

## Search for ‘invisible’ Higgs signals at LHC via Associated Production with Gauge Bosons

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### Abstract

A light Higgs boson with substantial branching ratio into invisible channels can occur in a variety of models with: light neutralinos, spontaneously broken lepton number, radiatively generated neutrino masses, additional singlet scalar(s) and/or right handed neutrinos in the extra dimensions of TeV scale gravity. We study the observability of the  $WH$  and  $ZH$  modes at LHC with  $H$  decaying invisibly, by carrying out a detailed simulation with two event generators (HERWIG and PYTHIA) and realistic detector simulations (GETJET and CMSJET). We find that the signal with ‘single lepton plus missing  $E_T$ ’ resulting from  $WH$  production suffers from a very large background due to the (off-shell)  $W^*$  production via the Drell-Yan process. In contrast, the  $ZH$  mode provides a clean signal in the ‘dilepton plus missing  $E_T$ ’ channel. By exploiting this second signature, we show that invisible branching ratios of Higgs bosons,  $\text{BR}_{\text{inv}}$ , larger than  $\sim 0.42(0.70)$  can be probed at  $5\sigma$  level for  $M_H = 120(160)$  GeV respectively, assuming an accumulated luminosity of  $\mathcal{L} = 100 \text{ fb}^{-1}$ .

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# Introduction

The search for Higgs bosons and the study of their properties is one of the main goals of physics studies at Tevatron upgrade (Run 2) and the upcoming Large Hadron Collider (LHC). The precision measurements with Electro-Weak (EW) data indicate the existence of a light Higgs boson ( $M_H < 204$  GeV at 95% C.L.) whereas direct searches rule out the case  $M_H < 114.4$  GeV [1], also giving a hint of a possible signal at the very upper end of the experimentally excluded interval [2]. Naturalness arguments along with the indication of a light Higgs state suggest that Supersymmetry (SUSY) is a likely candidate for new physics Beyond the Standard Model (BSM). In most SUSY scenarios, the Lightest SUSY Particle (LSP) is the neutral, weakly interacting and stable neutralino, denoted as  $\tilde{\chi}_1^0$ . The current combined limits on the neutralino and Higgs boson masses in a general SUSY model [3] are such that, for non-universal gaugino masses at high scale, it is still kinematically possible for a relatively light Higgs state to decay into two LSPs with a large Branching Ratio (BR), as high as 0.70, without being in conflict with the relic density and the  $(g-2)_\mu$  constraints [4]. In such a case, the Higgs boson becomes *invisible*. Other models of invisible Higgs decay are connected to possible scenarios for neutrino ( $\nu$ ) mass generation. One of the mechanisms for the latter arising in theories with extra dimensions and TeV scale gravity [5], for example, can cause the  $H$  to have several invisible decay modes. Here,  $H$  states can decay into  $\nu_L \bar{\nu}_R^j$  where  $\bar{\nu}_R^j$  denotes the  $j$ th Kaluza-Klein (KK) excitation of the light neutrino which is a singlet. The tall tower of KK resonances can cause the width  $\sum_j \Gamma(H \rightarrow \nu_L \bar{\nu}_R^j)$  to be sizable. Besides, in models where a Majorana mass of  $\nu$ 's results from a spontaneously broken global symmetry [6],  $H$  states can have appreciable branching fractions into two Nambu-Goldstone bosons. This type of decay mode may also arise in some models with extended higgs sector with an additional higgs singlet in the framework of Standard Model(SM) [7]. Finally, if the neutrino mass is generated radiatively by some mechanism below the TeV scale, again a Higgs boson may decay invisibly into a  $\nu_{\text{light}}\nu_{\text{heavy}}$  pair [8]. Similarly, Higgs boson may also decay invisibly into a pair of neutrinos in the framework of models with 4th generation lepton [9].

Needless to say, the only possible mode in which a Higgs boson can decay invisibly in the SM is via  $H \rightarrow ZZ^* \rightarrow 4\nu$  which has a BR of about 1% at  $M_H > 180$  GeV and even lower at lower values of  $M_H$ . Thus it can not disturb the visible Higgs decay modes appreciably for any value of  $M_H$ . On the other hand in the above mentioned BSM scenarios the invisible decay mode can represent a large part of the decay BR for an Intermediate Mass Higgs (IMH) boson, with  $114 \text{ GeV} \lesssim M_H \lesssim 160 \text{ GeV}$ . In this mass range, in fact, detection of a Higgs signal relies mainly on the  $b\bar{b}$ ,  $\gamma\gamma$ ,  $WW \rightarrow 2\ell 2\nu_\ell$  and  $ZZ^* \rightarrow 4\ell$  final states, but only as long as the corresponding rates are not very different from the SM values. A reduction of the latter, due to the presence of sizable invisible decays of an IMH boson, could prevent its detection at Tevatron and LHC.

