SEARCH FOR INVISIBLE DECAY MODES OF THE HIGGS BOSON WITH THE ATLAS DETECTOR

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on behalf of the ATLAS Collaboration
Standard Model (SM) theory remarkably successful in describing particles and interactions, but:

1. Cannot accommodate general relativity as quantum field theory
2. Hierarchy problem ($m_H \ll M_{\text{Planck}}$)
3. Dark Matter
4. ...

Need to go beyond the SM

The Higgs boson can play a role in probing BSM physics through searches for invisible decays:

- SM BR($H \rightarrow \text{invisible}$) $\sim 0.1\%$ (from $H \rightarrow ZZ^* \rightarrow 4\nu$)
- BR enhanced if $H \rightarrow$ pairs of stable or long-lived massive particles (e.g. WIMP)
  $\Rightarrow$ any measurable rate would imply new physics
- $\Gamma_H$ is not precisely constrained $\Rightarrow$ still possible a sizeable BR in invisible particles
- Higgs as a mediator between SM particles and Dark Matter particles
  (Higgs-portal Dark Matter Model)
**Experimental signature:** H→invisible decay is INVISIBLE!
Will appear as large missing transverse momentum (MET) in the event

need a visible object to trigger the event

**Production modes:**

- gluon-gluon fusion (ggF)
  - Tag the event with an ISR jet (Mono-jet search)

- Vector boson fusion (VBF)
  - Tag the event with the two well-separated jets

- Associated production with a boson VH
  - Tag the event through the leptons/hadrons from the vector boson (e.g. Z→ℓℓ or Z→jj)

**If not excess found over SM predictions:**

- Limit on \( \sigma_{prod} \times BR \)
- BR (H→invisible) assuming production cross section & acceptance unchanged wrt SM
- Results interpreted in the context of WIMP-nucleon interaction models
Experimental Signature: Energetic jet from ISR + high MET
- High production rate at LHC
- Primarily sensitive to ggF mode => large background

Event Selection
- MET Trigger > 80 GeV
- Leading jet \( p_T > 120 \) GeV, |\( \eta \) | < 2.0
- MET > 150 GeV
- \( \Delta \Phi (\text{jet, } p_T^{\text{miss}}) > 1.0 \) (suppress multi-jets background)

 different Signal Regions (SR) with increasing MET threshold

Results
- Dominant uncertainties on jet & MET energy scale and resolution 8-10%
- No excess over the SM observed
- Results used to derive 95%CL upper limit on \( \sigma \times \text{BR}(H \rightarrow \text{invisible}) \) for \( m_H = (115, 300) \) GeV, in ggF(dominant), VH & VBF production modes

@125 GeV, \( (\sigma \times \text{BR})_{\text{obs}} < 1.59 \) SM_{pred} with \( (\sigma \times \text{BR})_{\text{exp}} < 1.91 \) SM_{pred}

- Better sensitivity at high \( m_H \)
**VBF CHANNEL**

**Experimental Signature:** Two jets with large separation in pseudorapidity + high MET
- Most sensitive channel for the Higgs invisible searches
- High QCD-initiated backgrounds rejection ⇒ S/B ~ 0.5

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**Event Selection**

- MET Trigger > 80 GeV
- Exactly two high-$p_T$ jets
- MET > 150 GeV
- Large jets separation $|\Delta\eta_{jj}|$
- Large dijet mass $M_{jj}$

**Backgrounds estimation**

**Dominant:**
- $Z\rightarrow\nu\nu +$ jets & $W+$jets (from leptonic $W/Z$ control samples in data)

**Sub-leading backgrounds:**
- Multijets (Data-driven data CR & jet smearing method for estimation)
- Others (~1%, MC-only)

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**Results**

- Uncert. on MC predictions dominated by jet energy scale & resol. (flavour dependent)
- No excess over the SM found
- Derived 95%CL upper limit on BR($H\rightarrow$invisible):
  - @125 GeV, $BR_{obs} < 0.28$ with $BR_{exp} < 0.31$
- Model independent 95%CL upper limit on fiducial $\sigma$ (small ggF+2jets treated as signal):
  - $3.93$ fb observed ($4.78$ fb expected)
**Experimental Signature:** Hadronically decaying vector boson (V=W/Z) in association with the invisible H → 2 jets + large MET

- Intermediate sensitivity between Mono-jet and VBF analyses

**Event Selection**
- MET Trigger > 80 GeV
- 2/3 jets
- MET > 120 GeV (correlated with Vp_T)
- Mjj - M_W/Z
- ΔRjj (boosted V-boson)
  - no VBF contamination

