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SEARCHING FOR THE INVISIBLE HIGGS AT THE LHC*

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The standard model of particle physics does not predict sizable branching ratios of the Higgs boson to invisible final states. Nevertheless, a variety of models exist that predict branching ratios of up to 100% to invisible final states. Several experimental signatures can be used to search for an invisibly decayed Higgs boson. Searches carried out in the CMS and in the ATLAS collaboration will be reviewed.

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1. Introduction

Among the principal goals of the multipurpose experiments at the LHC[1] is the study of the electroweak symmetry breaking mechanism. It has been shown repeatedly [1, 2] that a discovery of the standard model Higgs boson is possible with a high signal significance. The discovery of a Higgs boson in more exotic scenarios can be more challenging. Models in which the Higgs boson decays with a significant branching ratio into invisible final states are among these more challenging scenarios. Since the standard model predicts no decay of the Higgs boson into invisible final states at tree level, the observation of an invisibly decaying Higgs boson would be a clear indication of physics beyond the standard model.

This physics beyond the standard model could be, for example, the minimal supersymmetric extension of the standard model, which predicts, in some regions of parameter space the decay of at least one of the Higgs bosons into the lightest neutralino or gravitinos with a large branching ratio [3, 4]. Another possibility is an enlarged symmetry breaking sector, where Higgs bosons can decay into light weakly interacting scalars [5–7]. Also large extra dimensions [8, 9] or massive neutrinos of a fourth generation [10] would lead

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[1] LHC: **L**arge **H**adron **C**ollider.

to invisible Higgs boson decays. The lower limit on the mass of an invisibly decaying Higgs boson is given by negative searches at LEP [11]. A Higgs boson mass below 114.4 GeV could be excluded.

At a hadron collider, since only the measurement of *transverse* missing energy is possible, triggering and detection of an invisible final state is only possible if additional objects are produced together with the Higgs boson. The invisible Higgs boson can therefore be search for in associated production with vector bosons (WH, ZH), $t\bar{t}$-pairs ($t\bar{t}H$) and jets (vector boson fusion mode $q\bar{q}H$). All three production modes have been studied in the literature [12–15]. More detailed analysis have been carried out, including detector Monte Carlo for the CMS and the ATLAS experiment [16–18].

Even though additional objects are necessary to provide triggering and discrimination against backgrounds, a high missing transverse energy remains the key signature in these searches. A signal can only be extracted in a counting experiment, looking for an excess of events with high transverse missing energy over the estimated number of background events. Therefore the knowledge of these backgrounds is of paramount importance in these studies.

2. Production modes and channels

The Higgs boson is mainly produced in four production modes, shown in Fig. 1. It shows from left to right the Feynman diagrams for gluon fusion, vector boson fusion, Higgs strahlung and associated production with a top quark pair. The graphs are ordered in inclusive cross section. The gluon fusion production mode has the highest cross section, but lacks a clear experimental signature if the Higgs boson decays invisibly. Therefore analyses concentrate on the remaining three production modes.

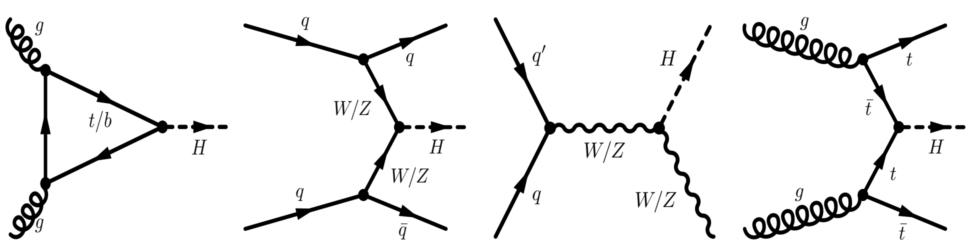

Fig. 1. Higgs boson production channels at the LHC. From left to right: gluon fusion, vector boson fusion, Higgs strahlung, associated production with a top quark pair.

2.1. Vector boson fusion

The vector boson fusion production mode was studied by both the CMS [19] and the ATLAS Collaborations [16].

