Searching for the light Higgsinos in the MSSM at future e - p colliders

Chengcheng Han,^{1,2,*} Ruibo Li,^{1,†} Ren-Qi Pan,^{1,‡} and Kai Wang^{1,§}

¹*Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou, Zhejiang 310027, China*

²*Kavli IPMU (WPI), The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

(Received 9 April 2018; revised manuscript received 2 October 2018; published 4 December 2018)

The search for the light Higgsino in the minimal supersymmetric standard model is a crucial test of the naturalness criteria in supersymmetry. On the other hand, the direct production of light Higgsinos is also known as one of the most challenging supersymmetry searches at the LHC. The lack of visible leptons due to the compressed spectrum and their small production rates limit their discovery potential in both monojet plus $\cancel{E}_T$ events and weak boson fusion (WBF) production. The signal-to-background ratio prediction is usually within the background systematic uncertainties at the LHC. Without color exchange between the beams, e - p colliders are well known to exhibit WBF. Therefore, we search for light Higgsinos at two future e - p colliders at CERN: the Large Hadron electron Collider (LHeC) and the Future Circular Collider in hadron-electron mode (FCC-eh). The light Higgsinos will be produced in pairs through weak boson fusion with controlled background at these colliders. We find that a 95/145 GeV Higgsino can be reached at the 2σ level at the future LHeC/FCC-eh with a luminosity of 3 ab^{-1} , respectively.

DOI: [10.1103/PhysRevD.98.115003](https://doi.org/10.1103/PhysRevD.98.115003)

I. INTRODUCTION: LIGHT HIGGSINO SURVIVAL IN DIRECT SEARCHES

The ATLAS and CMS experiments at the LHC have put stringent lower bounds on the supersymmetric (SUSY) particles, excluding a large parameter space for the low-energy SUSY models. As a consequence of R -parity conservation, SUSY particles are usually produced in pairs through gauge interactions at the LHC. Searches for final states with jets or leptons plus $\cancel{E}_T$ have excluded the $\mathcal{O}(1.5\text{--}2 \text{ TeV})$ colored SUSY particle production at this QCD machine [1,2]. The direct production of electroweak SUSY particles has a relatively small cross section, but the definite hard lepton tagging also helps the search in the multilepton plus $\cancel{E}_T$ final states and $\mathcal{O}(600 \text{ GeV})$ charginos have been excluded [3]. One well-known exception is the light Higgsinos, which have a nearly degenerate spectrum and relatively small production rate.¹

In the limit of $\mu \ll M_1, M_2$, the low-energy charginos/neutralinos are all Higgsino-like and nearly degenerate. If $M_1, M_2 > 1.5 \text{ TeV}$ and $\mu \sim 100 \text{ GeV}$, the mass splitting $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ is less than 5 GeV, while the mass splitting $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ is about half of that. The key property for these nearly degenerate electroweakinos of $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(\text{GeV})$ is the lack of hard leptons in the final states. Therefore, the final states of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \tilde{\chi}_1^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-$, etc. mostly manifest themselves as $\cancel{E}_T$.²

Without the hard leptons, the signal final states mostly consist of $\cancel{E}_T$. The general searches for such invisible-inos at the LHC can be categorized into three subchannels: indirect production from cascade decay of colored SUSY particles, direct pair production, and weak boson fusion (WBF) produced pairs [5]. If the gluino/squarks are of several TeV, the production rate will be significantly suppressed. Direct pair production always requires an additional object to be produced associatively for the event trigger purpose, and the final state is then a monojet, mono- Z , or monophoton plus $\cancel{E}_T$ [5,9–26]. However, this simple two-body final state lacks general kinematic feature and it only demonstrates robust power when the production rate is huge (for instance, a monojet plus top-squark pair in the compressed top squark–bino case). Due to the small signal rate for light Higgsinos, the signal deviation is only comparable to the systematic error as a few percent. WBF

*chengcheng.han@ipmu.jp

†bobli@zju.edu.cn

‡renqipian@zju.edu.cn

§wangkail@zju.edu.cn

¹Light Higgsinos may reside in the theory from the naturalness argument [4].

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

²If $\Delta m > 5 \text{ GeV}$, soft muons can sometimes serve as an additional handle to suppress the background [5–8].

