Search for invisible Higgs bosons produced via vector boson fusion at the LHC using the ATLAS detector

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Abstract

Despite dark matter abundance, its nature remains elusive. Many searches of dark matter particles are carried out using different technologies either via direct detection, indirect detection, or collider searches. In this work, the invisible Higgs sector was investigated, where Higgs bosons are produced via the vector boson fusion (VBF) process and subsequently decay into invisible particles. The hypothesis under consideration is that the Higgs boson might decay into a pair of weakly interacting massive particles (WIMPs), which are candidates for dark matter. The observed number of events are found to be in agreement with the background expectation from Standard Model (SM). Assuming a 125 GeV Higgs boson with SM production cross section, the observed and expected upper limits on the branching fraction of its decay into invisible particles are found to be 0.145 at 95% confidence level.

Keywords: VBF, invisible, Higgs, decay, dark matter, WIMPs, Higgs portal, vector, EFT

1. Introduction

Based on many astrophysical observations, there are strong evidences that dark matter exists and make up most of matter in the universe. Yet dark matter is completely invisible to traditional detectors, and its nature remains an open question; we can only infer its existence through its gravitational effects. Higgs portal model is considered as one of the important paths for dark matter searches, where the Higgs could be a mediator between SM particles and ones that belong to the dark sector.

The analysis uses data samples produced with a luminosity of 139 fb^{-1} of proton-proton collisions at center of mass of $\sqrt{s} = 13$ TeV, recorded by the ATLAS detector at the LHC. The SM predicts that no more than 0.1% of the branching fraction ($B_{H\to inv}$) of the Higgs bosons will decay into invisible particles [1]. Beyond Standard Model scenarios predict larger values for the invisible Higgs branching ratio, up to 10% [2]. The choice of VBF topology offers a powerful rejection against background. The contribution of the gluon-gluon fusion (ggF) process in the signal region (SR) is relatively small compared to that of the VBF process, but it is also considered to be part of the signal. The experimental signature of VBF is two leading jets with a large rapidity gap ($\Delta\eta_{jj}$) and large invariant masses m_{jj}.

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The events entering the SR are required to have large missing energy transverse. Events with two, three or four jets are considered as well. To benefit from the large data set, a binning on m_{jj} is applied (5 bins), and for the first time, a binning on $\Delta\Phi_{jj}$ (2 bins), an additional three bins for the jet multiplicity, and three bins in low E_T^{miss} region, resulting in a total of sixteen bins. The signal and control regions (CR) are defined using selections that exploit the four leading jets, the leptons, and the missing transverse energy (E_T^{miss}). The analysis defines two control regions to estimate the V+jets background; Z($\rightarrow ll$) and W($\rightarrow l\nu$); to estimate the contribution of Z($\rightarrow \nu\nu$) and W($\rightarrow l_{lost}\nu$) in the SR.

2. Background estimation

Principal backgrounds contributing to this analysis are V+jets, QCD multijet. Multi-boson (VVV), diboson (VV) and $t\bar{t}$, are minor backgrounds predicted directly from Monte Carlo simulation (MC).

The dominant, irreducible background is V+jets, constituting nearly 95% of background events and having large theoretical uncertainties. A data-driven technique that uses the $Z(\rightarrow \ell\ell)$+jets and $W(\rightarrow \ell\nu)$+jets CRs events, which are divided; using m_{jj}, $\Delta\phi_{jj}$, E_T^{miss}, and N_{jet} selections; into 16 bins identically to the SR binning. A small contribution of events with fake electrons (muons) from misidentified jets is expected in $W_{e\nu}$ ($W_{\mu\nu}$) CR, and is estimated by defining a further fake-e CR (fake-μ CR). To improve the Z+jets background estimation, the $W_{\ell\nu}$ CRs are used to determine the W+jets and Z+jets contributions to the SR.

QCD multijet can enter the signal region through a combination of mismeasurement of jet quantities and inappropriate pileup tagging, which can produce signal-like topologies. Two independent methods used to estimate the multijet background: a "Rebalance and Smear" technique and a data-driven approach called also "pile-up-CR method". The last step in multijet estimation consists of applying a correction to account for the inefficiency of the E_T^{miss} triggers used to collect data.

3. Systematic uncertainties

The high-order matrix element effects and parton shower matching uncertainties are evaluated using the renormalisation, factorisation, resumation (qsf) and ckkw matching scales. The renormalization and factorization scales are varied up and down by a factor of two, using on-the-fly varied event weights in the Sherpa MC samples. Uncertainties are calculated as relative error for the CKKW matching scales. The PDF uncertainties defined as the standard deviation of the ensemble of 100 PDFs within the NNPDF set. Three main categories of experimental uncertainties affect the sensitivity of the analysis; uncertainty on the luminosity, the trigger efficiency, and uncertainties related to the used physics objects.

4. Results

The event yields in the sixteen bins of all the signal and control regions after the likelihood fit are found to be in a good agreement with the expected yields from the SM background. Since no excess found above the SM background, a limit setting on the invisible Higgs branching fraction gives a more stringent value of 14.5% at 95% confidence level (CL). Analysis results are interpreted as an upper limit on the spin-independent WIMP-nucleon cross section using Higgs portal interpretations of B_{inv} at 90% CL as shown in Figure 1. The analysis considered the proposal of adding the WIMP vector and expanding the mass range to sub-GeV [3, 4].

