Higgs is a natural place to look for new physics and in particular for dark matter
- All Higgs production channels (even rare ones such as VBF+γ) are being studied by ATLAS or CMS
- Now probing $\mathcal{BR}(H \to \mathrm{invisible}) \approx 10\%$ with VBF.
- Combination efforts are ramping up.
- More data to come in Run 3 and Phase 2 will significantly increase our sensitivity reach... if one manages to tackle systematic uncertainties !

References:

- **VBF ATLAS**: arXiv:2202.07953 (submitted to JINST)
- **VBF CMS**: arXiv:2201.11585 (accepted in Phys. Rev. D)
- **VBF +γ ATLAS**: arXiv:2109.00925 (Eur. Phys. J. C 82 (2022) 105)
- **ggF ATLAS**: arXiv:2102.10874 (Phys. Rev. D 103 (2021) 112006)
- **ggF and V(qq)+H CMS**: arXiv:2107.13021 (JHEP 11 (2021) 153)
- **Z(ll)+H ATLAS**: arXiv:2111.08372 (Phys. Lett. B 829 (2022) 137066)
- **Z(ll)+H CMS**: arXiv:2008.04735 (Eur. Phys. J. C 81 (2021) 13)
- **$t\bar{t}$+H combination ATLAS**: ATLAS-CONF-2022-007 (http://cdsweb.cern.ch/record/2805211)
- **$t\bar{t}$+H combination ATLAS**: ATLAS-CONF-2020-052 (http://cdsweb.cern.ch/record/2743055)
- **HL-LHC projection CMS**: CMS-PAS-FTR-18-016 (https://cds.cern.ch/record/2647700)