FIG. 1. h represents a Higgs boson and $\tilde{h}$ represents a light Higgsino, i.e., $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{1,2}^0$.

production itself contains two forward-backward jets that can serve as triggers, but it suffers from a small Higgsino pair production rate in comparison with the standard model (SM) $2j + Z/W$ even with WBF kinematics, such as the tagging of two energetic forward-backward jets, a central-jet veto, etc. [27]. Recently, Ref. [28] discussed the Higgsino-like chargino search at colliders and found that a Higgsino mass as light as 75 GeV still survived, assuming the mass splitting of the chargino and lightest neutralino is less than 10 GeV. Since the difficulty is that the signal-to-background ratio (S/B) is within systematic error, the accumulation of LHC data will not improve the search.³

To improve the S/B ratio, we therefore study the search for such light Higgsinos at future e - p colliders. Without color exchange between the colliding beams, e - p colliders are the best places to study WBF processes with controlled backgrounds. There are currently two proposed examples of such colliders. The first is an economic LHC upgrade: a Large Hadron electron Collider (LHeC) [31]. LHeC is a proposed future deep inelastic scattering (DIS) facility that would add one electron beam of 60–140 GeV to the current LHC based on the 7 TeV proton beam with a forward detector; there have also been recent discussions of a “Higgs factory” or precision machine based on a high-luminosity LHeC [32–34]. A second example is the Future Circular Collider in hadron-electron mode (FCC-eh) [35], a future collider with a 60 GeV electron beam colliding with a 50 TeV proton beam. Light Higgsino pairs can be

produced at these e - p colliders via WBF with a lower $\sqrt{s}$ compared to the LHC. At the same time, the disappearance of QCD $2j + W/Z$ background may potentially enhance S/B .

The paper is organized as follows. In the next section, we discuss the survival parameter space for light Higgsinos from direct searches. It is followed by a discussion of the phenomenology of this collider search, which includes signal and background event simulations, some kinematic distributions of final states, and selection cuts. In Sec. III, we give results for the signal-to-background ratio S/B and significance Z for different μ values. We then conclude in the final section.

II. PHENOMENOLOGY OF LIGHT HIGGSINOS AT THE WBF MACHINES

A. Signal and backgrounds

At the e - p colliders, SUSY particles are produced in pairs via gauge interactions, so the dominant contribution for Higgsino production is through WBF processes. The light Higgsino contains three physical states $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{1,2}^0$, so Higgsino production corresponds to the following channels:

$$e^- p \rightarrow e^- j \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \quad e^- j \tilde{\chi}_1^\pm \tilde{\chi}_{1,2}^0, \quad e^- j \tilde{\chi}_{1,2}^0 \tilde{\chi}_{1,2}^0.$$

The contributions can be categorized into four topological diagrams, shown in Fig. 1.

As argued in the previous section, the survivor scenario for the light Higgsino requires all of the other SUSY particles to be generally heavy and decoupled. The mass spectrum shown in Table I is calculated using SUSPECT [36] and SUSY-HIT [37], where $M_1 = M_2 = 2$ TeV and all of the other SUSY particles are set to 3 TeV. We found that the SM-like neutral Higgs boson is essentially not affected by different values of μ . We focus on the range $\mu \lesssim 200$ GeV. In this case, the mass splitting between $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$, and $\tilde{\chi}_2^0$ is small ($\Delta m \lesssim 5$ GeV). Consequently, the leptons from the subsequent decays $\tilde{\chi}_1^\pm \rightarrow W^{\pm*} \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow Z^* \tilde{\chi}_1^0$ are too soft to be detected. Thus, all of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ final states will be identified as $\cancel{E}_T$ as the dark matter candidate $\tilde{\chi}_1^0$.

In our study, the Monte Carlo events are generated using MADGRAPH5_V2.5.5 [38] at the parton level. We implement

³On the other hand, besides the direct limit at the colliders, the light Higgsino also receives constraints from dark matter direct detection experiments. In the limit of $\mu \ll M_1, M_2$, the lightest neutralino $\tilde{\chi}_1^0$ can be identified as the dark matter candidate. One the other hand, the pure Higgsino dark matter of 1 TeV produces the correct relic density. Therefore, the light Higgsino only consists of a small portion of the dark matter and requires additional components such as the axion. As a result, a rescaling of the local abundance of Higgsino dark matter has to be taken into account in the calculation of direct detection bounds. In the conventional natural SUSY framework, the light Higgsino dark matter is completely covered by the XENON1T experiment [11,29]. However, this bound can be easily evaded by decoupling the top squark and M_1, M_2 . For instance, if $\mu = 120$ GeV, $M_1 = M_2 = 2$ TeV, $m_{t_L} \sim m_{t_R} \sim 3$ TeV, $A_t = 4.5$ TeV, the Higgs mass is 125.7 GeV, and the rescaled Higgsino $\sigma_{SI} = 0.05 \times 10^{-46} \text{ cm}^2$ which is still 1 order of magnitude lower than the current XENON1T bound [30].

TABLE I. Here $M_1 = M_2 = 2$ TeV, $m_{\tilde{t}_L} \sim m_{\tilde{t}_R} \sim 3$ TeV, and $A_t = 3.2$ TeV. h is the SM-like neutral Higgs boson.