In short, in a large number of BSM physics scenarios, all addressing the fundamental issues of  $\nu$  mass generation and/or radiative stability of the EW symmetry breaking scale, there exists the possibility of an IMH boson decaying into invisible channels, thus hindering the chances of its discovery via the customary decay modes studied so far that we have listed above. Hence, it is necessary to develop new search strategies for these otherwise lost signal events, in order to

confirm the ability of present and future colliders to resolve the structure of the Higgs sector.

## Leptonic Signatures of Invisible Higgs Decays

Since Tevatron is in operation at present and LHC is the next world machine, it is natural to review the current status of invisible Higgs decays starting from the case of hadronic colliders<sup>3</sup>. A study [11] of the possibilities at Tevatron Run 2 has shown that, even with an integrated luminosity of  $30 \text{ fb}^{-1}$ , evidence of an invisibly decaying Higgs boson is possible only at  $3\sigma$  level and no further than  $M_H = 135 \text{ GeV}$ . A  $5\sigma$  discovery for an  $M_H$  value beyond the LEP limit will require a luminosity as high as  $50\text{--}70 \text{ fb}^{-1}$ , which is unattainable at Tevatron. At LHC there is more scope because of the higher luminosity as well as the much larger Higgs boson production cross sections. Here, the dominant (at least in a SM scenario [12]) Higgs production process is gluon-gluon fusion via a top-quark loop ( $gg \rightarrow H$ ). If the Higgs boson decays invisibly, the only way the  $gg$  channel can be used is by looking at the production of  $H$  in association with a jet, i.e.,  $gg \rightarrow H + \text{jet}$ . The signature here would be events with modest amount of missing (transverse) energy and a large  $E_T$  jet, the ‘monojet’ events, in presence of underlying hadronic activity. This signal is however overwhelmed by the pure QCD background, so that the potential of this channel for Higgs detection is very limited already at the parton level [13].

It is then natural to turn to the subleading Higgs production channels. These are in turn dominated by vector-vector fusion ( $qq \rightarrow qqV^*V^* \rightarrow qqH$ ), followed by Higgs-strahlung ( $q\bar{q}^{(\prime)} \rightarrow VH$ )<sup>4</sup> and associate production with top-quarks ( $gg \rightarrow t\bar{t}H$ ). The vector-boson fusion process suffers from the same drawbacks of the leading channel, as the final signature would again be purely hadronic. Nonetheless, recent studies [14] have shown that simultaneous forward and backward jet tagging along with rejection of central jets in the  $VV$  fusion mode might provide possibilities of detecting an invisible Higgs, for a  $\text{BR}_{\text{inv}}$  value as low as 5%, with  $100 \text{ fb}^{-1}$  luminosity. In contrast, the last two production modes naturally offer the possibility of high  $E_T$  electron/muon tagging, by exploiting the leptonic decays of the vector bosons and top-quarks respectively, thus providing an effective handle against the pure QCD backgrounds. Previous studies of both the Higgs-strahlung production modes,  $ZH$  and  $WH$ , followed by the leptonic decays of  $W/Z$  [13, 15], showed that this channel can be efficient for  $\text{BR}_{\text{inv}} \gtrsim 25\%$  at  $100 \text{ fb}^{-1}$ , whereas the  $t\bar{t}H$  mode would require  $\text{BR}_{\text{inv}} \gtrsim 60\%$  at the same luminosity [16]. Notice that all such studies are however in need of more rigorous analyses, as all of them have been carried out only at the parton level. Full simulations, in presence of parton shower, hadronisation and detector effects, with varying degrees of sophistication, are currently in progress for  $VV$  fusion [17],  $VH$  [18] and  $t\bar{t}H$  production [19]. For example, the ATLAS studies of the  $VV$  fusion case find a sensitivity to  $\text{BR}_{\text{inv}} \gtrsim 25\%$ , for  $M_H = 120 \text{ GeV}$  with an integrated luminosity of  $30 \text{ fb}^{-1}$ . CMS expects to probe upto  $\text{BR}_{\text{inv}} \sim 12.5\%$  in the same mass region with  $10 \text{ fb}^{-1}$ .

<sup>3</sup>In the more distant future, leptonic colliders may be of some help in extracting signatures of invisibly decaying Higgs bosons. For example, at a TeV scale  $e^+e^-$  linear collider (LC), invisible Higgs decays should be readily accessible via  $e^+e^- \rightarrow ZH \rightarrow (Z \rightarrow b\bar{b})(H \rightarrow \text{invisible})$  [10].

