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Invisible Higgs decay at the Large Hadron-Electron Collider

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The possibility that the 125 GeV Higgs boson may decay into invisible non-standard-model (non-SM) particles is theoretically and phenomenologically intriguing. In this paper, we investigate the sensitivity of the Large Hadron Electron Collider (LHeC) to an invisibly decaying Higgs, in its proposed high-luminosity running mode. We focus on the neutral current Higgs production channel which offers more kinematical handles than its charged current counterpart. The signal contains one electron, one jet, and large missing energy. With a cut-based parton-level analysis, we estimate that if the hZZ coupling is at its standard model (SM) value, then assuming an integrated luminosity of 1 ab^{-1}, the LHeC with the proposed 60 GeV electron beam (with -0.9 polarization) and 7 TeV proton beam is capable of probing $\mathrm{Br}(h \to \not{E}_T) = 6\%$ at 2σ level. Good lepton veto performance (especially hadronic τ veto) in the forward region is crucial to the suppression of the dominant Wje background. We also explicitly point out the important role that may be played by the LHeC in probing a wide class of exotic Higgs decay processes and emphasize the general function of lepton-hadron colliders in the precision study of new resonances after their discovery in hadron-hadron collisions.

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I. INTRODUCTION

After the discovery of the 125 GeV Higgs boson [1,2], naturally the next step is measuring its properties as accurately as possible, which tests the standard model (SM) in its most elusive sector and may hopefully reveal its connection to physics beyond the standard model (BSM). So far, determination of the Higgs boson spin and parity and measurements of the Higgs signal strength in various production and decay channels have been carried out, all of which turned out to be consistent with SM predictions. It is worth noting that besides the decay modes which have promising observability in SM, attention has also been paid to interesting, rare (e.g., flavor-changing [3,4]), or exotic [5] decay modes. These modes may easily get enhanced in various BSM theories, and with the potentially large number of Higgs bosons expected to be produced at various colliders, may even surprise us with a spectacular discovery [5].

One of the most interesting exotic Higgs decay channels is the Higgs decaying into invisible non-SM particles [6,7]. Long before the Higgs boson discovery, the search of this mode was drawing a lot of attention [8–13]. With the LHC run I data, the most stringent limit from direct search now comes from the ATLAS search for an invisibly decaying Higgs (h) in the vector boson fusion (VBF) channel [14], which constrains $\mathrm{Br}(h \to \not{E}_T) < 28\%$ at 95% C.L. The importance of this exotic Higgs decay channel, however, cannot be overemphasized because it may shed light on the link between the Higgs boson and dark matter (DM). Indeed, the situation of the Higgs interacting with DM occurs in many extensions of the SM, for example, in models which aim to solve the hierarchy problem such as supersymmetry (SUSY) [15–19], composite Higgs [20], extra dimensions [21], Little Higgs [22], and Twin Higgs [23,24], in simple dark matter models [25–27], and in Higgs portal models [28–34]. If the dark matter (or dark sector) particle is sufficiently light, then the invisible Higgs decay can naturally reach a detectable branching fraction. Invisible Higgs decay is also an important signature of some Majoron and neutrino mass models [35–39]. It is, thus, highly recommended to investigate all sensitive search strategies within the possibly available accelerator and detector designs.

At the LHC, it has been recognized that the VBF and ZH associated production channels will provide the most sensitive probe of an invisibly decaying Higgs in the long run [40–44]. At future lepton colliders, sensitivity to $\mathrm{Br}(h \to \not{E}_T) < 1\%$ can easily be gained due to the much cleaner collider environment and the availability of mass recoil methods [45,46]. However, it is still helpful to investigate whether other options exist and may help to provide useful information for our understanding of physics behind the scene.

In this paper, we investigate the possibility of utilizing the Large Hadron Electron Collider (LHeC) [47] with its recently proposed high-luminosity run [48–51] to probe an invisibly decaying Higgs. The LHeC plans to collide a

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60 GeV electron beam with the 7 TeV proton beam in the LHC ring and is designed to run synchronously with the High Luminosity Large Hadron Collider (HL-LHC). It was originally designed to deliver an integrated luminosity of 100 fb^{-1}. With recognition of the potential role of the LHeC in precision Higgs physics, recently there have been proposals on the collider's 1 ab^{-1} luminosity upgrade [48,50,51]. With such conditions, the LHeC indeed becomes a Higgs boson factory and offers exciting opportunities in precision Higgs studies, especially with respect to exotic Higgs decays. We note that there have been quite a few studies on Higgs boson physics at the LHeC [52–60]. The possibility of using the LHeC to study BSM Higgs decays has been mentioned in [51].

At the LHeC, the Higgs boson is produced via two major channels: charged current (CC) and neutral current (NC). When searching for an invisible Higgs, CC production results in mono-jet plus missing energy, which accidentally coincides with the enormous CC deeply inelastic scattering (DIS) background. Therefore, we focus on NC production which results in one electron, one jet, and large missing energy (see Fig. 1 for its Feynman diagram). Our analysis of this channel reveals high-energy DIS as a promising new avenue to study a wide class of important exotic Higgs decays and demonstrates the promising potential of lepton-hadron colliders in precision studies of new resonances. We emphasize that an electron-proton collider with even higher beam energies (e.g., $E_e = 120$ GeV, $E_p = 50$ TeV) may have better sensitivity to the invisible Higgs decay (and other exotic Higgs decays), which is interesting but beyond the scope of this paper.

II. COLLIDER SENSITIVITY

A. Signal and backgrounds

We take Higgs production at the LHeC through ZZ fusion as our signal process. We use κ_Z to denote the hZZ coupling strength relative to its SM value and define

$$C_{\mathrm{MET}}^2 = \kappa_Z^2 \times \mathrm{Br}(h \to \not{E}_T) \qquad (1)$$

with which we are able to conveniently present the sensitivity results. The SM process $h \to ZZ^* \to 4\nu$ has

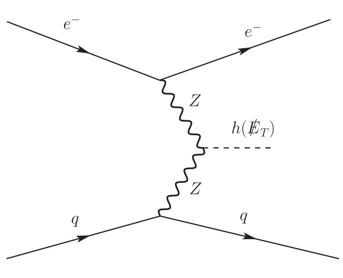

FIG. 1. Feynman diagram of the NC production of an invisible Higgs at the LHeC.

an extremely small branching ratio and will not be included in the signal or backgrounds.

The main irreducible backgrounds include

$$p + e^- \to W^- + j + \nu_e, \qquad (Wj\nu) \qquad (2)$$

$$p + e^- \to Z + j + e^-, \qquad (Zje), \qquad (3)$$

which result in one electron, one jet, and missing transverse energy via $W \to e\nu$ and $Z \to \nu\nu$, respectively. Photoproduction of $W + j$ is also an irreducible background if W decays to an electron. Although its cross section is initially very large, it is found to be negligible after all selection cuts described below, due to its distinct kinematic features. We do not expect that the $W + j$ production via resolved photons contributes sizably to the total background because we require large missing energy in the event which should boost the W boson to the kinematic regime, where the resolved photon contribution is expected to be small [61].

We note that these irreducible backgrounds do not contain strong coupling at leading order, which is different from the VBF search for an invisible Higgs encountered at the LHC. At the LHC, the VBF search of an invisible Higgs boson has important QCD $Vjj(V = W, Z)$ backgrounds. However at the LHeC the corresponding process is of purely electroweak nature which is one of the attractive features of a lepton-hadron collider machine.

There are also reducible backgrounds which come from a variety of sources. Anti-top production in which $\bar{t}$ decays to $\bar{b} + e^- + \bar{\nu}_e$ constitutes a background because b anti-tagging cannot be expected to be fully efficient. However this background also turns out to be negligible after all selection cuts below. A threatening reducible background is

$$p + e^- \to W^\pm + j + e^-, \qquad (Wje), \qquad (4)$$

in which the W boson decays to $l\nu (l = e, \mu, \tau)$, and the (e, μ, τ) from the W decay falls out of detector acceptance or fails to be reconstructed and identified. In fact, this background turns out to be dominant after all selection cuts.

$e +$ multijet production is a reducible background in which missing energy comes from jet energy mismeasurement. We do not simulate this background, but its contribution is expected to be negligible after several demanding cuts required in the analysis, especially $\not{E}_T > 70$ GeV and the missing energy isolation cut $I \equiv \Delta\phi_{\not{E}_T, j} > 1$ rad. One further reducible background is CC $jj\nu$ production in which one jet is misidentified as an electron. In the following, we simply assume a competent detector performance and drop this background from the analysis.

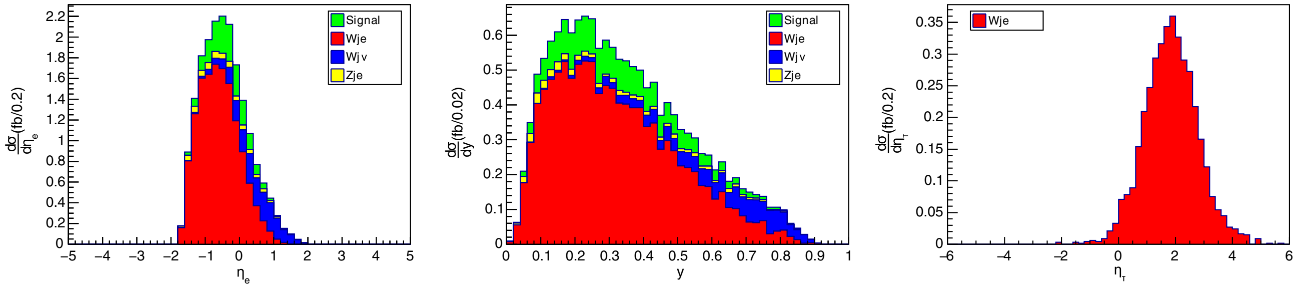

FIG. 2. Left: η_e distribution of the signal and major backgrounds just before the η_e cut. Middle: y distribution of the signal and major backgrounds just before the y cut. Right: τ lepton pseudorapidity distribution of the $Wje(W \to \tau\nu)$ background just before the lepton veto.

B. Analysis and results

We generate the signal and background samples at leading order with MADGRAPH5_AMC@NLO [62]. The collider parameters are taken to be $E_e = 60$ GeV and $E_p = 7$ TeV with the electron beam being −0.9 polarized. The parton distribution function used is NNPDF2.3 at leading order [63]. We take the renormalization and factorization scale to be the Z boson mass. For all the signal and background considered, K factors are taken to be 1 [64–66]. We perform a parton-level analysis with detector resolution taken into account by the jet and lepton energy resolution formula $\frac{\sigma_E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta$ where for jet energy smearing $\alpha = 0.6\ \mathrm{GeV}^{1/2}$ and $\beta = 0.03$, and for lepton energy smearing $\alpha = 0.05\ \mathrm{GeV}^{1/2}$ and $\beta = 0.0055$ [67]. Event analysis is performed with the help of MADANALYSIS 5 [68]. Whenever needed, the expected statistical significance Z is calculated according to the formula $Z = \sqrt{2((S+B)\ln(1+S/B) - S)}$ [69], where S and B denote the expected signal and background event number, respectively.

As to signal and background analysis, we require at least one electron and at least one jet in the final state. All the signal and background samples are required to pass the following basic cuts:

$$p_{Tj} > 20\,\mathrm{GeV}, \quad |\eta_j| < 5.0,$$
$$p_{Tl} > 20\,\mathrm{GeV}, \quad |\eta_l| < 5.0, \quad \Delta R_{jl} > 0.4. \tag{5}$$

Then we impose the following sequence of cuts to further discriminate between signal and backgrounds:

(1) $\not{E}_T > 70$ GeV.
(2) Missing energy isolation: $I > 1$ rad.
(3) Pseudorapidity gap of the jet and the electron satisfies $\eta_j - \eta_e > 3.0$.
(4) The azimuthal angle difference of the electron and the jet satisfies $\Delta\phi_{ej} \equiv |\phi_j - \phi_e| < 1.2$.
(5) The pseudorapidity of the electron satisfies $\eta_e \in [-1.2, 0.6]$.
(6) Inelasticity cut: the inelasticity variable y is defined as $y = \frac{p_1 \cdot (k_1 - k_2)}{p_1 \cdot k_1}$, where p_1 is the 4-momenta of the initial proton, k_1 is the 4-momenta of the initial electron, and k_2 is the 4-momenta of the outgoing electron. Then we require $y \in [0.06, 0.5]$.
(7) Lepton veto: additional electron, muon, or tagged hadronic τ are vetoed.

We assume additional electrons satisfying $p_T > 7$ GeV and $|\eta| < 5.0$ and muons satisfying $p_T > 5$ GeV and $|\eta| < 5.0$ can all be vetoed. As to the τ decay, we adopt the collinear approximation in which we simply assume, on average, that the visible electron or muon from τ decay carries 1/3 of the parent τ momentum and the visible part of a hadronically decaying τ carries 1/2 of the parent τ momentum. We consider a 70% tagging efficiency [70] for a hadronically decaying τ for the veto purpose if the τ lepton satisfies $p_{T,\tau_{\text{had-vis}}} > 20$ GeV and $|\eta| < 5.0$ ($p_{T,\tau_{\text{had-vis}}}$ denotes the transverse momentum of the visible part of the hadronically decaying τ). We note that we have allowed the lepton veto

TABLE I. The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding column. Other backgrounds contribute less than 0.1 fb in total after all cuts and are not displayed in the table.

Cross section (fb)	Basic cuts	$\not{E}_T > 70$ GeV	$I > 1$	$\eta_j - \eta_e > 3.0$	$\Delta\phi_{ej} < 1.2$	$\eta_e \in [-1.2, 0.6]$	$y \in [0.06, 0.5]$	Lepton veto
Signal ($C^2_{\mathrm{MET}} = 1$)	16.1	8.80	8.23	4.68	2.37	2.16	1.77	1.77
Wje	816	158	143	51.7	13.9	11.3	9.13	1.96
$Wj\nu$	192	102	101	5.68	2.36	1.33	0.387	0.387
Zje	42.7	13.8	12.1	1.64	0.683	0.464	0.326	0.326

capability to extend to $|\eta_{\max}| = 5.0$, in contrast to the commonly assumed $|\eta_{\max}| = 2.5$ assumed in the usual LHC analysis. This is due to the expected very large pseudorapidity coverage of the LHeC tracking detector and muon detector [47,71].

In the sequence of cuts listed above, $\not{E}_T > 70$ GeV and the missing energy isolation requirement will significantly suppress the $e +$ multijet background. When calculating the missing energy, the electron and hadronic τ which satisfy $|\eta| < 5.0$ but fail to be identified are counted in the p_T balance, while muons which fail to be identified are always excluded in the p_T balance. The pseudorapidity gap requirement and azimuthal angle difference cut are analogous to $|\eta_{j_1} - \eta_{j_2}|$ and ϕ_{jj} cuts employed in the LHC VBF search for an invisible Higgs boson [10]. They are very effective in reducing all three major backgrounds. Then we try simple kinematic variables like the electron pseudorapidity η_e and inelasticity y to further enhance the statistical significance. To motivate those cuts beyond the counterparts of the usual ones employed in the VBF search for an invisible Higgs at the LHC, we plot the η_e, y distribution of the signal and major backgrounds in Fig. 2 (left and middle) just before applying the corresponding cuts [72]. The signal and background cross sections after each cut are listed in Table I, in which the signal cross section is calculated assuming $C^2_{\mathrm{MET}} = 1$. We note that if we target $C^2_{\mathrm{MET}} = 0.06$, we will get an expected signal cross section of 0.106 fb and total background cross section 2.761 fb (we have included here about 0.1 fb contribution from other minor backgrounds), thus $S/B \approx 3.8\%$, and with an integrated luminosity of 1 ab^{-1}, the expected statistical significance will reach $Z = 2.00$ [73,74]. We also plot the significance contour for a targeted range of C^2_{MET} and the luminosity parameter in Fig. 3.

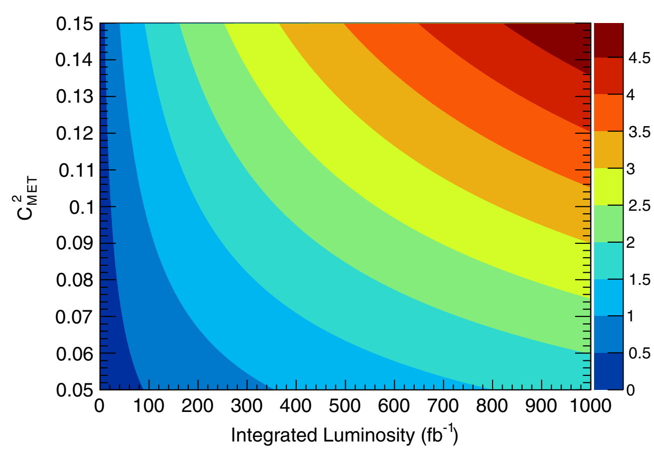

FIG. 3. The expected significance contour for an invisible Higgs at the LHeC. The colors indicate the value of the expected statistical significance with the correspondence displayed by the scale on the right.

III. DISCUSSION AND CONCLUSION

In this paper, we have studied the possibility of using the LHeC to search for an invisibly decaying Higgs boson and find that the LHeC has promising potential to discover or constrain this important exotic Higgs decay mode. The η_e cut and the inelasticity cut are found to be very effective in suppressing the $Wj\nu$ background. After all selection cuts, the largest background turns out to be the Wje process in which the charged lepton (especially τ) from the W decay fails to be identified. We take advantage of the expected large acceptance of the LHeC tracking detector and muon detector, with which the lepton veto is able to remove nearly 80% of the Wje background. In particular, we find that the lepton veto capability in the forward region $\eta \in [2.5, 4.0]$ is essential. To illustrate this point, we plot the pseudorapidity distribution of the τ lepton from the W boson decay in the Wje background [Fig. 2 (right)]. This also represents the pseudorapidity distribution of the electron/muon from W boson decay in the Wje background. From the plot it is clear that the charged leptons from W boson decay in Wje background are mostly distributed in $\eta \in [0.0, 4.0]$ and large portions of events still reside in $\eta \in [2.5, 4.0]$. If the lepton veto is only possible in $\eta \in [-2.5, 2.5]$, the total background will nearly double. It is, thus, highly recommended that a good lepton veto capability should be maintained in the forward region $\eta \in [2.5, 4.0]$.

The sensitivity of the LHeC to an invisibly decaying Higgs boson could be further enhanced via a multivariate analysis, which is worth pursuing [75] but beyond the scope of the present paper. Compared with the concurrent search at the HL-LHC, the invisible Higgs search at the LHeC has the further advantage of not suffering from pile-up, a crucial factor of which is commonly not taken account sufficiently in the LHC analysis. Of course, both searches are worth exploiting and being combined to produce the best sensitivity to the invisible Higgs decay with the available LHC infrastructure. Even if an excess of VBF dijet $+ \not{E}_T$ events is first observed at the HL-LHC, signals from additional channels are still required to pin down the origin of the $\not{E}_T$ signature. The LHeC search for an invisible Higgs may play an important role in this process.

Our study clearly justifies a luminosity upgrade to 1 ab^{-1} for the LHeC to become a Higgs boson factory [48] and demonstrates its huge potential in the study of exotic Higgs decays. Besides the invisible Higgs decay, the LHeC is suited to the study of those exotic Higgs decays which suffer from large backgrounds or trigger or p_T threshold problems at the (HL-)LHC, such as $h \to 4b$, $h \to 2b2\tau$, $h \to 4j$, $h \to b\bar{b} + \not{E}_T$ [76], $h \to \gamma + \not{E}_T$, and $h \to Z + \not{E}_T$ [77]. Work on these issues is in progress [78]. The demonstration of the LHeC potential in studying exotic Higgs decays reveals an important aspect of lepton-hadron colliders with respect to precision study after the discovery of a new resonance in hadron-hadron collisions, which has not been unexpected since the early study of measuring the bottom Yukawa coupling at the LHeC [52]. Although usually the ideal precision measurement would finally be achieved at a lepton collider, this most precise measurement can only be reached with sufficient center-of-mass energy available. Without the help of such a lepton collider, the best use of a hadron beam can be made via colliding it against a lepton beam to make foreseeable precision studies, which may even unravel exciting deviations from the SM within the shortest time.

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[72] In particular, we note that the inelasticity cut $y < 0.5$ is found to be very effective in suppressing the $Wj\nu$ background and photoproduction Wj background.
[73] Due to the cleanness of lepton-hadron collisions compared to hadron-hadron collisions, the sensitivity shown in this paper is not expected to be substantially degraded with the inclusion of systematic uncertainties. If there is a 1%–2% systematic uncertainty on the total background (which is a reasonable expectation for the LHeC), the 2σ exclusion sensitivity on C^2_{MET} with the cut-based analysis drops to about 7%–9%. Small degradation in sensitivity due to systematic uncertainties is expected to be compensated for by a further multivariate analysis and other refinements.
[74] Reference [43] estimates that at the HL-LHC in the VBF channel $C^2_{\mathrm{MET}} = 3.5\%$ can be probed at the 95% C.L. level with a multivariate analysis (6.9% before a multivariate analysis). Reference [44] estimates that HL-LHC will probe $C^2_{\mathrm{MET}} = 5\%–20\%$ in the VBF channel depending on assumptions of systematic uncertainties. However, for the purpose of sensitivity comparison with the LHeC, it should be noted that these analyses do not taken into account the large pile-up effect at the HL-LHC environment which will significantly impact the performance of jet and missing energy measurements which are crucial in the VBF search for an invisible Higgs boson.
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