Parameter μ						
Higgs boson	$\mu = 80$ GeV	$\mu = 90$ GeV	$\mu = 100$ GeV	$\mu = 110$ GeV	$\mu = 120$ GeV	$\mu = 130$ GeV
h	125.52 GeV	125.52 GeV	125.51 GeV	125.50 GeV	125.49 GeV	125.48 GeV
H	3000.09 GeV	3000.09 GeV	3000.09 GeV	3000.09 GeV	3000.09 GeV	3000.09 GeV
A	3000.01 GeV	3000.01 GeV	3000.01 GeV	3000.01 GeV	3000.01 GeV	3000.01 GeV
H^+	3001.45 GeV	3001.45 GeV	3001.44 GeV	3001.44 GeV	3001.43 GeV	3001.43 GeV

Parameter μ						
Higgs boson	$\mu = 140$ GeV	$\mu = 150$ GeV	$\mu = 160$ GeV	$\mu = 170$ GeV	$\mu = 180$ GeV	$\mu = 190$ GeV
h	125.47 GeV	125.47 GeV	125.46 GeV	125.46 GeV	125.45 GeV	125.45 GeV
H	3000.09 GeV	3000.09 GeV	3000.09 GeV	3000.09 GeV	3000.09 GeV	3000.09 GeV
A	3000.01 GeV	3000.01 GeV	3000.01 GeV	3000.01 GeV	3000.01 GeV	3000.01 GeV
H^+	3001.43 GeV	3001.42 GeV	3001.42 GeV	3001.42 GeV	3001.41 GeV	3001.41 GeV

PYTHIA6.420 [39] and DELPHES3.3.0 [40] for parton shower and detector simulations, respectively. At the parton level, we require the following basic cuts:

- (1) $p_T^j > 20$ GeV.
- (2) $p_T^\ell > 5$ GeV.
- (3) $|\eta_{\ell,j}| < 5$.
- (4) $\Delta R_{j\ell} > 0.4$ and $\Delta R_{\ell\ell} > 0.4$.

The production cross sections for Higgsino pairs as a function of Higgsino mass μ are given in Fig. 2 for different colliders, E_e , and channels. When $E_e = 140(60)$ GeV, the total cross section can be as large as 1.3(0.38) fb for $\mu = 100$ GeV. We also show the dependence on the cross section for the electron $p_T > 5, 10, 15$ GeV in Table II to argue that the result would not break the perturbative description [41] even though we set $p_T^\ell > 5$ GeV in basic

cuts. With the enlarged center-of-mass energy at the FCC-eh, the production rates are also significantly enhanced.

Since all of the light Higgsino states are invisible in the detector, the final states consist of a forward-backward jet and electron with $\cancel{E}_T$. The irreducible background can be classified into two categories:

$$e^- p \rightarrow e^- j \nu_e \bar{\nu}_e,$$

$$e^- p \rightarrow e^- j \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau},$$

where the invisible SM neutrinos make up the $\cancel{E}_T$. The backgrounds in the first category mainly come from the W bremsstrahlung process $e^- p \rightarrow \nu_e W^- j$ with $W^- \rightarrow e^- \bar{\nu}_e$, and also partly from the Z bremsstrahlung process

FIG. 2. The parton-level cross sections of the signals varying with the Higgsino mass μ at LHeC (a) and FCC-eh (b). The combination of the cross section of all final states in the signal is defined as “Total.” Solid lines represent the signal when $E_e = 140$ GeV, while the dashed line represents $E_e = 60$ GeV in the left panel.

TABLE II. The cross section varying with the lower limit of the electron p_T with $E_e = 140$ and 60 GeV, respectively.

Beam energy	Electron p_T		
	> 5 GeV	> 10 GeV	> 15 GeV
140 GeV $\times$ 7000 GeV	1.30 fb	1.04 fb	0.89 fb
60 GeV $\times$ 7000 GeV	0.38 fb	0.30 fb	0.25 fb

$e^- p \rightarrow e^- Z j$ with $Z \rightarrow \nu_e \bar{\nu}_e$ as well as the interference terms between them. Backgrounds in the second category are purely from $e^- p \rightarrow e^- Z j$ production with $Z \rightarrow \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}$. The total cross sections of these two backgrounds are 243.6 (115.5) and 58.11(32.82) fb when $E_e = 140(60)$ GeV, respectively, which are hundreds of times larger than Higgsino production. Effective cuts are needed to reduce the huge backgrounds.

For the reducible background, the production of τ in the final state would be the largest one,

$$\begin{aligned} e^- p &\rightarrow e^- j \tau^+ \nu_\tau, \\ e^- p &\rightarrow e^- j \tau^- \bar{\nu}_\tau. \end{aligned}$$

The total cross sections are 330.2(163.8) and 302.0 (146.8) fb when $E_e = 140(60)$ GeV, respectively. There are two main cases where these processes might fake the signal: (i) the τ fakes a hard jet in the detector, or (ii) the products from hadronic τ decays are too soft to be tagged, and thus contribute to the $\cancel{E}_T$. In fact the latter is similar to the contribution from the irreducible background. Of course, leptonic τ decay would contribute to our process as well, but by taking into account the existence of extra leptons in the final states we can easily cut this background by vetoing events with extra hard leptons. The other distinct reducible backgrounds are $e^- p \rightarrow j \nu_e \tau^+ \nu_\tau$ and $e^- p \rightarrow j \nu_e \tau^- \bar{\nu}_\tau$. They might mimic the signal since there is one electron from leptonic τ decays. Fortunately, we could suppress them to an insignificant order because of the totally different kinematic distribution of the final electron. According to the above analysis, these backgrounds will not be considered in the following.

A left-handed polarization of the electron beam may in principle enhance the signal production rate, but the background will be enlarged at the same time [42,43]. The polarization of the electron beam does not significantly improve the result, so we focus on the unpolarized cases.

B. Selection cuts

In order to suppress reducible backgrounds, we adopt the following veto criteria at LHeC⁴:

⁴Extra leptons would also appear in the signal from chargino decays, but they are very soft because of the compressed mass spectrum.

- (i) Events containing any central jets $p_T^{j_i} > 3.0$ GeV, $|\eta_{j_i}| < 2.0$ ($i \geq 2$; $i \in \mathbb{N}$) are vetoed.
- (ii) Events with extra hard electrons with $p_T^{e_m} > 5.0$ GeV ($m \geq 2$; $m \in \mathbb{N}$) or muons with $p_T^{\mu_k} > 5.0$ GeV ($k \geq 1$; $k \in \mathbb{N}$) are vetoed.
- (iii) Any events with a tagged τ jet are vetoed.

Since the signal final state contains two massive invisible Higgsinos, which presumably leads to large $\cancel{E}_T$, a cut on $\cancel{E}_T$ may help to distinguish the signal and backgrounds.

In Fig. 3 we show the missing transverse energy distributions of the signal and backgrounds, where the blue and magenta lines correspond to the above two irreducible backgrounds, the green and red lines correspond to the two reducible backgrounds, while the grey line corresponds to $\mu = 100$ GeV. It is clearly shown that the $e^- j \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}$ and two τ backgrounds have smaller missing transverse energy than the signal due to the small recoil mass. $e^- j \nu_e \bar{\nu}_e$ tends to have larger missing transverse momentum because the missing energy is not only from W decay but also from scattering with the initial electron. On the other hand, the missing transverse energy tends to be larger when the electron beam energy increases, as shown in Fig. 3.

Comparing the signal with the background events, the signal electron in the WBF final state is forward, while in the leading SM background electrons are from W^- decay. Therefore, one would expect the leading electron to have a larger rapidity but less p_T in the signal. For the background, leading electrons from $W^- \rightarrow e^- \bar{\nu}_e$ have a larger p_T than the signal, and its p_T distribution have a peak at $m_W/2$ as well-known as Jacobian peak.

Another typical WBF cut is the invariant mass between the forward-backward jet/electron $M(e_1, j_1)$. The inelasticity variable y introduced in Ref. [44] is defined as

$$y = \frac{k_P \cdot (k_e - p_e)}{k_P \cdot k_e}, \quad (1)$$

where k_P is the 4-momenta of the initial proton, k_e is the 4-momenta of the initial electron, and p_e is the 4-momenta of the outgoing electron. This inelasticity variable is used to reflect the momentum transformation between the initial and final states. In Fig. 4 we plot the distributions for the pseudorapidities η_{e_1} and η_{j_1} , the invariant mass $M(e_1, j_1)$, and the inelasticity y .

Therefore, additional cuts are imposed as follows:

- (i) Missing transverse energy cut: $\cancel{E}_T > 30$ GeV.
- (ii) Transverse momentum of the leading electron: $p_T^{e_1} < 30$ GeV.
- (iii) Pseudorapidity of the leading electron and the forward leading jet in the final state: $\eta_{e_1} > 1.0$, $\eta_{j_1} < -2.0$.
- (iv) Invariant mass of the leading electron and the forward leading jet in the final state: $M(e_1, j_1) > 400$ GeV.
- (v) Inelasticity variable cut: $y > 0.3$.

FIG. 3. The normalized missing transverse energy E_T distributions when $E = 60$ GeV (left panel) and $E = 140$ GeV (right panel), respectively.

FIG. 4. The normalized distributions for the pseudorapidities η_{e_1} (top left) and η_{j_1} (top right) and the invariant mass $M(e_1, j_1)$ (bottom left) after veto criteria cuts i–ii when $E_e = 140$ GeV. The normalized inelasticity variable y (bottom right) distributions after veto criteria cuts i–iii when $E_e = 140$ GeV.

TABLE III. Cut-flow of the signal and background events for $\mu = 100$ GeV for a 140 GeV electron beam energy LHeC with $\mathcal{L} = 1 \text{ ab}^{-1}$.

