

# Search for invisible decay modes of the Higgs boson with the ATLAS detector

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The Higgs boson provides a unique way to probe the production of Dark Matter particles in the proton-proton collisions at the Large Hadron Collider, through searches for its decay into invisible particles. With the data sample collected at the centre-of-mass energy of 8 TeV the ATLAS Collaboration has performed searches in a number of production modes of the Higgs boson. The results are compatible with the Standard Model expectations and they have been used to set upper limits on the branching ratio for the Higgs decay into invisible particles. A first result obtained with data collected at the new energy regime of 13 TeV in the  $ZH$ ,  $Z \rightarrow \ell\ell H \rightarrow \text{invisible}$  channel has also been presented.

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## 1. Introduction

Several astrophysical observations provide strong evidence for the presence of Dark Matter (DM) in the Universe, that may be explained by the existence of weakly interacting massive particles (WIMP). In understanding the origin of DM, the Higgs boson plays a key role through searches for its decays into invisible particles. In some extensions of the Standard Model theory (SM) known as "Higgs-portal DM" models [1, 2], the Higgs boson is in fact allowed to decay in a pair of neutral long-lived, and so invisible, massive particles, as the WIMP.

In the SM the Higgs decays into invisible particles through the  $H \rightarrow ZZ \rightarrow 4\nu$  channel, but with a branching fraction (BR) much smaller,  $\sim 0.1\%$  [3], of the current sensitivity of the ATLAS experiment [4] searches at the Large Hadron Collider (LHC) [5]. Moreover, the Higgs boson width is so far only weakly constrained, leaving opened the possibility of a considerable fraction of the Higgs boson decays in particles beyond the SM. A measurement of the rate  $H \rightarrow \text{invisible}$  ( $H_{\text{inv}}$ ) would then imply the existence of new physics.

With a dataset corresponding to  $20.3 \text{ fb}^{-1}$  of integrated luminosity collected in proton-proton (pp) collisions at a centre-of-mass energy  $\sqrt{s} = 8 \text{ TeV}$ , the ATLAS Collaboration has carried on an extensive program of searches for  $H_{\text{inv}}$  decays, exploiting the experiment sensitivity to different Higgs boson production modes. The analyses are presented below. The new  $13 \text{ TeV}$  energy regime of the LHC allows to extend the sensitivity of these analyses and improve the previous results. A first result based on the  $13.3 \text{ fb}^{-1}$  dataset collected during 2015 and 2016 data taking is reported.

## 2. $H \rightarrow \text{invisible}$ searches

The experimental signature for an invisibly decaying Higgs boson consists in large missing transverse momentum  $E_T^{\text{miss}}$ ; to tag the event the presence of a visible object is thus needed. For this reason, the searches are performed in ATLAS in a variety of final states: the mono-jet channel, in which the event is tagged through the emission of a very energetic initial state radiation (ISR) jet, the vector boson fusion (VBF) channel, identified through the presence of two forward jets, and the associated production with a vector boson  $VH$ ,  $V = W$  or  $Z$ , with the boson decaying either hadronically or leptonically. In all cases, no excess over the SM predictions were found and the results were translated into upper bounds at the 95% Confidence level (CL) on the  $\text{BR}(H \rightarrow \text{invisible})$ ,  $\text{BR}_{\text{inv}}$ , assuming that the Higgs boson production cross sections  $\sigma_{\text{SM}}$  and acceptances are unchanged relative to the SM expectations. More model-independent limits have been placed on the product  $\sigma \times \text{BR}_{\text{inv}}$ .

### 2.1 Mono-jet search

The mono-jet analysis [6], targeting primarily the gluon-gluon fusion production mechanism, has limited sensitivity due to the huge multi-jets background. The analysis is optimised to select events with at least one jet with  $p_T > 120 \text{ GeV}$ ,  $|\eta| < 2.0$  and  $E_T^{\text{miss}} > 150 \text{ GeV}$ . Additional selections are imposed to reduce the multi-jet background contribution where the large  $E_T^{\text{miss}}$  originates mainly from jet energy mis-measurement. The dominant  $Z(\rightarrow \nu\nu)$ +jets and  $W$ +jets backgrounds are estimated in data from control samples built with leptonic  $W/Z$  events. Good agreement is

found between the data and the background expectation. The result translates in  $\sigma \times BR(H \rightarrow \text{invisible})_{\text{obs}} < 1.59$  SM prediction with  $\sigma \times BR(H \rightarrow \text{invisible})_{\text{exp}} < 1.91$  SM prediction for a Higgs boson with mass  $m_H = 125$  GeV.