The signature of this production mode consists of two jets, called tagging jets, usually at high $|\eta|$ and large missing transverse energy due to the invisible decay of the Higgs boson. Thanks to the lack of colour flow between the two incoming partons, a lack of activity is expected between the tagging jets.

For the vector boson fusion production mode, QCD multi-jet production is considered to be the most dangerous background, due to the overwhelming rate, which can mimic the signal characteristics of two forward–backward jets with large separation between them. Large missing transverse energy can either result from neutrinos produced in heavy flavour decays or be due to experimental resolution.

Additional standard model processes can lead to final states similar to that of the signal events, *e.g.* QCD and electroweak production of Wjj and Zjj events, with $W \to e/\mu/\tau\nu$ if the lepton is not identified or below the transverse energy threshold or $Z \to \nu\bar{\nu}$.

Both CMS and ATLAS use the PYTHIA event generator [20] for the simulation of the signal and the QCD background. The Vjj backgrounds are produced with PYTHIA in the ATLAS study and with MadCUP [21] and CompHEP [22] for study carried out by the CMS Collaboration.

TABLE I

Cut	CMS	ATLAS
$E_{\rm T}^{j_{1/2}} >$	40 GeV	40 GeV
$\eta_{j_{1/2}} <$	5	5
$\|\eta_{j_1} - \eta_{j_2}\| <$	4.4	4.4
$\eta_{j_1} \times \eta_{j_2} <$	0	0
$\not{E}_{\rm T} >$	100 GeV	100 GeV
$M_{j_1,j_2} >$	1200 GeV	1200 GeV
no jet between j_1, j_2 with $E_{\rm T} >$	20 GeV	20 GeV
$\phi_{j_1,j_2} <$	1 rad	1 rad
no identified electron, $E_{\rm T} >$	10 GeV	5 GeV
no identified muon, $E_{\rm T} >$	5 GeV	6 GeV
no identified τ, $E_{\rm T} >$	—	20 GeV

Both collaborations used their parametrised detector simulation to estimate the exclusion potential. The jet veto is expected to be sensible to detector effects which are not fully reproduced by the parametrised detector simulation, therefore studies of the jet veto have been carried out for the signal and the QCD background using a GEANT based simulation. The results have been parametrised for the use in the parametrised detector simulation and use is this study.

Events are selected if they fulfill the criteria given in the Table I.

Hence the selection is the same for CMS and ATLAS, beside the lepton veto which use different transverse energy thresholds.

The discovery potential is shown in Fig. 2 for CMS (left) and for ATLAS (right) in terms of the variable ξ^2 which is defined as:

$$\xi^2 = \frac{\sigma(H) \times \mathrm{BR}(H \to \mathrm{inv.})}{\sigma_{\mathrm{SM}}(H)} .$$

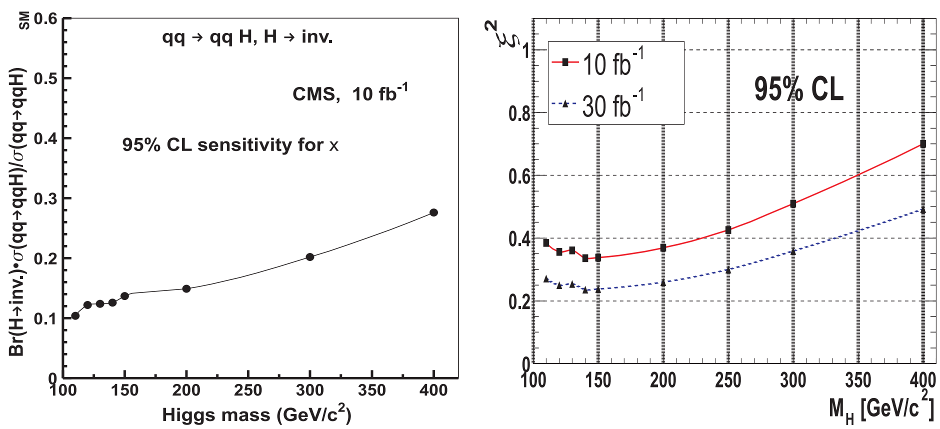

Fig. 2. 95% confidence level exclusion for the variable ξ^2 as obtained from a search for vector boson fusion production of $H \to$ inv. as found by: the CMS collaboration assuming an integrated luminosity of 10 fb^{-1} (left) and the ATLAS collaboration assuming an integrated luminosity of 10 and 30 fb^{-1} (right).