Cut	$e^- j \tau^+ \nu_\tau$	$e^- j \tau^- \bar{\nu}_\tau$	$e^- j \nu_e \bar{\nu}_e$	$e^- j \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}$	$\mu = 100 \text{ GeV}$
Basic cuts	330 100	302 000	243 600	58 110	1300
Detector efficiency	210 340	189 475	156 055	35 783	832.75
Veto criteria	52 446.3	43 572.6	116 056	24 085.4	590.20
$\cancel{E}_T > 30 \text{ GeV}$	38 073.7	28 925.6	101 849	16 794	514.10
$p_T^{e_1} < 30 \text{ GeV}$	21 482.9	16 163	27 034.7	7489.87	267.23
$\eta_{j_1} < -2.0 \ \& \ \eta_{e_1} > 1.0$	10 219.9	7042.64	2260.61	2208.18	161.64
$M(e_1, j_1) > 400 \text{ GeV}$	5631.51	3412.60	570.02	728.70	80.02
$y > 0.3$	805.44	567.76	253.34	58.11	48.54

TABLE IV. The production cross sections of all backgrounds and the signal with $\mu = 100$ GeV at different e - p collider setups.

e - p collider	$e^- j \tau^+ \nu_\tau$	$e^- j \tau^- \bar{\nu}_\tau$	$e^- j \nu_e \bar{\nu}_e$	$e^- j \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}$	$\mu = 100 \text{ GeV}$
LHeC with $E_e = 60 \text{ GeV}$	163.8	146.8	115.5	32.82	0.38
LHeC with $E_e = 140 \text{ GeV}$	330.2	302.0	243.6	58.11	1.3
FCC-eh	546.5	567.0	446.6	100.7	3.0

We presented the cut-flow for signal and background events in Table III for a 140 GeV electron beam energy with an integrated luminosity of 1 ab^{-1} . After cuts, the total backgrounds are reduced by $\mathcal{O}(10^{-3})$, while the signal remains around 4%. It is shown that after the parton shower and detector simulations, both the signal and backgrounds have a 60–70% survival probability. Veto criteria will suppress two reducible backgrounds by a factor of 4 and the requirements for η_{e_1, j_1} dramatically reduce the $\nu_e \bar{\nu}_e$ background by approximately one order. After the inelasticity variable cut, the remaining reducible background events are small and could be compared to the signal. However, the τ background is still about 30 times larger than the signal, which could lead to a dramatic decline in the significance, in particular for the 60 GeV beam case. In order to increase the production cross section of the signal,

we study the future higher-energy e - p collider FCC-eh to search for light Higgsinos via WBF processes.

As mentioned in the Introduction, FCC-eh collides a 60 GeV electron beam with the 50 TeV proton beam of the planned FCC, which is a typical deep inelastic facility with $\sqrt{s} \approx 3.5 \text{ TeV}$. Because of its higher energy and smaller QCD backgrounds, some precision physics and probes of supersymmetric particles were recently proposed [45–47]. According to the above analysis, we focus on the FCC-eh to compensate for the small production cross section of the signal at LHeC. The total cross sections of the different backgrounds and signal are shown in Table IV.

Since FCC-eh has a higher proton beam energy than LHeC, we need to modify the above veto criteria and kinematic cuts to adjust to the progressive detector simulation. The modified values for the cuts and cut-flow are presented in Tables V and VI, respectively. It is clearly shown that we concentrate on the more forward region of the final jets as well as larger missing transverse energy because of the 50 TeV proton beam. $\cancel{E}_T$ and $p_T^{e_1}$ cuts could reduce all backgrounds by one order. The last inelasticity variable is still a fine complementary cut without severe loss of signal. We see that the remaining signal events in Table VI are approximately 3 times larger than at LHeC with a 140 GeV electron beam, while the background increase is less than 3 times larger. We expect that the significance would show an obvious improvement at the FCC-eh.

TABLE V. The modified veto criteria and kinematic cuts for FCC-eh.

Basic cuts	The same
Central jets veto	$p_T^{j_i} > 3.0 \text{ GeV}$ and $ \eta_{j_i} < 3.0 \ (i \geq 2; i \in \mathbb{N})$
Hard extra leptons(e, μ) veto	$p_T^{e_m} > 5.0 \text{ GeV}, p_T^{\mu_k} > 5.0 \text{ GeV} \ (m \geq 2, k \geq 1; m, k \in \mathbb{N})$
τ -jet veto	vetoing any events with a τ jet
Missing transverse energy cut	$\cancel{E}_T > 70 \text{ GeV}$
Transverse momentum cut	$p_T^{e_1} < 25 \text{ GeV}$
Pseudorapidity cuts	$\eta_{e_1} > 0.0, \eta_{j_1} < -3.0$
Invariant mass cut	$M(e_1, j_1) > 400 \text{ GeV}$
Inelasticity variable cut	$y > 0.15$

III. RESULTS

We calculate the signal significance Z after a full detector simulation using the formula

TABLE VI. Cut-flow of the signal and background events for $\mu = 100$ GeV at FCC-eh with $\mathcal{L} = 1 \text{ ab}^{-1}$.

Cut	$e^- j\tau^+\nu_\tau$	$e^- j\tau^-\bar{\nu}_\tau$	$e^- j\nu_e\bar{\nu}_e$	$e^- j\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$	$\mu = 100 \text{ GeV}$
Basic cuts	546 500	567 000	446 600	100 700	3000
Detector efficiency	346 251	356 121	285 270	62 017.1	1926.54
Veto criteria	41 329	36 968	169 842	30 955.2	1069.08
$\cancel{E}_T > 70 \text{ GeV}$	13 400.2	9 888.48	103 549	9810.19	737.22
$p_T^{e_1} < 25 \text{ GeV}$	4842	3742.2	16 292	2469.16	283.44
$\eta_{j_1} < -3.0 \ \& \ \eta_{e_1} > 0.0$	3432.1	2381.4	946.66	846.01	203.88
$M(e_1, j_1) > 400 \text{ GeV}$	3169.7	2177.3	625.24	797.54	178.02
$y > 0.3$	1103.93	635.04	303.69	130.91	138.1

TABLE VII. The signal-to-background ratio and significance of the Higgsino with $\mu = 80, 90$, and 100 GeV with $\mathcal{L} = 1$ and 3 ab^{-1} at LHeC with $E_e = 140 \text{ GeV}$, and the FCC-eh results.

		$\mu = 80 \text{ GeV}$	$\mu = 90 \text{ GeV}$	$\mu = 100 \text{ GeV}$
LHeC (140 GeV)	S/B	5.1%	3.5%	2.7%
	Z with $\mathcal{L} = 1 \text{ ab}^{-1}$	2.1σ	1.5σ	1.1σ
	Z with $\mathcal{L} = 3 \text{ ab}^{-1}$	3.6σ	2.4σ	1.8σ
FCC-eh	S/B	10.3%	8.3%	6.6%
	Z with $\mathcal{L} = 1 \text{ ab}^{-1}$	4.5σ	3.7σ	3.0σ
	Z with $\mathcal{L} = 3 \text{ ab}^{-1}$	7.9σ	6.4σ	5.3σ

$$Z = \frac{S}{\sqrt{S+B}},$$

where S represents the number of signal events and $B = \sum_i B_i$ denotes the overall background ($i = e^- j\tau^+\nu_\tau, e^- j\tau^-\bar{\nu}_\tau, e^- j\nu_e\bar{\nu}_e, e^- j\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$). The signal-to-background ratio S/B and significance Z , which are dependent on different Higgsino masses and integrated luminosities, are shown in Table VII. When $\mu = 80 \text{ GeV}$, the signal-to-background ratio is about 5.1%. Even though μ goes up to 100 GeV , S/B is still 2.7%, and we expect that it would not be overshadowed by uncertainties. At $\mathcal{L} = 3 \text{ ab}^{-1}$, the Higgsino mass could be probed beyond 2σ significance for $\mu \lesssim 95 \text{ GeV}$. Note that the above results are based on a 140 GeV electron beam at LHeC; we do not show the results for a 60 GeV beam since the τ backgrounds overshadow the tiny signal and thus the sensitivity cannot reach 2σ after detector simulations. We also compare the results for FCC-eh to those for LHeC. It shows that the higher energy would improve the significance dramatically. However, a more comprehensive and complete analysis need to be performed with a realistic detector.

In Fig. 5, we show the dependence of the signal significance Z on the Higgsino mass μ at LHeC with $E_e = 140 \text{ GeV}$ and the FCC-eh results. With an increase of μ the significance drops rapidly due to the reduction in the signal cross sections. At the 140 GeV LHeC, $\mu = 85(95) \text{ GeV}$ with $\mathcal{L} = 1(3) \text{ ab}^{-1}$ is the threshold for 2σ significance. One can see that the signal cross section is too small to probe greater Higgsino masses even when we update the

integrated luminosity to 3 ab^{-1} . On the other hand, for FCC-eh we can easily reach 2σ significance near $\mu = 115 \text{ GeV}$ with $\mathcal{L} = 1 \text{ ab}^{-1}$ and $\mu = 145 \text{ GeV}$ with $\mathcal{L} = 3 \text{ ab}^{-1}$, respectively. A higher electron beam energy and luminosity at future $e-p$ colliders could potentially probe heavier Higgsinos.

FIG. 5. The significance Z varying with the Higgsino mass μ at LHeC with $E_e = 140 \text{ GeV}$, and the FCC-eh results.

IV. CONCLUSION

Searching for Higgsinos is a crucial test of the naturalness criteria in supersymmetry. It has proven difficult to detect them at hadron colliders, due to the small signal rates and large systematic uncertainties. On the other hand, electron-positron colliders may have better control of systematic uncertainties; however, the capabilities are limited by the central energy. In this paper, we discussed looking for Higgsinos at the future LHeC, which is a DIS facility designed for high-precision measurements of patron distribution functions and forward-physics detection. Through our simulations, we found that a Higgsino mass around 85(95) GeV can be reached at the 2σ level with a luminosity of $1(3) \text{ ab}^{-1}$, while at FCC-eh we can

reach 2σ significance near $\mu = 115(145) \text{ GeV}$ with $\mathcal{L} = 1(3) \text{ ab}^{-1}$. Heavier Higgsinos can be approached by increasing the luminosity and beam energy.