  Four MET ranges and #b-jets (up to 2) for the event categorisation

**Results**
- Combined fit to the MET and mjj distributions in SRs and p_T(V) in CRs
  → No excess over SM found: \( \mu = -0.13^{+0.43/-0.44} \)
- 95%CL upper limit on BR(H→invisible), SM VH & ggF contributions combined:
  @125 GeV, BR_{obs} < 78% with BR_{exp} < 86%
- 95%CL upper limit on \( \sigma_{VH} \times BR(H→invisible) \):
  1.1 pb observed (1.1 pb expected)

**Backgrounds estimation**

**Dominant:**
- Multi-jets background (from data with ABCD method)
- V+jets (data normalisation from CRs with \( \geq 1 \) lepton with p_T > 25 GeV + 2jets)

**Sub-leading backgrounds:**
- ttbar (Data-driven)
Experimental Signature: Leptonically decaying Z-boson + high MET

- Clean final state
- Low sensitivity

New energy regime to extend the sensitivity of this analysis and improve Run-I result

Result based on 2015+2016 integrated luminosity of 13.3 fb⁻¹

Event Selection

Remarks: Quite different event selection & bkg composition wrt other channels, since no jets expected

- Single lepton trigger
- Exactly one e⁺e⁻ or μ⁺μ⁻ pair
- |M_\ell\ell - M_Z| < 15 GeV
- MET > 90 GeV
- ΔR_\ell\ell (boosted Z-boson)
- ΔΦ(Z, MET) > 2.7 (back-to-back)
- No b-tagged jets

Specific selections to suppress Drell-Yan events

- |p_T(miss-jet) - p_T\ell\ell| / p_T\ell\ell < 0.2
- ΔΦ(MET, jet(p_T>25GeV)) > 0.7
- p_T\ell\ell/m_T < 0.9

☞ Signal acceptance ~18% in both ee & μμ channels
ZH, Z→ℓℓ CHANNEL

Irreducible Background
- **ZZ continuum** background is the leading bkg (~50% qqZZ, ~3% ggZZ)
- Both contributions estimated from MC
- NNLO QCD & NLO EW corrections applied
- QCD scales and PDF variations have a ~3-4% impact on the normalisation
- ggZZ @LO, but 1.7±1.0 k-factor applied

Reducible Backgrounds (data-driven)
- **WZ, W→ℓν Z→ℓℓ** is the 2nd leading background (~24%)
- Lepton from the W escaping detection or decaying hadronically
- Estimated from a 3-lepton CR.
  20% correction of WZ normalisation in SR
- **Drell-Yan Z(→ℓℓ)+jets** has no genuine MET, but may enter due to jets mis-measurements (Hard to model with MC!)
- Highly reduced by the event selection (~8-10% of total bkg in SR)
- Estimated with ABCD method
- Large uncertainties (~80%) on the final yield in SR due mainly to lack of statistics effects in the sideband regions → instabilities in the B/D ratio

**ttbar/WW/Wt/Z→ττ** estimated in different flavour eμ events
- Low contaminated CR
- Extrapolate to SR by accounting for e/μ reco efficiency differences
ZH, Z→ℓℓ CHANNEL

Results

• The limit on the invisible branching ratio extracted with a maximum likelihood fit of the MET distribution
• Data-driven estimates used for the bkgs normalisation (but for ZZ), MET shape taken from MC
• ee and μμ results statistically combined

<table>
<thead>
<tr>
<th>Low Mass Signal Region</th>
<th>ee</th>
<th>μμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>220</td>
<td>236</td>
</tr>
</tbody>
</table>

Signals

ZH (m_H ≈ 125 GeV) with BF(H → invisible)=100%

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-Z (m_ℓ = 1 GeV, m_{med} = 10 GeV)</td>
<td>40.5 ± 1.2 ± 4.1</td>
</tr>
<tr>
<td>Mono-Z (m_ℓ = 50 GeV, m_{med} = 300 GeV)</td>
<td>175 ± 24 ± 14</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>95.0 ± 1.5 ± 5.8</td>
</tr>
<tr>
<td>ggZZ (MC-based)</td>
<td>5.6 ± 0.1 ± 3.3</td>
</tr>
<tr>
<td>WZ (Data-driven)</td>
<td>44.0 ± 1.1 ± 3.3</td>
</tr>
<tr>
<td>Z(→ ee,μμ)+jets (Data-driven)</td>
<td>23 ± 5 ± 11</td>
</tr>
<tr>
<td>non-resonant-ℓℓ (Data-driven)</td>
<td>16.9 ± 2.8 ± 1.0</td>
</tr>
<tr>
<td>fake-lepton (Data-driven)</td>
<td>0.18 ± 0.04 ± 0.03</td>
</tr>
<tr>
<td>tV/VVV (MC-based)</td>
<td>0.44 ± 0.02 ± 0.06</td>
</tr>
<tr>
<td>Total background</td>
<td>185 ± 6 ± 13</td>
</tr>
</tbody>
</table>

