Study of the VBF Higgs production channel Higgs(→invisible) with the ATLAS experiment at the HL-LHC

Ian T. Lim,[1] Benjamin Nachman,[2] and Maurice Garcia-Sciveres[2]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Dated: April 26, 2018)

We describe a projection for a measurement to observe the invisible decay of a Higgs produced via the vector boson fusion (VBF) channel with the ATLAS detector. In the context of the high luminosity LHC (HL-LHC) upgrade, we report on the anticipated sensitivity to these invisible decays and a projected upper bound on the invisible Higgs decay branching ratio once the HL-LHC data collection has finished.

INTRODUCTION

The ATLAS Experiment is one of two general purpose detectors at the Large Hadron Collider (LHC), a particle accelerator near Geneva, Switzerland run by the European Organization for Nuclear Research, CERN. Currently observing at $\sqrt{s} = 13\,\text{TeV}$ center-of-mass energy,[1] ATLAS focuses on the analysis of proton-proton interactions, using a system of subdetectors to reconstruct particles produced by the proton collisions. A few of these (at most one in 10^{12}) especially energetic collisions may provide indications of new physics beyond the Standard Model, such as supersymmetry and the nature of dark matter.

We are especially interested in so-called invisible decays of the Higgs boson, a particle of central importance to the Standard Model. Because the Higgs boson is relatively massive compared to many other particles produced at the LHC, it has a very short lifetime in our detector, so we can only observe it indirectly through the particles it breaks down into. Sometimes, the Higgs boson decays into particles which are functionally invisible to the ATLAS detector, i.e. these particles will pass through the apparatus without depositing their energy in the detector[2]. These invisible decays include some known Standard Model processes, but they may also help us test possible models for dark matter, such as those involving weakly interacting massive particles (WIMPs)[3]. Therefore, studying the Higgs→invisible process will be a key measurement for the High-Luminosity LHC (HL-LHC), a planned upgrade to the LHC designed with a higher collision rate[1].

Fortunately, these decays are not completely invisible to our detector. If we analyze the kinematics of a collision, we might notice that some momentum is missing from the outgoing particles we measured, and this may be an indication that some energy has been carried off by invisible particles like the ones we want to study. To observe this process, we look for decays where the Higgs, and therefore its decay products, are boosted by accompanying particles such as quarks and gluons, so that we can look for events with missing momentum. These accompanying quarks and gluons produce energetic and highly directed showers of particles called jets, which are relatively easy to identify in the detector.

In one Higgs production mode, called vector boson fusion (VBF), the Higgs is boosted by two quark-initiated jets. This VBF Higgs production channel is especially useful for studying invisible decays of the Higgs because it features two energetic jets in the far forward region of the detector and no other visible decay products. This decay signature is very distinctive and provides good rejection against other Standard Model decays which might look like our process of interest.

In 2014, the CMS Experiment placed an observed upper limit on the invisible branching fraction of 0.58 at the 95% confidence level[4]. More recently, the ATLAS Experiment set an upper bound of 0.28 at the 95% confidence level using $20.3\,\text{fb}^{-1}$ of data in its Run 1 search[5], with similar results in Run 2[6]. A generic theorist projection from 2015 also suggests that following the HL-LHC upgrade, our analysis may be sensitive to branching ratios as low as 2-3.5%[7].

Here, we present the projected cross-section sensitivity for VBF Higgs→invisible once the HL-LHC data collection has concluded. Projections for the HL-LHC are particularly interesting because the full dataset will be thirty to forty times larger than the current dataset, and we also believe that the extended detectors may benefit our analysis by allowing us to collect more forward tracks from close to the beamline. Because of the high signal-to-noise ratio of this process, we expect VBF Higgs→invisible to be a powerful tool for probing the dark sector of physics beyond the Standard Model.

MATERIALS AND METHODS

For this project, we used ROOT 6.10.04,[8] the standard analysis framework used to process experimental particle physics datasets like those produced at the LHC. ROOT is primarily written in C++ but can also be used with other languages such as Python and R. The ROOT framework contains functionality to read, process, and visualize the large datasets generated by the ATLAS detector and Monte Carlo simulations thereof. Its data structures (the most important of which is the TTree) are designed for efficient data retrieval.

Using ROOT, we implemented the standard event selection cuts for VBF Higgs→invisible based on the Run 1 search for this process[9]. These cuts are displayed in Table I. The only completely irreducible Standard Model background for VBF Higgs→invisible is the process $H \rightarrow ZZ \rightarrow 4\nu$, and the expected branching fraction for this process is 0.1%[10], which is well below the expected sensitivity of this analysis. Therefore, the main backgrounds for this decay are strongly produced (QCD) W/Z+jets and weakly produced (EW) W/Z+jets.