## 2.2 VBF search

The Higgs boson production via VBF [7] provides the best sensitivity to the search for  $H_{\text{inv}}$ , thanks to very clean signature of two jets with large separation in pseudorapidity and large  $E_T^{\text{miss}}$ . The analysis exploits the topology of the VBF process by defining several signal regions with different cuts on the invariant mass  $m_{jj}$  of the two highest-pT jets and their angular separation  $\Delta\eta_{jj}$ . The harsh selections lead to a strong rejection against the QCD-initiated backgrounds and a signal-over-background ratio of  $\sim 0.5$ . The major backgrounds,  $Z \rightarrow vv$  and  $W \rightarrow lv$ , are determined from leptonic  $W$  and  $Z$  events where two additional jets are required, following the same requirements as the signal regions. Good agreement is observed between data and SM background expectations. A 95% CL upper limit on the  $BR_{\text{inv}} < 0.28$  obs. (0.31 exp.) for  $m_H = 125$  GeV is obtained.

## 2.3 $VH, V \rightarrow jj$ search

The  $VH, V \rightarrow jj$  [8] has a sensitivity between that of the previous two channels. The experimental signature consists in large  $E_T^{\text{miss}}$  resulting from the  $H_{\text{inv}}$  decay plus two jets reconstructed with  $m_{jj} \sim m_{W/Z}$ . Other selections are applied to the events to profit from the strongly correlation between the  $E_T^{\text{miss}}$  and the transverse momentum of the vector boson  $p_T(V)$ . Additional sensitivity in the analysis is gained by optimising the selection cuts separately for four  $E_T^{\text{miss}}$  ranges, above the nominal  $E_T^{\text{miss}} > 120$  GeV threshold. The dominant background consists in multi-jets and  $V+jets$  events, where the  $E_T^{\text{miss}}$  is due to jets mis-reconstruction; their contribution is estimated using data control samples. No significant data excess over the background prediction is observed, and from a combined likelihood fit to the observed  $E_T^{\text{miss}}$  and the  $p_T(V)$  distribution a 95% CL upper limit on  $BR_{\text{inv}}$  at 78% (obs) (86% exp) obtained.

## 2.4 $ZH, Z \rightarrow \ell\ell$ search

The analysis targets final states with two leptons ( $e/\mu$ ) from the decay of a  $Z$  boson, and  $E_T^{\text{miss}} > 90$  GeV, from the Higgs invisible decay [9]. The relative low sensitivity of this channel is balanced by a very clean final state, where no genuine jets are expected. A preliminary 13 TeV result, based on  $13.3 \text{ fb}^{-1}$  collected by ATLAS in 2015 and 2016, has been presented. This follows the previous result based on  $20.3 \text{ fb}^{-1}$  collected at the centre-of-mass energy of 8 TeV [10]. A quite different event selection with respect to the other channels: the large  $E_T^{\text{miss}}$  values selects events with a boosted  $Z$  boson therefore a small angular separation  $\Delta R_{ll}$  between the two leptons is expected. Events with fake  $E_T^{\text{miss}}$  are largely reduced by requiring the  $Z$  boson to be produced back-to-back with respect to the  $E_T^{\text{miss}}$  in the azimuthal plane. Reducible backgrounds are normalised to data in control regions, while the leading irreducible  $ZZ^* \rightarrow llvv$  background is modelled with POWHEG-BOX Monte Carlo [11, 12] generator. No significant excess has been observed over SM predictions. From a maximum likelihood fit to the  $E_T^{\text{miss}}$  spectrum a 95% CL upper limit on  $BR_{\text{inv}}$  at 98% (obs)/ 65% (exp) is obtained.

### 3. Combination of 8 TeV results and indirect constraint from Higgs boson visible rates

The 8 TeV  $H_{inv}$  searches have been statistically combined to obtain a more stringent upper limit on the  $BR_{inv}$  [13]. All channels are used, except the "mono-jet" channel, due to its very low sensitivity. The result of the combination is given in the first row of table 3 and it is clearly dominated by the VBF analysis. Table 3 also reports an indirect constraint on  $BR_{inv}$  obtained from the measured 7 and 8 TeV Higgs boson visible decay rates. These are in fact complementary to the direct searches for invisible decays since they are indirectly sensitive to undetectable decays as well. In this case the extraction of  $BR_{inv}$  is performed using a coupling parameterisation that includes separate scale factors  $k_j$  for the couplings of the Higgs boson to the various SM particles. In this coupling framework the scale factor  $k_h^2$  for the Higgs total width can be written as:

$$k_h^2 = \Gamma_h / \Gamma_{h,SM} = \sum_j k_j^2 BR_j / (1 - BR_{inv}) \quad (3.1)$$

The production and decay rates of all channels are fit with functions of  $k_j$  under several assumptions on  $k_{W,Z}$ . The most stringent upper limit on  $BR_{inv}$  is obtained fitting both the visible and invisible rates in various channels.