Moderate excess observed in both ee & μμ channels

No significant excess observed over SM predictions

95% CL limits results

<table>
<thead>
<tr>
<th>Upper limit on BR(H→invisible)</th>
<th>Run-II result</th>
<th>Run-I result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs.</td>
<td>Exp.</td>
<td>Obs.</td>
</tr>
<tr>
<td>Upper limit on BR(H→invisible)</td>
<td>0.98</td>
<td>0.65</td>
</tr>
<tr>
<td>Upper limit on σ(Z→ℓℓ) × BR(H→inv) [fb]</td>
<td>88</td>
<td>58</td>
</tr>
</tbody>
</table>

M. Trovatelli - ICHEP 3-11 August 2016, Chicago
8 TeV Combination of the Direct Searches

A statistical combination of the Run-I searches was performed.

VH and VBF searches combined (Mono-jet left outside, since less sensitive to Higgs-mediated interactions), any possible overlap between SRs & CRs removed by jet veto and $m_{jj}$ cuts.

Simultaneous maximum likelihood fit to the event count in SRs & CRs.

Luminosity uncertainty, jet absolute energy scale and resolution uncertainties as well as theory uncertainties treated as fully correlated across the individual searches.

Uncertainty on the soft component of the MET affecting only ZH, $Z\to\ell\ell$ search.

### Run-I only

<table>
<thead>
<tr>
<th></th>
<th>Upper limit on BR(H→inv)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Obs.</td>
</tr>
<tr>
<td>VBF</td>
<td>0.28</td>
</tr>
<tr>
<td>VH, $V\to jj$</td>
<td>0.78</td>
</tr>
<tr>
<td>VH, $V\to \ell\ell$</td>
<td>0.75</td>
</tr>
<tr>
<td>Combined</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Sensitivity dominated by VBF search.
**INDIRECT CONSTRAINT ON H→INVISIBLE**

- Use the measured visible rate in a more general couplings fit to constraint the H→invisible
- Visible rates indirectly sensitive to undetectable final states (e.g. BR_{gg}): \( \Gamma_h = \text{BR}_{\text{vis}} + \text{BR}_{\text{inv}} + \text{BR}_{\text{undetectable}} \)
- Extract a conservative limit on BR_{inv} assuming BR_{undetectable} \( \sim 0 \), as predicted in SM

\[
k_h^2 = \frac{\Gamma_h}{\Gamma_{h,\text{SM}}} = \sum_j k_j^2 \frac{\text{BR}_j}{(1 - \text{BR}_{\text{inv}})}
\]

**Scale factor for total width**

- The coupling parametrisation includes separate scale factors for the coupling to bosons and fermions: \( K_W, K_Z, K_t, K_b, K_\tau, K_\mu \)
- Scale factors for effective loop-induced couplings to gluons/photons and Z\gamma to include possible contributions from new particles in the loops
- Fit one POI and treat the others as nuisance parameter (NP)

<table>
<thead>
<tr>
<th>Coupling parametrisation</th>
<th>( k_i ) assumption</th>
<th>Upper limit on BR_{inv}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Obs.</td>
</tr>
<tr>
<td>( k_W, k_Z, k_t, k_b, k_\tau, k_\mu, k_g, k_Y, k_{Z\gamma} )</td>
<td>( k_W, Z \leq 1 )</td>
<td>0.49</td>
</tr>
</tbody>
</table>
**INTERPRETATIONS**

- Direct Dark Matter searches look for the atomic recoil from scatter of DM particles in the detector.
- Results of the $H \rightarrow \text{invisible}$ searches at LHC provide complementary sensitivity to these astroparticles searches, being sensitive to masses of the DM particle of $m_\chi < m_H/2$.
- Run-I limits have been interpreted in terms of the Higgs-portal DM Model.