ACKNOWLEDGMENTS

We thank the LHeC Higgs & Top group for sharing their DELPHES card with a LHeC and FCC-eh setup. This work is supported in part by the National Science Foundation of China (11875232, 11422544), the World Premier International Research Center Initiative (WPI), MEXT, Japan, and by the Zhejiang University K. P. Chaos High Technology Development Foundation. C. H. would like to thank Zhejiang University for its hospitality when this work was initiated.

-
- [1] M. Aaboud *et al.* (ATLAS Collaboration), Search for squarks and gluinos in events with an isolated lepton, jets, and missing transverse momentum at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector, *Phys. Rev. D* **96**, 112010 (2017).
 - [2] M. Aaboud *et al.* (ATLAS Collaboration), Search for squarks and gluinos in final states with jets and missing transverse momentum using 36 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ pp collision data with the ATLAS detector, [arXiv:1712.02332](#).
 - [3] M. Aaboud *et al.* (ATLAS Collaboration), Search for the direct production of charginos and neutralinos in $\sqrt{s} = 13 \text{ TeV}$ pp collisions with the ATLAS detector, [arXiv:1708.07875](#).
 - [4] R. L. Arnowitt and P. Nath, Loop corrections to radiative breaking of electroweak symmetry in supersymmetry, *Phys. Rev. D* **46**, 3981 (1992).
 - [5] G. F. Giudice, T. Han, K. Wang, and L.-T. Wang, Nearly degenerate gauginos and dark matter at the LHC, *Phys. Rev. D* **81**, 115011 (2010).
 - [6] Z. Han, G. D. Kribs, A. Martin, and A. Menon, Hunting quasi-degenerate Higgsinos, *Phys. Rev. D* **89**, 075007 (2014).
 - [7] H. Baer, A. Mustafayev, and X. Tata, Monojet plus soft dilepton signal from light Higgsino pair production at LHC14, *Phys. Rev. D* **90**, 115007 (2014).
 - [8] C. Han, D. Kim, S. Munir, and M. Park, Accessing the core of naturalness, nearly degenerate higgsinos, at the LHC, *J. High Energy Phys.* **04** (2015) 132.
 - [9] C. H. Chen, M. Drees, and J. F. Gunion, Searching for Invisible and Almost Invisible Particles at $e + e$ -Colliders, *Phys. Rev. Lett.* **76**, 2002 (1996).
 - [10] J. L. Feng, T. Moroi, L. Randall, M. Strassler, and S.-f. Su, Discovering Supersymmetry at the Tevatron in Wino LSP Scenarios, *Phys. Rev. Lett.* **83**, 1731 (1999).
 - [11] C. Han, A. Kobakhidze, N. Liu, A. Saavedra, L. Wu, and J. M. Yang, Probing light Higgsinos in natural SUSY from monojet signals at the LHC, *J. High Energy Phys.* **02** (2014) 049.
 - [12] P. Schwaller and J. Zurita, Compressed electroweakino spectra at the LHC, *J. High Energy Phys.* **03** (2014) 060.
 - [13] H. Zhang, Q.-H. Cao, C.-R. Chen, and C. S. Li, Effective dark matter model: Relic density, CDMS II, Fermi LAT and LHC, *J. High Energy Phys.* **08** (2011) 018.
 - [14] M. Beltran, D. Hooper, E. W. Kolb, Z. A. Krusberg, and T. M. Tait, Maverick dark matter at colliders, *J. High Energy Phys.* **09** (2010) 037.
 - [15] S. Gori, S. Jung, L.-T. Wang, and J. D. Wells, Prospects for electroweakino discovery at a 100 TeV hadron collider, *J. High Energy Phys.* **12** (2014) 108.
 - [16] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait, and H.-B. Yu, Constraints on dark matter from colliders, *Phys. Rev. D* **82**, 116010 (2010).
 - [17] A. Rajaraman, W. Shepherd, T. M. P. Tait, and A. M. Wijangco, LHC bounds on interactions of dark matter, *Phys. Rev. D* **84**, 095013 (2011).
 - [18] P. J. Fox, R. Harnik, J. Kopp, and Y. Tsai, Missing energy signatures of dark matter at the LHC, *Phys. Rev. D* **85**, 056011 (2012).
 - [19] G. Aad *et al.* (ATLAS Collaboration), Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector, *J. High Energy Phys.* **04** (2013) 075.
 - [20] S. Chatrchyan *et al.* (CMS Collaboration), Search for dark matter and large extra dimensions in monojet events in pp collisions at $\sqrt{s} = 7 \text{ TeV}$, *J. High Energy Phys.* **09** (2012) 094.
 - [21] H. Baer, A. Mustafayev, and X. Tata, Monojets and mono-photons from light Higgsino pair production at LHC14, *Phys. Rev. D* **89**, 055007 (2014).
 - [22] V. Khachatryan *et al.* (CMS Collaboration), Search for dark matter, extra dimensions, and unparticles in monojet events in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$, [arXiv:1408.3583](#).
 - [23] G. Brooijmans *et al.*, Les Houches 2013: Physics at TeV Colliders: New Physics Working Group Report, [arXiv:1405.1617](#).