<sup>4</sup>Here, the labels  $\bar{q}^{(\prime)}$  refer to (anti)quarks of any possible flavour whereas  $V = W, Z$ .

Note both studies have assumed central jet veto survival probabilities obtained from parton level simulation at the level of NLO. However these studies have not taken into account the potentially serious background from diffractive scattering.

The question naturally arises now whether one can continue to use the SM values for the  $HVV$  couplings controlling the  $WH$  and  $ZH$  production cross sections of our interest, while probing BSM scenarios with a large invisible decay rate of an IMH boson. In the BSM scenarios associated with neutrino mass generation, the SM values of the  $HVV$  couplings are generally compatible with large Higgs BRs into invisible decay channels [5, 6, 8]. In contrast, in the Minimal Supersymmetric Standard Model (MSSM), with or without high scale universality, the SM values of the  $HVV$  couplings are suppressed by the factor  $\sin(\alpha - \beta)$ , where  $\alpha$  and  $\beta$  are the mixing angles between the two doublets in the neutral and charged Higgs sectors. It is well known that  $\sin(\alpha - \beta) \simeq 1$  if the pseudoscalar Higgs mass is in the range  $M_A \gtrsim 120$  GeV [20]. The LEP lower limit on this mass is  $M_A > 90$  GeV if  $\tan\beta \gg 1$  and much larger when  $\tan\beta \gtrsim 1$ . Thus, except for a tiny slice of the allowed  $(\tan\beta, M_A)$  parameter plane, i.e.,  $M_A = 90\text{--}115$  GeV, the SM values for the  $HVV$  couplings can be used for the MSSM as well.

We may add a few general comments here regarding the Higgs production cross-sections in the MSSM. While the strength of the  $VVH$  couplings may be taken as the SM value for most of the MSSM parameter space, the presence of relatively light squarks and gluinos (i.e., below 1 TeV) can affect the  $gg$  fusion channel and also induce more production modes for Higgs bosons than those considered so far. For example, while light squarks may induce cancellation effects against the quark loops in gluon-gluon fusion [21], an abundant generation of Higgs states would result from squark and gluino decays [22] and/or associated production with squark pairs [23]–[26]. It has also been pointed out that  $H\tilde{\chi}_i^0$  ( $i > 1$ ) production is sizable and it is maximal [27] where invisible Higgs decays are large. Moreover, for  $\tan\beta \gtrsim 7$ , Higgs production in association with bottom-quark pairs becomes dominant over the gluon-gluon fusion mode and the top-loop contribution to the latter is overwhelmed by the bottom one.

For the Higgs-strahlung process of our interest it will then be adequate to simply use the SM production rates for  $q\bar{q} \rightarrow VH$ , allow for the Higgs scalar to go undetected, whatever its final decay products, and sample the detectable  $\text{BR}_{\text{inv}}$  values that would allow for the signal extraction above purely SM backgrounds. The model independent approach chosen here is sufficiently simple to cover most of the MSSM as well as all the other BSM scenarios that we have described above. In short we will only consider the associated production processes  $q\bar{q} \rightarrow WH$ , followed by the leptonic decay  $W \rightarrow \ell\nu$  (hereafter,  $\ell = e, \mu$ ), giving rise to a ‘single lepton +  $\cancel{E}_T$ ’ signature, plus  $q\bar{q} \rightarrow ZH$ , followed by the leptonic decay  $Z \rightarrow \ell\bar{\ell}$ , giving rise to a ‘dilepton +  $\cancel{E}_T$ ’ signal. We shall restrict our analysis to the case of LHC.

## Kinematic Properties of Signal and Background

We begin by considering the signal for  $WH$  production coming from the process

$$q\bar{q}' \rightarrow W^* \rightarrow W + H \quad (1)$$

$\downarrow$   
 $\xrightarrow{3}$

$\ell\nu_\ell$

$\downarrow$   
 $\rightarrow$  invisible

This will result in events with a single high  $E_T$  lepton and  $\not{p}_T$ <sup>5</sup>. Since at the parton level  $E_T^\ell = \not{p}_T$ , demanding a large  $E_T$  lepton automatically ensures a large  $\not{p}_T$  value. This also means that one has essentially only one four-momentum at disposal for kinematic cuts. Leading backgrounds to the signal are the following with  $\ell = e, \mu$ .

- a) Charged Drell-Yan (DY) production via  $q\bar{q}' \rightarrow W^{(*)} \rightarrow \ell\nu_\ell$ .
- b) The irreducible background  $q\bar{q}' \rightarrow WZ \rightarrow (\ell\nu_\ell)(\nu_{\ell'}\bar{\nu}_{\ell'})$ , with  $\ell' = e, \mu, \tau$ .
- c)  $q\bar{q} \rightarrow WW \rightarrow (\ell\nu_\ell)(\ell'\nu_{\ell'})$ , where one of the leptons lies outside the fiducial volume.
- d)  $q\bar{q}' \rightarrow W(\rightarrow \ell\nu_\ell) + \text{jet}$ , when the jet is not detectable due its low  $E_T$  or passes through detector cracks and then the lost jet would add onto the missing  $E_T$  of the decay  $\nu$  from the  $W$ .
- e)  $q\bar{q} \rightarrow Z + \text{jets}$  production with  $Z \rightarrow \nu\bar{\nu}$  can also give a background if one jet is misidentified as lepton.
- f)  $q\bar{q}, gg \rightarrow t\bar{t} \rightarrow WWb\bar{b} \rightarrow \ell\nu_\ell\ell'\nu_{\ell'}b\bar{b}(\ell\nu_\ell q\bar{q}'b\bar{b})$ , which may mimic the signal if the  $b$ -jets are lost along with one of the decay leptons(the  $W$  decay jets).

The level of jet activity in background f), coming from hadronic decays of  $W$  bosons and/or high  $E_T$   $b$ -quarks, helps to distinguish this process from the signal in eq. (1). In fact, the hadronic activity in the signal as well as the purely leptonic background processes mentioned above comes entirely from initial state radiation which is mostly in the forward-backward region of the detector. Hence, a veto on central jet activity can help handle  $t\bar{t}$  production effectively. With an expected rejection factor of  $10^{-5}$  against jet misidentification, the background in e) will not be a serious one in the end.

A useful kinematic variable is the transverse mass, defined as:

$$M_T^{n\ell} = \sqrt{2E_T^{n\ell}\not{p}_T(1 - \cos\phi(E_T^{n\ell}, \not{p}_T))}, \quad (2)$$

where  $n = 1$  for the single lepton channel and  $n = 2$  for the dilepton one, respectively. In the latter case,  $E_T^{2\ell}$  refers to the transverse component of the three-momentum of the dilepton system.

Demanding that  $M_T^{1\ell} > 100$  GeV can remove the background coming from a (real)  $W$  in a) without any effect on the signal and the irreducible background in b). Unfortunately, it can not suppress the contribution coming from a (virtual)  $W^*$  in a), which was not considered in [13]. In fact, while the sizes of the expected cross sections for  $WH$  and  $WZ$  production are similar for the  $M_H$  values under consideration, the  $W^*$  contribution is much larger in comparison. Besides, both the signal and the DY background are generated via the same  $s$ -channel annihilation, preventing one from exploiting angular distributions of the visible lepton, in order to enhance

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<sup>5</sup>A subleading contribution to the signal will also come from  $ZH$  production, with  $Z \rightarrow \ell\bar{\ell}$ , when one of the leptons is lost beyond the lepton detection region (typically,  $|\eta| \leq 2.5$ ).

the signal-to-background ratio. One noticeable difference would be a somewhat broader  $E_T^\ell$  (or equivalently the  $\cancel{p}_T$  at the parton level) distribution for the  $W^*$  background than for the signal or the  $WZ$  background. So, one could imagine choosing a window in the  $E_T^\ell$  (or  $M_T^{1\ell}$ ) spectrum to handle the off-shell contribution in a). As we will see later, this is of too little help to suppress  $W^* \rightarrow \ell\nu_\ell$  events from a), so that the single lepton channel will in the end prove to be unusable. Other possible backgrounds that we consider are those coming from  $ZZ$  and single top production. These however have a very small event rate to start with and do not need any special kinematic treatment.

The signal for  $ZH$  production comes from the process:

$$q\bar{q} \rightarrow Z^* \rightarrow Z \quad + \quad H \quad (3)$$

$$\begin{array}{ccc} \downarrow & & \downarrow \\ \ell\bar{\ell} & & \text{invisible} \end{array}$$

This gives rise to a dilepton +  $\cancel{p}_T$  signature in the final state. The  $ZH$  production rate, though a factor of  $\sim 5$ – $6$  smaller than that of  $WH$ , is more suitable for our search. The main backgrounds here are the following.

- x) DY production of  $Z^* \rightarrow \ell\bar{\ell}$  in presence of jets when the latter get lost.
- y) Irreducible  $q\bar{q} \rightarrow ZZ$  production followed by an invisible decay of one  $Z$  (i.e.,  $Z \rightarrow \nu_\ell\bar{\nu}_\ell$ ), with the other  $Z$  decaying into a  $\ell\bar{\ell}$  pair.
- z)  $q\bar{q}' \rightarrow WZ$  followed by the leptonic decays of both the  $W$  and  $Z$ , giving rise to  $\ell\nu_\ell\ell'\bar{\ell}'$ , where one lepton is lost.
- w)  $q\bar{q}' \rightarrow WW$  production followed by leptonic decays of both the  $W$ 's.
- v)  $q\bar{q}, gg \rightarrow t\bar{t} \rightarrow WWb\bar{b} \rightarrow \ell\nu_\ell\ell'\nu_\ell\bar{\nu}_\ell\bar{b}\bar{b}$ , which can cause a background if the  $b$ -jets escape detection.