**SM extended to introduce one new particle which couple exclusively to Higgs boson through $\lambda_{h\chi\chi}$**

- Limits translated in upper bounds on the DM-Nucleon scattering cross section:
  \[ \Gamma(H \rightarrow \chi\chi) \leftrightarrow \lambda_{h\chi\chi}^2 \leftrightarrow \sigma_{N\chi} \]

- Scalar, vector and fermion hypothesis probed (model-dependent limits).
- Particular sensitive to low $m_\chi$ region.

**WIMP-nucleon cross section [cm$^{-2}$]**

<table>
<thead>
<tr>
<th>WIMP mass [GeV]</th>
<th>DAMA/LIBRA (99.7% CL)</th>
<th>CRESST II (95% CL)</th>
<th>CDMS SI (95% CL)</th>
<th>CoGeNT (99% CL)</th>
<th>CRESST II (90% CL)</th>
<th>SuperCDMS (90% CL)</th>
<th>XENON100 (90% CL)</th>
<th>LUX (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^{-41}$</td>
<td>$10^{-42}$</td>
<td>$10^{-43}$</td>
<td>$10^{-44}$</td>
<td>$10^{-45}$</td>
<td>$10^{-46}$</td>
<td>$10^{-47}$</td>
<td>$10^{-48}$</td>
</tr>
<tr>
<td>10</td>
<td>$10^{-41}$</td>
<td>$10^{-42}$</td>
<td>$10^{-43}$</td>
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<td>$10^{-48}$</td>
</tr>
</tbody>
</table>

**Vis. & inv. Higgs boson decay channels**

- [\$W, Z, \kappa \rightarrow \gamma, Z, \kappa, \gamma, \kappa, g, \kappa, \mu, \kappa, \tau, \kappa, b, \kappa, t, Z, W \kappa\$]
  \[ <0.22 \text{ at } 90\% \text{ CL} \]

**ATLAS 90% CL in Higgs portal model**

- Scalar WIMP
- Majorana WIMP
- Vector WIMP

**M. Trovatelli - ICHEP 3-11 August 2016, Chicago**
SUMMARY OF H→INVISIBLE SEARCHES

✓ With data collected in the 8 TeV Run ATLAS has carried out a comprehensive programme of searches for the invisible decay of the Higgs boson

✓ Great number of analyses involved, different analysis techniques employed

✓ No evidence for the Higgs boson invisible decay has been observed

✓ Run-I concluded with a statistical combination of the H→invisible direct and indirect search, from the coupling parametrisation:

<table>
<thead>
<tr>
<th>Decay channels</th>
<th>Coupling parameterisation</th>
<th>$\kappa_i$ assumption</th>
<th>Upper limit on BR$_{inv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invisible decays</td>
<td>$[k_W, k_Z, k_\ell, k_b, k_\tau, k_\mu, k_\gamma, k_{Z, Y}, \text{BR}_{inv}]$</td>
<td>$\kappa_{W,Z} = 1$</td>
<td>0.25 (Obs.), 0.27 (Exp.)</td>
</tr>
<tr>
<td>Visible decays</td>
<td>$[k_W, k_Z, k_\ell, k_b, k_\tau, k_\mu, k_\gamma, k_{Z, Y}, \text{BR}_{inv}]$</td>
<td>$\kappa_{W,Z} \leq 1$</td>
<td>0.49 (Obs.), 0.48 (Exp.)</td>
</tr>
<tr>
<td>Inv. &amp; vis. decays</td>
<td>$[k_W, k_Z, k_\ell, k_b, k_\tau, k_\mu, k_\gamma, k_{Z, Y}, \text{BR}_{inv}]$</td>
<td>None</td>
<td>0.23 (Obs.), 0.24 (Exp.)</td>
</tr>
<tr>
<td>Inv. &amp; vis. decays</td>
<td>$[k_W, k_Z, k_\ell, k_b, k_\tau, k_\mu, k_\gamma, k_{Z, Y}, \text{BR}_{inv}]$</td>
<td>$\kappa_{W,Z} \leq 1$</td>
<td>0.23 (Obs.), 0.23 (Exp.)</td>
</tr>
</tbody>
</table>

Table 7: Summary of upper limits on BR(h → invisible) at the 95% CL from the combination of direct searches for invisible Higgs boson decays, the combination of measurements of visible Higgs boson decays, and the overall combination using both the invisible and visible Higgs boson decays. The results are derived using different assumptions about $\kappa_{W,Z}$. The results with the baseline configuration for the combination of invisible and visible decay channels are indicated in bold.