- [24] A. Anandakrishnan, L. M. Carpenter, and S. Raby, Degenerate gaugino mass region and mono-boson collider signatures, *Phys. Rev. D* **90**, 055004 (2014).
- [25] D. Barducci, A. Belyaev, A. K. M. Bharucha, W. Porod, and V. Sanz, Uncovering natural supersymmetry via the interplay between the LHC and direct dark matter detection, *J. High Energy Phys.* **07** (2015) 066.
- [26] R. Mahbubani, P. Schwaller, and J. Zurita, Closing the window for compressed dark sectors with disappearing charged tracks, *J. High Energy Phys.* **06** (2017) 119; Erratum **10** (2017) 61.
- [27] A. Berlin, T. Lin, M. Low, and L.-T. Wang, Neutralinos in vector boson fusion at high energy colliders, *Phys. Rev. D* **91**, 115002 (2015).
- [28] D. Egana-Ugrinovic, M. Low, and J. T. Ruderman, Charged fermions below 100 GeV, [arXiv:1801.05432](#).
- [29] H. Baer, V. Barger, and D. Mickelson, Direct and indirect detection of Higgsino-like WIMPs: Concluding the story of electroweak naturalness, *Phys. Lett. B* **726**, 330 (2013).
- [30] E. Aprile *et al.* (XENON Collaboration), First Dark Matter Search Results from the XENON1T Experiment, *Phys. Rev. Lett.* **119**, 181301 (2017).
- [31] J. L. Abelleira Fernandez *et al.* (LHeC Study Group), A large hadron electron collider at CERN: Report on the physics and design concepts for machine and detector, *J. Phys. G* **39**, 075001 (2012).
- [32] T. Han and B. Mellado, Higgs boson searches and the $Hb\bar{b}$ coupling at the LHeC, *Phys. Rev. D* **82**, 016009 (2010).
- [33] S. S. Biswal, R. M. Godbole, B. Mellado, and S. Raychaudhuri, Azimuthal Angle Probe of Anomalous HWW Couplings at a High Energy ep collider, *Phys. Rev. Lett.* **109**, 261801 (2012).
- [34] R. Li, X.-M. Shen, K. Wang, T. Xu, L. Zhang, and G. Zhu, Probing anomalous $WW\gamma$ triple gauge bosons coupling at LHeC, [arXiv:1711.05607](#).
- [35] M. Kuze, Energy-frontier lepton-hadron collisions at CERN: The LHeC and the FCC-eh, *Int. J. Mod. Phys. Conf. Ser.* **46**, 1860081 (2018).
- [36] A. Djouadi, J.-L. Kneur, and G. Moultaka, SUSPECT: A FORTRAN code for the supersymmetric and Higgs particle spectrum in the MSSM, *Comput. Phys. Commun.* **176**, 426 (2007).
- [37] A. Djouadi, M. Muhlleitner, and M. Spira, Decays of supersymmetric particles: The program SUSY-HIT (SUSpect-SdecaY-Hdecay-InTerface), *Acta Phys. Pol.* **B38**, 635 (2007).
- [38] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [39] T. Sjostrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026.
- [40] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaitre, A. Mertens, and M. Selvaggi (Delphes 3 Collaboration), DELPHES 3, a modular framework for fast simulation of a generic collider experiment, *J. High Energy Phys.* **02** (2014) 057.
- [41] C. Degrande, O. Mattelaer, R. Ruiz, and J. Turner, Fully-automated precision predictions for heavy neutrino production mechanisms at hadron colliders, *Phys. Rev. D* **94**, 053002 (2016).
- [42] S. Mondal and S. K. Rai, Polarized window for left-right symmetry and a right-handed neutrino at the large hadron-electron collider, *Phys. Rev. D* **93**, 011702 (2016).
- [43] L. Duarte, G. Zapata, and O. A. Sampayo, Angular and polarization trails from effective interactions of Majorana neutrinos at the LHeC, *Eur. Phys. J. C* **78**, 352 (2018).
- [44] Y.-L. Tang, C. Zhang, and S.-h. Zhu, Invisible Higgs decay at the LHeC, *Phys. Rev. D* **94**, 011702 (2016).
- [45] D. Britzger and M. Klein, Precision electroweak physics at the LHeC and FCC-eh, *Proc. Sci. DIS2017* (2018) 105.
- [46] C. Schwanenberger (LHeC/FCC-eh Study Group), Top and EW physics at the LHeC and the FCC-eh, *Proc. Sci. EPS-HEP2017* (2018) 464.
- [47] S. P. Das, J. Hernandez-Sanchez, S. Moretti, and A. Rosado, Prospects for discovering a light charged higgs boson within the NMSSM at the FCC-eh collider, [arXiv:1806.08361](#).