For the dilepton signal one can demand a large  $E_T$  lepton *and* a high threshold for  $\cancel{p}_T$ . The latter will largely remove both the on- and off-shell components of the background in x) and to a smaller extent the background in z). The additional requirement that the  $\ell\bar{\ell}$  mass reconstructs to  $M_Z$  will strongly reduce backgrounds w) and v). As usual, a veto on the accompanying hadronic activity in the event further helps to remove the  $t\bar{t}$  background. The only limiting factor will be seen to be the irreducible background coming from  $ZZ$  production. The  $\cancel{p}_T$  and  $E_T^\ell$  distributions are softer for the irreducible background than for the signal as the  $ZH$  production is an  $s$ -channel process and the  $ZZ$  production occurs via light quark exchange in the  $t, u$ -channel. Bearing in mind a possible misidentification of a jet as a lepton, we also consider the contributions from  $WH$ ,  $W$  production via DY and single top production. These will be however seen to be negligible. We also checked the background where a final state radiation off a  $Z$  boson of a neutrino–anti-neutrino pair produced via DY process. The production cross

section corresponding to this process,  $pp \rightarrow \nu\bar{\nu}Z$  turns out to be only 27 fb at LHC, going down to 0.26 fb after the cuts discussed below. Therefore, it does not appear to be a serious background to our signal.

## Simulation and Results

In our simulation, we have used two different Monte Carlo (MC) event generators, HERWIG [28] and PYTHIA [29], for comparison. In the two cases, the default settings of v6.4 and 6.2 (respectively) were adopted. While using HERWIG, we have adopted GETJET [30] for calorimeter emulation and jet reconstruction, whereas in conjunction with PYTHIA we have used CMSJET [31] to simulate the detector response specific to the CMS experiment. All the possible decay modes for the particles generated in the hard scattering process have been considered and finite width effects have been included for all the unstable particles with the exception of the top (anti)quark. This procedure thus includes  $\tau$ -decays for  $W$ 's and  $Z$ 's. However, as is clear from the previous sections, we only consider as signals those involving an  $e$  and/or  $\mu$  trigger. Thus, hadronic  $\tau$ -decays are typically discarded while leptonic ones do enter our samples of single and double lepton events, with little effect in both cases, though. We have used  $\text{BR}(W \rightarrow \ell\nu_\ell) = 22\%$  and  $\text{BR}(Z \rightarrow \ell\bar{\ell}) = 6.6\%$ . In total, we have generated  $10^6$  MC events for each channel in Tabs. 1–2 and processed them through our selection cuts listed below<sup>6</sup>.

For the  $\ell + \cancel{p}_T$  channel we have enforced the following ‘preliminary’ acceptance constraints.

- 1a. Select only one lepton with  $E_T^\ell > 10$  GeV and  $|\eta^\ell| < 3$ .
- 2a. Impose a hadronic veto, by rejecting any events containing jets with  $E_T^j > 30$  GeV and  $|\eta^j| < 4$ .
- 3a. Enforce a missing transverse momentum threshold:  $\cancel{p}_T > 30$  GeV.

Tab. 1 summarises our results for the single lepton channel, assuming  $\text{BR}_{\text{inv}} = 1$  and  $M_H = 120$  GeV, coming from both  $WH$  and  $ZH$  production. One sees from the table that, while all other backgrounds can in the end be reduced to manageable level by our sequence of cuts (including those in  $E_T^\ell$  and  $M_T^{1\ell}$ ), the background due to off-shell  $W^*$  production and its leptonic decay overwhelms the signal by a factor of more than 200 ! Thus the single lepton channel is clearly of little use in the invisible Higgs signal extraction. This is confirmed by the  $E_T^\ell$  spectrum for the signal and the leading background shown in Fig. 1 for the luminosity  $100 \text{ fb}^{-1}$ . We do not give the the  $M_T^{1\ell}$  spectrum as it is strongly correlated to the one in  $E_T^\ell$ .

For the  $\ell\bar{\ell} + \cancel{p}_T$  channel the situation is much better, in spite of the lower signal rates which one starts with. In this case, the preliminary acceptance requirements are as follows.