Event selection cuts	
Requirement	Cut values
Leading jet p_T	$> 75\,\text{GeV}$
Second jet p_T	$> 50\,\text{GeV}$
m_{jj}	$> 1\,\text{TeV}$
$\eta_1 \times \eta_2$	< 0
$\lvert\Delta\eta_{jj}\rvert$	> 4.8
$\lvert\Delta\phi_{jj}\rvert$	< 2.5
Third jet veto p_T threshold	$30\,\text{GeV}$
$\lvert\Delta\phi_{j,E_T^{\text{miss}}}\rvert$	> 1.6 for j_1, > 1 otherwise
E_T^{miss}	$> 150\,\text{GeV}$

TABLE I. Summary of the event selection cuts for VBF Higgs→invisible.

The large separation in pseudorapidity between the leading and subleading jets in VBF Higgs→invisible provides strong rejection against the W/Z+jets backgrounds. This is particularly important because the SM backgrounds have much larger cross-sections as compared to our signal, and will therefore be produced more often in the detector.

In addition, the identification of jets as originating from the hard scatter or from pile-up is of key importance to our analysis. This matters because we expect pile-up jets to be uniformly distributed in η, and so it may happen that two pile-up jets (or one pile-up jet and one hard scatter jet) coincidentally pass our kinematic cuts, producing a fake event. By identifying jets as hard scatter or pile-up, we can reduce the rate of fake events and improve our sensitivity to the physics of interest.

To distinguish hard scatter and pile-up jets, we use a metric called R_{pT}, defined as follows:

$$R_{pT} = \frac{\sum_k p_T^k(\text{PV}_0)}{p_T^{\text{jet}}}, \tag{1}$$

where the sum is taken over all tracks within the jet associated to the zeroth primary vertex, i.e. the hard scatter candidate.

R_{pT} is therefore a measure of the hard scatter p_T (transverse momentum) contribution to the overall p_T of the jet, and a jet with higher R_{pT} is more likely to have been produced by the hard scatter interaction. We can place additional quality cuts on the tracks in the sum (e.g. a cut on Δz_0, the spatial separation between the track origin and the hard scatter vertex) in order to optimize our jet selection. In Figure 1, we show that R_{pT} can be used to reliably distinguish hard scatter and pile-up jets with a high signal efficiency.

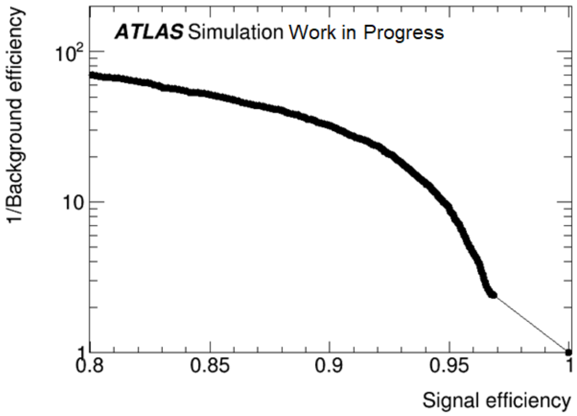

FIG. 1. A ROC (Receiver Operating Characteristic) curve for our jet classifier using different values of the R_{pT} working point. At an R_{pT} cut of 0.2, we can distinguish hard scatter and pile-up jets with a signal (true positive) efficiency over 90% and a background (false positive) efficiency of $\sim 3\%$.

RESULTS

From our series of event cuts on full detector simulations of both the VBF Higgs→invisible signal and the main QCD Z+jets background, we demonstrate that our background rejection for the Z+jets background is extremely strong.

By comparing the signal and background situations, we observe that by placing cuts on the leading and subleading jet p_Ts, the pseudorapidity separation $\Delta\eta_{12}$, and the dijet invariant mass m_{jj}, we can reduce the backgrounds by a factor of ten thousand (99.99% background rejection), while keeping ~3.7% of our signal events. Moreover, after these cuts, the two tagging jets in the signal both originated from the hard scatter interaction over 99% of the time.

This strong background rejection is particularly important because of the large cross-sections associated to the backgrounds relative to our signal. The Standard Model cross-section for the QCD Z+jets, $Z \rightarrow \nu\nu$ background is 12 000 pb, while a Higgs→invisible branching ratio of 2% (i.e. two of every hundred Higgs bosons produced decay to invisible particles) would yield a cross-section of 88 fb. This means that for every signal event, we expect roughly 150,000 background events.

However, we can take this analysis a step further. Rather than assuming a value for the Higgs→invisible branching ratio, we can compute the statistical significance for the anticipated signal at various values of the branching ratio given our known signal and background efficiencies. In particular, we compute the signal confidence level CL_S that a null measurement (i.e. an observation consistent with background alone) is compatible with the alternative hypothesis that a signal is present on top of the background.