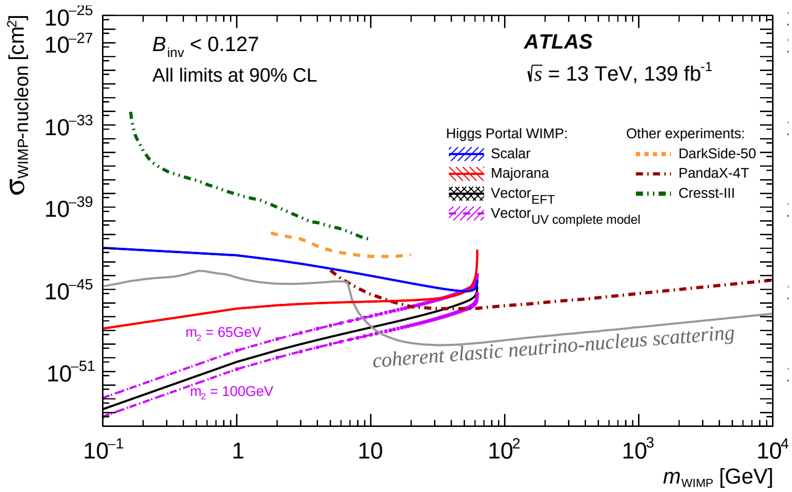

Figure 1: Upper limits on the spin independent WIMP-nucleon cross section using Higgs portal interpretation of invisible branching fraction at 90% CL vs $\mathrm{m_{WIMP}}$. For the vector-like WIMP hypothesis, the dependence on mass m_2 of the new scalar particle, which is often predicted by renormalizable models, is shown for three different values covering a wide range [4]. For comparison with direct searches for DM, the graph shows results from Refs.[4, 3]. The neutrino floor for coherent elastic neutrino-nucleus scattering assumes germanium as the target over over the whole WIMP mass range [4, 3].

The result is interpreted also as a search for invisible decays of heavy scalar particles acting as mediator to dark matter particles. Figure 2 shows the product of the cross section and the branching ratio to invisible particles in the range from 50 GeV to 2 TeV. The derived limit improves at high masses because of the accumulation of signal in high m_{jj} SR bins.

5. Conclusions

This work presents a search for Higgs boson produced via VBF mechanism and decay into invisible particles using a luminosity of 139 fb^{-1} of proton-proton collision at center of mass $\sqrt{s}$ =13 TeV collected during the Run2 period using the ATLAS detector at the LHC. The experimental signature of the VBF process is two leading jets with a large rapidity gap ($\Delta\eta_{jj}$) and large invariant masses m_{jj} and E_T^{miss}. Events with three or four jets are considered as well if they originate from initial or final state radiations. An upper limit of 0.145 at 95% CL is set on $B_{H\rightarrow inv}$ assuming the SM Higgs boson production [3]. This result is interpreted using Higgs portal models to exclude regions in the $\sigma_{WIMP-nucleon}$ parameter vs the WIMP mass parameter space.

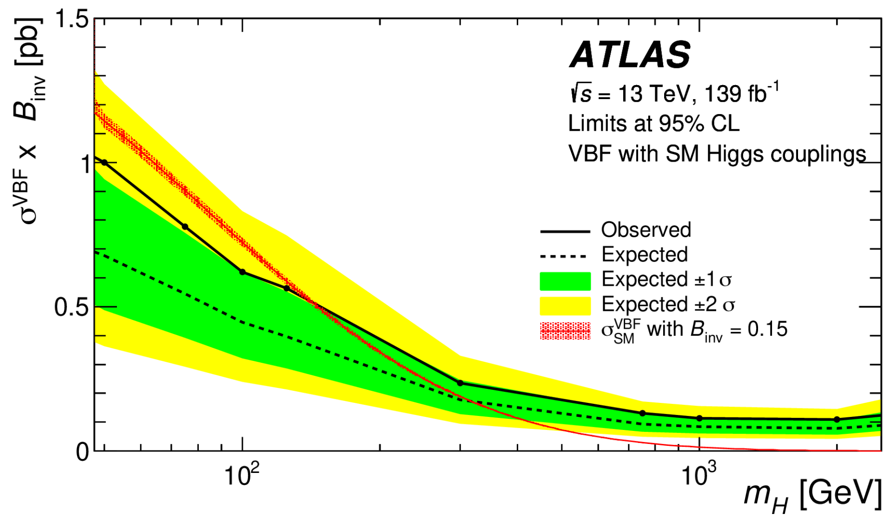

Figure 2: Upper limit on cross section times branching ratio to invisible particles for heavy scalar mediator particle as a function of its mass. For comparison the VBF cross section at NLO in QCD, i.e. without the electroweak corrections, for a particle with SM Higgs boson couplings, multiplied by a Binv value of 15%, is overlaid [3].

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