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<sup>6</sup>We have always found consistent results between HERWIG and PYTHIA, with the only exception of the  $W^+W^-$  process, where differences as large as 50% emerged in the case of the single lepton analysis but not for the dilepton case. We have not been able to fully understand the discrepancy. However, as this background is subleading and the  $\ell + \cancel{p}_T$  signal will be shown to be unviable in any case, we have not pursued this matter further. In the remainder of the paper, we will only present results from HERWIG.

Process	$\sigma$ (no BRs) [pb]	Events after cuts 1a.–3a.	Add $E_T^\ell > 100$ GeV	Add $M_T^{1\ell} > 200$ GeV	$\epsilon$	Events after $\mathcal{L}=100$ fb $^{-1}$
$WH$	1.2	116569	14101	13030	0.013	1564
$ZH$	.69	9148	794	702	0.00070	48
$WW$	64.	38635	334	235	0.00024	1504
$ZZ$	10.	4677	288	253	0.00025	253
$WZ$	26.	32771	1180	1049	0.0010	2727
$W$	$1.4 \times 10^5$	81118	28	24	$2.4 \times 10^{-5}$	336000
$Z$	$7.5 \times 10^4$	280	1	0	0	0
$t\bar{t}$	441.	661	55	41	$4.1 \times 10^{-5}$	1808
$tq$ + c.c.	146.	9854	10	0	0	0
$W$ + jet	$6.5 \times 10^4$	70127	1	0	0	0
$Z$ + jet	$2.2 \times 10^4$	619	0	0	0	0

Table 1: Results of the HERWIG simulation for the single lepton channel. The first column gives the normalisation of the hard scattering processes. The second shows the number of events, out of the  $10^6$  generated in each case, that survive our preliminary acceptance requirements in 1a.–3a. The following two columns show the numbers of events surviving the ‘sequential’ application of the additional cuts on  $E_T^\ell$  and  $M_T^{1\ell}$ . The next column gives the overall efficiency of our selection while the last one presents the final number of events for a luminosity of  $100 \text{ fb}^{-1}$ . Note that  $Z$ + jet and  $W$ + jet are already included and better emulated in  $Z$  and  $W$  production, which in HERWIG includes the  $Z$ + jet and  $W$ + jet matrix element corrections by default. The last two lines are presented for illustrative purposes only and will not be used in the following for the estimation of the signal significance.

- 1b. Select events with exactly two leptons, same flavour and opposite sign, fulfilling the kinematic requirements:  $|M_{\ell\bar{\ell}} - M_Z| < 10$  GeV,  $E_T^\ell > 10$  GeV and  $|\eta^\ell| < 3$ .
- 2b. Impose a hadronic veto, by rejecting events containing jets with  $E_T^j > 30$  GeV and  $|\eta^j| < 4$ .
- 3b. Enforce a missing transverse momentum threshold:  $\cancel{p}_T > 30$  GeV.

The additional selection cuts here are in  $\cancel{p}_T$  (rather than  $E_T^\ell$ ) and  $M_T^{2\ell}$ . The former is increased to 100 GeV while the latter is maintained at 200 GeV like the cut on  $M_T^{1\ell}$  for the single lepton channel. Fig. 2 shows the  $\cancel{p}_T$  distribution for the signal and the leading background for the luminosity  $100 \text{ fb}^{-1}$ . Again, we avoid plotting the  $M_T^{2\ell}$  spectrum as it is very much correlated to the one in  $\cancel{p}_T$  and does not bring any further insights into the kinematics. The final results for the dilepton channel, for  $\text{BR}_{\text{inv}} = 1$  and  $M_H = 120$  GeV, are summarised in Tab. 2. We find that even in this case the signal is surpassed by the background, specifically by the  $ZZ$  irreducible one and, to a somewhat lesser extent, by  $WZ$  production. However both the  $ZZ$  and  $WZ$  cross-sections are expected to be measured at LHC to a very good precision via the  $4\ell$  and  $3\ell + \cancel{p}_T$  channels respectively with  $Z$  and  $W$  mass reconstructions. Since these channels



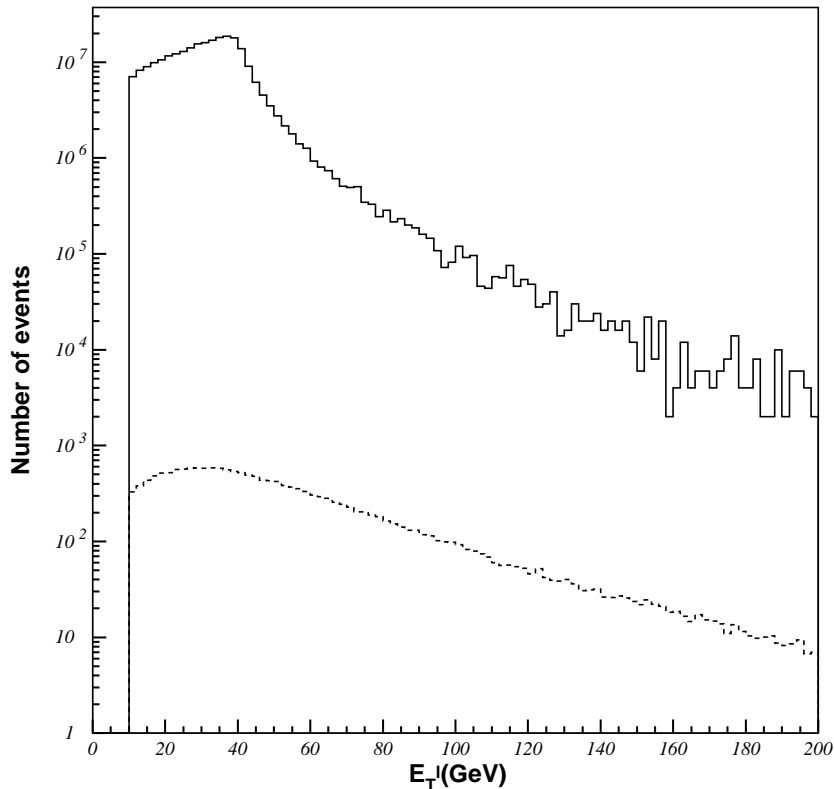


Figure 1: The  $E_T^\ell$  distribution for the signal (dashed histogram) and the dominant charged DY background (solid histogram) in the case of the one-lepton signature.

should be background free the accuracy of the measured cross-section will be determined by statistics, i.e about 1% for the luminosity of  $100 \text{ fb}^{-1}$ . Similarly the  $t\bar{t}$  cross-section is also expected to be measured to a very good precision. Hence the uncertainty in the number of background events should be dominated by the statistical fluctuation. Moreover, here one can confidently extract a signal excess, by simply counting the number of dilepton events surviving our cuts. From Tab. 2, the total background cross section turns out to be 27 fb whereas the signal rate is 6.22 fb for  $M_H = 120 \text{ GeV}$ , thus yielding  $S/\sqrt{B} \simeq 7(12)$  for  $\mathcal{L} = 30(100) \text{ fb}^{-1}$  with  $\text{BR}_{\text{inv}} = 1$ .

These numbers are promising enough to further investigate the chances of extracting a signal for other combinations of  $\text{BR}_{\text{inv}}$  and  $M_H$ . In Tab. 3, we present the lower limits on  $\text{BR}_{\text{inv}}$  for which a  $\gtrsim 5\sigma$  excess is possible in the dilepton channel for an IMH boson, for two different values of integrated luminosities, 30 and  $100 \text{ fb}^{-1}$ . We see that with a luminosity of  $100 \text{ fb}^{-1}$  a discovery is possible down to  $\text{BR}_{\text{inv}} = 0.42$  for  $M_H = 120 \text{ GeV}$  and to  $\text{BR}_{\text{inv}} = 0.7$  for  $M_H = 160 \text{ GeV}$ . It should be mentioned here that, even for  $\mathcal{L} = 30 \text{ fb}^{-1}$ , a  $\sim 4\sigma$  level signal is possible

Process	$\sigma$ (no BRs) [pb]	Events after cuts 1b.–3b.	Add $\not{p}_T > 100$ GeV	Add $M_T^{2\ell} > 200$ GeV	$\epsilon$	Events after $\mathcal{L}=100$ fb $^{-1}$
$WH$	1.2	3	0	0	0	0
$ZH$	.69	28811	9593	9016	0.0090	622
$WW$	64.	1160	16	13	$1.3 \times 10^{-5}$	83
$ZZ$	10.	10618	1745	1606	0.0016	1606
$WZ$	26.	3374	308	266	0.00026	692
$W$	$1.4 \times 10^5$	2	0	0	0	0
$Z$	$7.5 \times 10^4$	6	0	0	0	0
$t\bar{t}$	441.	69	13	9	$9.0 \times 10^{-6}$	397
$tq$ + c.c.	146.	62	0	0	0	0
$W$ + jet	$6.5 \times 10^4$	2	0	0	0	0
$Z$ + jet	$2.2 \times 10^4$	16	0	0	0	0

Table 2: Like in Tab. 1 but for the double lepton channel, upon replacing the cuts in 1a.–3a. with those in 1b.–3b. and that on  $E_T^\ell$  with  $\not{p}_T$ .