If our confidence level CL_S drops below 0.05 for a given branching ratio, we conclude that that branching ratio is excluded. That is, a measurement statistically consistent with the null hypothesis (only Standard Model physics) is inconsistent with the alternative hypothesis (Standard Model with new physics), and so we rule out the alternative hypothesis with 95% certainty.

By repeating this computation for many values of the Higgs→invisible branching ratio, we find that a preliminary analysis assuming an integrated luminosity of $3000\,\mathrm{fb}^{-1}$ in the final dataset yields a sensitivity to invisible decays with branching ratio as small as 1%, a great improvement over the previous limit of ∼28% reported in the ATLAS Run 1 and Run 2 searches. The results of this calculation appear in Figure 2.

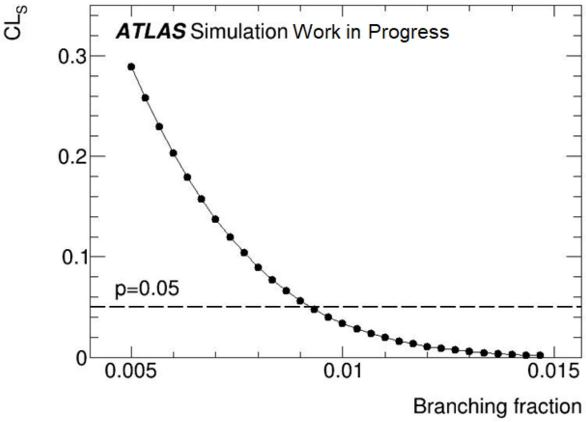

FIG. 2. Based on our preliminary calculations using the QCD Z+jets background, we see that our analysis can potentially exclude Higgs→invisible branching ratios down to 1%.

CONCLUSIONS

While this work has primarily explored the impact of the QCD W+jets background on the Higgs→invisible signal, it will be important to consider how other backgrounds such as the Z+jets (both QCD and electroweak) will change the final projection. In addition, it will be informative for future studies to consider the effects of inefficiencies on visible decays, e.g. where the Higgs turns into visible decay products but these decay products are not reconstructed due to detector effects. We defer a full analysis of these effects to future work.

Full detector simulations of some of the other Standard Model backgrounds have not been generated yet, and so we have already begun work on validating pileup overlay techniques and jet smearing functions for truth-level simulations (i.e. without the full detector simulation). However, these methods still present some difficulties in terms of producing an accurate p_T spectrum and distribution in the detector after smearing.

In spite of these obstacles, we remain optimistic about the prospects for Higgs→invisible sensitivity with the increased dataset, and hope the implementations we have developed here may be of use to future analyses involving similar cutflows.

We thank Ariel Schwartzman of SLAC National Accelerator Laboratory and his students Randy White and Nicole Hartman of Stanford University. Thanks to Federico Meloni, Simone Pagan Griso, and the Upgrade Physics group for their feedback on our projections. Thanks to Laleh Cot and the WD&E staff for their technical and logistical support. Finally, we thank Ian Hinchliffe and the ATLAS group at LBNL for their constant support throughout the research process.

This work was prepared in partial fulfillment of the requirements of the Berkeley Lab Undergraduate Research (BLUR) Program, managed by Workforce Development & Education at Berkeley Lab.

---

[1] A. Collaboration, *Technical Design Report for the ATLAS Inner Tracker Strip Detector*, Tech. Rep. CERN-LHCC-2017-005. ATLAS-TDR-025 (CERN, Geneva, 2017).
[2] R. E. Shrock and M. Suzuki, Physics Letters B **110**, 250 (1982).
[3] A. Djouadi, O. Lebedev, Y. Mambrini, and J. Quevillon, Physics Letters B **709**, 65 (2012).
[4] C. collaboration *et al.*, arXiv preprint arXiv:1404.1344 (2014).
[5] A. Collaboration *et al.*, Journal of High Energy Physics **1** (2016).
[6] K. Assamagan, W. K. Balunas, B. T. Carlson, and et al., *Search for invisible Higgs boson decays in vector boson fusion using 36 fb^{-1} at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Tech. Rep. ATL-COM-PHYS-2017-1811 (CERN, Geneva, 2017).
[7] C. Bernaciak, T. Plehn, P. Schichtel, and J. Tattersall, Physical Review D **91**, 035024 (2015).
[8] R. Brun and F. Rademakers, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **389**, 8186 (1997).
[9] G. Aad and etal, Journal of High Energy Physics **2016**, 172 (2016).
[10] S. Heinemeyer and et al. (LHC Higgs Cross Section

Working Group), *Handbook of LHC Higgs Cross Sections: 3. Higgs Properties: Report of the LHC Higgs Cross Section Working Group*, Tech. Rep. CERN-2013-004. CERN-2013-004 (Geneva, 2013) comments: 404 pages, 139 figures, to be submitted to CERN Report. Working Group web page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections.