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

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on behalf of the ATLAS and CMS collaborations

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Higgs as a dark matter portal

- In the Standard Model $BR(H \to ZZ \to 4\nu)$: 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.
  - $BR \sim 0(10\%)$ 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.
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.
VBF (ATLAS+CMS): signal extraction details


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 $e/\mu$, enriched in $W(l\nu)/Z(ll)$)
- CMS also includes a $\gamma$+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

CMS likelihood

EWK and/or VBF $W/y/Z$ contributions, expressed as $Z\rightarrow \nu\nu$ (strong) yields times transfer factors taken from simulations

$Z\rightarrow \nu\nu$ (VBF) /$Z\rightarrow \nu\nu$ (strong) contribution
$Z\rightarrow W$ transfer factor
$\text{CR\rightarrow SR}$ transfer factor
Channel dependent factors (1 for ee/$\mu\mu$)
VBF (ATLAS+CMS): Background predictions and validation

- 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.

![Graph showing $R_{TH}/R_{MC}$ vs generator-level $m_j$ (GeV)]

**ATLAS Simulation**  
$\sqrt{s} = 13$ TeV, EW V+jets

![Graph showing ATLAS and CMS data vs $\Delta \phi(p_{miss}^T, Trk, p_{miss}^T)$ (rad)]

**ATLAS**  
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$  
Low MET VR

**CMS**  
$101$ fb$^{-1}$ (13 TeV)  
Leading-p$_T$ jet: 3.00 < |$p_T$| < 3.25
- Data compatible with SM expectation
- Observed 95% CL limit: $\mathcal{B}(H \rightarrow \text{invisible}) < 0.145$ (ATLAS), 0.18 (CMS)
- Similar exp. limit at 0.10.
- By far the most sensitive production mode for $H \rightarrow \text{invisible}$
- Interpretations in terms of DM candidate mass $m_{DM}$.
  - Outperforms direct searches experiments for $m_{DM} \lesssim 10$ GeV.
VBF (ATLAS+CMS): High $m_{jj}$ events

Yellow cones: jets, red/purple arrow: MET
Vector boson fusion with associate $\gamma$ production (ATLAS)  

- 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 $H \rightarrow$ invisible
  - Deep Neural Network trained using 8 most significant kinematic features (incl. $\Delta\eta(jj)$, MET, $m_{jj}$)
  - 95%CL upper limit on $BR(H \rightarrow$ 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 $p_T (> 150 \text{ GeV})$ central jet and $p_T^{\text{recoil}} (= \text{MET in SR}) > 200 \text{ GeV}$

- 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 $p_T^{\text{recoil}}$ of 1 TeV.
- 95%CL upper limit on $BR(H \rightarrow \text{invisible}) < 0.34 (0.39^{+0.16}_{-0.11} \text{ exp.})$
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 $W/Z \rightarrow qq$.
Three categories based on DeepAK8 score and jet soft-drop mass ($\epsilon/\delta [65,120]$).
95%CL upper limit on $BR(H \rightarrow$ invisible) $< 0.28$ (0.25 exp.)
**Z(\bar{\nu}\nu) + H (ATLAS+CMS): search strategy**

- 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 $ZZ(2/2\nu)$ and $WZ(1/3\nu)$ with lost lepton (ATLAS: also $e\mu$ CR)
- Main uncertainty from background (mostly ZZ) modelling at high MET.

### Uncertainty source $\Delta B$ [%]

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<tr>
<th>Source</th>
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<td>Statistical uncertainty</td>
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<td>Non-ZZ background modelling</td>
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<td>Experimental uncertainties (excl. MC stat.)</td>
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<td>Luminosity, pile-up</td>
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<td>Jets, $E_{T}^{\text{miss}}$</td>
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<td>Flavour tagging</td>
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<td>MC statistical uncertainty</td>
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<td>Total uncertainty</td>
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\( BR(H \rightarrow \text{invisible}) < 0.19 \) 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.
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!
Phase 2 projections

- 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 $BR(H \rightarrow \text{invisible}) < 0.038$ at 95%CL
- ATLAS + CMS, VBF+ZH combination could reduce this down to 2.5%
- N.B. Current expected limit (VBF only, 13 TeV, $\approx 150 \text{ fb}^{-1}$) already at 0.1!

The challenge will be to deal with systematic uncertainties.

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**Minimum threshold on $E_T^{\text{miss}}$ (GeV)**

<table>
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<tr>
<th>(%)</th>
<th>SM $\sigma_{inv}$/$\sigma_{SM}$</th>
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**Upper limit on $BR(H \rightarrow \text{invisible})$ (%)**

- $L_{\text{data}} = 300 \text{ fb}^{-1}$
- $L_{\text{data}} = 1000 \text{ fb}^{-1}$
- $L_{\text{data}} = 3000 \text{ fb}^{-1}$

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L. Thomas (ULB)  
H → invisible searches at ATLAS and CMS  
May 16th, 2022
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 $\mathcal{BR}(H \rightarrow \text{invisible}) \approx 10\%$ 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)
- **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)