$M_H$ (GeV)	$n_S$ (# events)	BR $_{\text{inv}}$ [minimum value]
120	187(622)	0.77(0.42)
130	158(528)	0.88(0.49)
140	139(462)	--(0.55)
150	122(407)	--(0.64)
160	110(366)	--(0.70)

Table 3: The  $5\sigma$  discovery limit on the BR of a Higgs boson decaying invisibly in  $ZH$  production, in the dilepton +  $\not{p}_T$  channel, for two LHC luminosities, 30(100) fb $^{-1}$ , along with the total number of signal events ( $n_S$ ), with the cuts in 1b–3b and the additional ones mentioned in the caption of Tab. 2.

up to  $M_H = 160$  GeV for BR $_{\text{inv}} = 1$ . Notice all the BR $_{\text{inv}}$  values discussed here are consistent with current LEP limits on ‘ $H \rightarrow$  invisible’ processes [32].

Finally note that the differential shape of the signals and backgrounds have become very similar after our selection cuts and hence one should expect only a limited margin of improvement on the rates presented here, from the application of any further kinematic constraints<sup>7</sup>.

<sup>7</sup>Our results for both the channels are consistent with those obtained by the ATLAS study in [18].

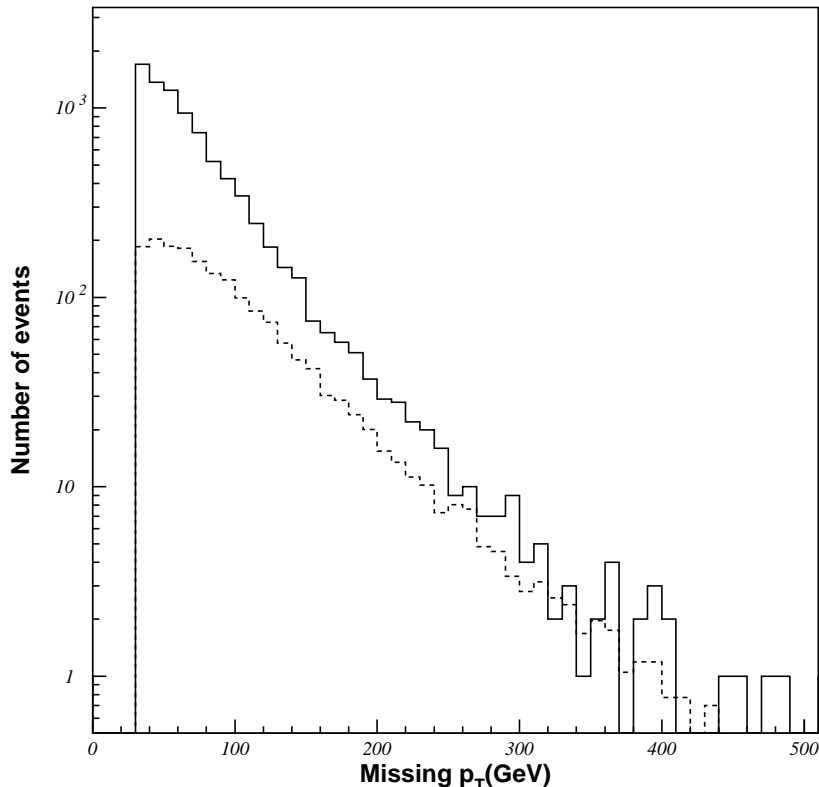


Figure 2: The  $p_T$  distribution for the signal (dashed histogram) and the dominant  $ZZ$  background (solid histogram) in the case of the two-lepton signature.

## Conclusions

In summary, we have studied possibility of Higgs detection in invisible channels at LHC, via the production mode  $q\bar{q} \rightarrow ZH$ , followed by leptonic decays of the gauge boson using electrons and/or muons in the final state. The signature arises in the form of an excess in the total number of ‘dilepton plus missing transverse energy’ events. The channel is viable over the entire intermediate mass interval  $114 \text{ GeV} \lesssim M_H \lesssim 160 \text{ GeV}$  for an accumulated luminosity of  $100 \text{ fb}^{-1}$  and the viability is limited to  $M_H \lesssim 130 \text{ GeV}$  if the available luminosity is also limited to  $30 \text{ fb}^{-1}$ .

Should the reach in the traditional  $b\bar{b}$ ,  $\gamma\gamma$  and  $VV^*$  detection modes be diminished for a relatively light Higgs boson due to its novel invisible decays, one sees a reasonable chance to detect the latter, which may thus help to compensate for the suppression of the former. We have demonstrated this by performing a rather detailed and largely model independent MC study at hadron level and in presence of detector effects. Our results call for a combined analysis of the

$H \rightarrow b\bar{b}, \gamma\gamma, VV^*$  and ‘invisible’ modes to establish LHC potential to discover an intermediate mass Higgs boson even in the presence of substantial partial decay width into the invisible mode.

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