✓ The second run of the LHC offers the possibility to improve Run-I results

✓ First result from the ZH, Z→$\ell\ell$ H→invisible channel presented today, many more to come in the next months!
BACKUP
GENERAL METHODOLOGIES FOR BACKGROUNDS

\( Z \rightarrow \nu \nu \) & \( W \rightarrow \ell \nu \)

- \( Z \rightarrow \nu \nu \) + jets background constrained using a combination of estimates from \( W + \text{jets} \) & \( Z \rightarrow \ell \ell + \text{jets} \) CRs:
  - Data control samples with identified e/\( \mu \) & same requirements on jets/MET as in SR
  - Data-driven techniques allow to reduce the theoretical & experimental systematic uncertainties associated with MC predictions

\( W \rightarrow \mu \nu \) & \( Z \rightarrow \mu \mu \)
\( W \rightarrow e \nu \) & \( Z \rightarrow e e \)

- MET online trigger w/o the \( \mu \) information \( \Rightarrow \) events in the CR selected with the same trigger as in SR
- Use electrons online trigger
- MET corrected for removing the contribution of electrons energy cluster in the calorimeter

Example: \( Z \rightarrow \nu \nu \) from \( W \rightarrow \mu \nu \)

\[
N_{Z(\rightarrow \nu \bar{\nu})}^{\text{signal}} = \frac{(N_{\text{data}}^{W(\rightarrow \mu \nu), \text{control}} - N_{\text{non-}W/Z}^{W(\rightarrow \mu \nu), \text{control}})}{N_{\text{MC}}^{W(\rightarrow \mu \nu), \text{control}}} \times N_{\text{MC}}^{Z(\rightarrow \nu \bar{\nu})} \times \xi_\ell \times \xi_{\text{RF}}
\]

Four corrections factors from the 4 CRs, results statistically combined

MC-to-Data normalisation factor \(~(0.9\div0.6)\) as MET increase (MC exceeds data for \( W/Z+\text{jets} \) processes)
GENERAL METHODOLOGIES FOR BACKGROUNDS

Non-collision background

- Cosmic muons, beam-halo and detector noise give rise to large energy deposits in the calorimeter
- Below the percent level after the mono-jet event selection
- Collision jets are in time with the bunch crossing \( \Rightarrow \) events with one jet out-of-time are non-collision events
- Shape of the fake jets extracted from signal events identified as beam-induced backgrounds based on the spatial alignment of the signals in the calorimeter and the muon system
HIGGS PORTAL DARK-MATTER MODEL

- Dark matter portal models introduce the existence of a WIMP as dark-matter candidate
- The WIMP is assumed to interact weakly with all the particles but for the Higgs boson
- The combined upper limit from visible & invisible searches is translated into constraint on the coupling of WIMP to the Higgs boson $\lambda$
- The partial width to the DM particles pairs depends on the spin of the DM particles

$$\text{scalar } S : \Gamma^{\text{inv}}(h \rightarrow SS) = \frac{\lambda_{hSS}^2 v^2 \beta_S}{128 \pi m_h}$$

$$\text{fermion } f : \Gamma^{\text{inv}}(h \rightarrow ff) = \frac{\lambda_{hff}^2 v^2 \beta_f}{\Lambda^2} \frac{64 \pi}{v^2} m_f^3 m_h^3$$

$$\text{vector } V : \Gamma^{\text{inv}}(h \rightarrow VV) = \frac{\lambda_{hvV}^2 v^2 \beta_v}{512 \pi m_V^3} \times \left(1 - 4 \frac{m_V^2}{m_h^2} + 12 \frac{m_V^4}{m_h^4}\right)$$

- Used to deduce the couplings to the WIMP
- Couplings re-parametrised in terms of the cross section for scattering between WIMP and nucleon, via the Higgs boson exchange

$$\text{scalar } S : \sigma_{S-N} = \frac{\lambda_{hSS}^2}{16 \pi m_h^2 (m_S + m_N)^2} \frac{m_N f_N^2}{m_h(m_S + m_N)^2}$$

$$\text{fermion } f : \sigma_{f-N} = \frac{\lambda_{hff}^2}{4 \pi m_h^2 (m_f + m_N)^2} \frac{m_N f_N^2 m_f^2}{m_h(m_f + m_N)^2}$$

$$\text{vector } V : \sigma_{V-N} = \frac{\lambda_{hvV}^2}{16 \pi m_h^2 (m_V + m_N)^2} \frac{m_N f_N^2}{m_h(m_V + m_N)^2}$$