CMS took into account a full simulation of all trigger levels and reports an efficiency of 96-99% for the signal with respect to the offline analysis.

2.2. Associated ZH production

The associated ZH production was studied repeatedly by the ATLAS collaboration [18, 23]. Due to its cross section, which is about a factor of 30 lower than the gluon-fusion cross section, it only plays a minor role in the search for a Higgs boson in the standard decay modes. However, due to the accompanying Z boson, which can be well reconstructed in its leptonic decay modes $Z \to \ell\bar{\ell}$, it is important in the search for invisible decays.

To establish the nature of an invisibly decaying particle, it is of utmost importance to combine the information from several channels. Therefore this channel complements the search in the $t\bar{t}H$ and $q\bar{q}H$ production modes.

The principle backgrounds results from diboson ZZ, WW and WZ, $t\bar{t}$ and Z production.

The event selection is given in the Table II.

TABLE II

Cut	Value
two electrons, $E_{\mathrm{T}} >$	15 GeV
or two muons, $E_{\mathrm{T}} >$	10 GeV
no additional e/μ, $E_{\mathrm{T}} >$	7 GeV
leptons have same flavour and opposite charge	
$M_{\ell\ell}$	$M_Z \pm 10$GeV
$\not{E}_{\mathrm{T}} >$	100 GeV
no jet, $E_{\mathrm{T}} >$	30 GeV
no identified b jets, $E_{\mathrm{T}} >$	15 GeV
$M_{\mathrm{T}} = \sqrt{2\, p_{\mathrm{T}}^{\ell\ell}\, (1 - \cos\Delta\phi)} >$	200 GeV

After the application of these selection criteria the signal to noise ratio is about 1/4 depending on the Higgs boson mass. It has to be stressed that a claim for signal is based entirely on the excess of events over the estimated number of background events. Therefore the systematic error on the estimate of these background will determine the reach of LHC in this channel.

For each background a strategy was devised how to estimate the background from measurements at LHC itself.

2.2.1. ZZ background

The diboson production of ZZ contributes mainly in its decay mode $ZZ \rightarrow \ell\bar{\ell}\nu\bar{\nu}$ which can be estimated measuring the cross section times branching ratio for $ZZ \rightarrow \ell\bar{\ell}\ell\bar{\ell}$. It is expected to have negligible background itself with cuts similar to the ones used in the selection of the invisible Higgs boson decay. The difference in selection is given by requiring two reconstructed Z masses and the requirement on $\not{E}_{\mathrm{T}}$ is replaced by requiring a randomly chosen reconstructed Z to have $E_{\mathrm{T}} > 30$GeV. The tranverse mass cut is not applied for the background normalisation. The expected normalisation factor due to the differences in branching ratios is 5.98. A careful examination of the background normalisation factor yielded a value of 13.65. The biggest contribution to the difference from the branching ratio estimate stems from the differences in the treatment of isolation for leptons and neutrinos.

For an integrated luminosity of 30 fb^{-1} 148 $ZZ \to 4\ell$ events are expected after selection. This leads to a systematic error of 8.5% on the estimation of the $ZZ \to \ell\bar{\ell}\nu\bar{\nu}$ background.

2.2.2. WZ, WW and $t\bar{t}$ background

Also the WZ background can be estimated from data. A careful Monte Carlo study has shown that the WZ background contributes in $WZ \to \nu\bar{\nu}e/\mu/\tau\nu$, with $WZ \to \nu\bar{\nu}\tau\bar{\nu}$ dominating. The cross section can be estimated measuring $WZ \to \ell\bar{\ell}\ell\bar{\nu}$, inverting the lepton veto. The transverse mass cut can be dropped and the missing transverse energy cut relaxed to $E_{\mathrm{T}} > 30$ Gev to decrease the statistical error on the cross section measurement. The background normalisation factor has to be taken from Monte Carlo. Assuming an integrated luminosity of 30 fb^{-1} to total systematic error on the WZ background is expected to be $\pm$ 7.8%.