**Table 1:** Summary of upper limits on  $BR_{inv}$  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 [13]. The visible rates and couplings have been obtained combining both the 7 TeV dataset, corresponding to  $4.5\text{-}4.7\text{ fb}^{-1}$  and the  $20.3\text{ fb}^{-1}$  from the 8 TeV run, while for the invisible searches only the latter has been used.

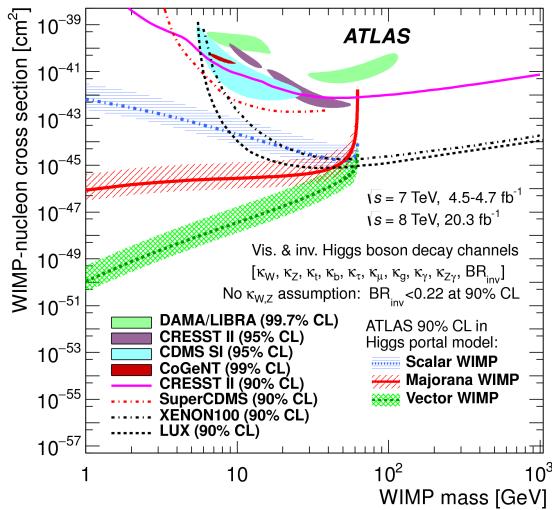
Decay channels	Coupling parametrisation	$k_i$ assumption	Upper limit on $BR_{inv}$	
			Obs.	Exp.
Invisible decays	$[k_W, k_Z, k_t, k_b, k_\tau, k_\mu, k_g, k_\gamma, k_{Z\gamma}, BR_{inv}]$	$k_{W,Z,g} = 1$	0.25	0.27
Visible decays	$[k_W, k_Z, k_t, k_b, k_\tau, k_\mu, k_g, k_\gamma, k_{Z\gamma}, BR_{inv}]$	$k_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	$[k_W, k_Z, k_t, k_b, k_\tau, k_\mu, k_g, k_\gamma, k_{Z\gamma}, BR_{inv}]$	None	0.23	0.24
Inv. & vis. decays	$[k_W, k_Z, k_t, k_b, k_\tau, k_\mu, k_g, k_\gamma, k_{Z\gamma}, BR_{inv}]$	$k_{W,Z} \leq 1$	0.23	0.23

### 4. Dark Matter interpretations

The searches for the invisible decays of the Higgs boson at LHC provide complementary sensitivity to the astroparticle searches of DM, since they are sensitive to low dark matter masses,  $m_{DM} < m_H/2$ , not accessible to the other experiments. Within the context of the Higgs-portal DM models, the 8 TeV limits have been translated to upper bounds on the WIMP-nucleon cross section, for different hypothesis of the spin-nature of the DM candidate, and in this way directly compared to the astroparticle limits. The 90% CL on the WIMP-nucleon scattering cross section are shown in figure 1.

## 5. Summary

With data collected at 8 TeV pp collisions ATLAS has carried out a comprehensive program of searches for the invisible decay of the Higgs boson. The first LHC run concluded with a statistical combination of the Higgs visible and invisible searches, and an upper bound of 23% on  $BR_{inv}$ . The second run of the LHC offers the possibility to improve previous results, providing a unique opportunity to fully explore the Higgs-dark sector.



**Figure 1:** ATLAS upper limit on the WIMP-nucleon scattering cross section in a Higgs-portal model as a function of the mass of the dark matter particle, shown separately for a scalar, Majorana fermion, or vector-boson WIMP [13]. It is determined using  $BR_{inv} < 0.22$  at the 90% CL derived using both the visible and invisible Higgs boson decay channels; the result is obtained using both  $4.5\text{--}4.7 \text{ fb}^{-1}$  from the 7 TeV run and  $20.3 \text{ fb}^{-1}$  from the 8 TeV run. Excluded and allowed regions from direct detection experiments at the confidence levels indicated are also shown.

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