The non resonant WW and $t\bar{t}$ background can be estimated from the sidebands of the invariant dilepton mass. For an integrated luminosity of 30 fb^{-1} the systematic error on the WW and $t\bar{t}$ background is expected to be $\pm$ 6.4%.

The exclusion limits obtained, including systematic uncertainties are shown in Fig. 3 (left). It shows the 95% confidence limit on exclusion for 30 fb^{-1} and 100 fb^{-1} in the variable ξ^2.

2.3. $t\bar{t}H$ production

The $t\bar{t}H$ production mode has been studied by the ATLAS collaboration [24]. Two channels, the semileptonic channel $t\bar{t} \to WbWb \to \ell\nu b\, q\bar{q}b$ and the fully hadronic channel $\to q\bar{q}b\, q\bar{q}b$ have been studied and combined. Due to the complex final state with two or four light jets, two b jets and one or zero leptons, the combinatorial background renders the analysis challenging.

An in-depth estimate of systematic errors has not been performed so far for this channel.

The 95% exclusion limit on the variable ξ^2 is shown in Fig. 3 (right) as round dots. The limits one can set using this channel are less stringent than what can be set using the vector boson fusion production mode, but are comparable to the ZH analysis.

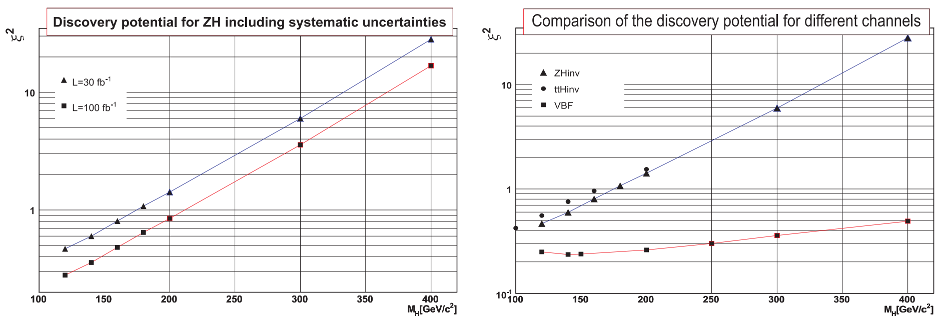

Fig. 3. Left: 95% confidence level exclusion for the variable ξ^2 as obtained from a search for ZH production with $Z \to \ell\bar{\ell}$ and $H \to$ inv. Right: 95% confidence level exclusion for the variable ξ^2 as obtained in the search for invisible Higgs boson decays in the ZH, $t\bar{t}H$ and $q\bar{q}H$ associated production assuming an integrated luminosity of 30 fb^{-1}.

3. Conclusion

The potential of the CMS and the ATLAS experiment for the search of an invisibly decaying Higgs boson produced in vector boson fusion, associated ZH production mode and associated production with a $t\bar{t}$ pair has been studied. Evidence for a signal is extracted from an excess of events with large $\not{E}_{\mathrm{T}}$ above the background.

The most promising production mode is the vector boson fusion mode which allows to exclude an invisible Higgs decay with ξ^2 down to at least 0.4 for M_H=115GeV.

The associated production ZH provides less stringent limits but a clear signal thanks to two leptons with an invariant mass around the Z mass. The systematic errors of the ZH analysis have been studied thoroughly and results have been given including systematic errors.

The associated production with a top pair provides exlusion limits comparable to the ZH analysis. But, due to its complex final state, it suffers from combinatorial background.

Assuming, an integrated luminosity of 30 fb^{-1}, the standard model cross section and 100% BR($H \to$ inv.) all three modes make an exclusion with a confidence level of 95% possible up to $M_H < 175$ GeV. When all production modes contribute, additional information on the nature of the invisibly decaying particle is accessible. Above $M_H = 175$ GeV only the vector boson fusion mode provides an exclusion limit at least up to $M_H = 400$ GeV.

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