Long-lived light neutralinos at future $Z$–factories

Zeren Simon Wang$^{1}$ and Kechen Wang$^{2}$

$^1$Physikalisches Institut der Universität Bonn, Bethe Center for Theoretical Physics, Nußallee 12, 53115 Bonn, Germany
$^2$Department of Physics, School of Science, Wuhan University of Technology, 430070 Wuhan, Hubei, China

Future lepton colliders such as the CEPC and the FCC-ee would run as high-luminosity $Z$–boson factories, which offers a unique opportunity to study rare $Z$–decays. We investigate the potential of detecting the lightest neutralinos pair ($\tilde{\chi}^0\tilde{\chi}^0$) produced from $Z$–decays at these colliders in the context of the R-parity violating supersymmetry. Our analysis indicates that when assuming $\text{BR}(Z \rightarrow \tilde{\chi}^0\tilde{\chi}^0) = 10^{-3}$ and $m_{\chi^1} \sim 40$ GeV, the model parameter $\frac{\lambda_{\tilde{\chi}^0\tilde{\chi}^0}}{m_{\tilde{\chi}^0}}$ can be discovered down to as low as $\sim 1.5 \times 10^{-14}$ ($3.9 \times 10^{-14}$) at the FCC-ee (CEPC) with 150 (16) ab$^{-1}$ integrated luminosity. These limits exceed the sensitivity reaches of some future experiments at the LHC.

I. INTRODUCTION

Long-lived particles (LLPs) arise in many physics scenarios beyond the Standard Model (BSM) and are often motivated by dark matter or the massive neutrinos. While at the Large Hadron Collider (LHC), efforts have been mostly focused on searching for prompt decays of new heavy particles, it is also legitimate to look for exotic signatures of displaced vertices stemming from LLPs. For reviews, see [1, 2].

Supersymmetry [3, 4] (SUSY) has been one of the leading candidates of BSM physics since it offers elegant solutions to many important fundamental physics problems such as the hierarchy problem [5, 6]. The mass eigenstates of electroweak gauginos predicted by SUSY models are known as neutralinos and charginos. While lower mass bounds on charginos have been derived from the LEP data [7], the limits on the mass of the lightest neutralino are much looser. If the GUT-motivated relation between the gaugino mass terms $M_1$ and $M_2$, $M_1 \approx 1/2 M_2$, is not imposed and the dark matter in the universe does not comprise of the lightest neutralino, $O(10)$ GeV-scale and even massless neutralinos, which are necessarily binolike, are still allowed by experimental and observational data [8–15], though they must decay with a lifetime much shorter than the age of the universe so as to be consistent with the dark matter density.

R-parity-violating SUSY (RPV-SUSY) (see Refs. [16–18] for reviews) naturally leads to decays of the lightest neutralino via RPV couplings, allowing for light neutralinos of $O$(GeV) mass. The smallness of the neutralino mass and RPV couplings renders the lightest neutralino long lived, potentially resulting in displaced vertex signatures at colliders. Such signatures may be observed at a variety of experiments including the fixed target experiment SHIP [19], the LHC experiment ATLAS [20] or some proposed future detectors: CODEX-b [21], MATHUSLA [22], FASER [23] and AL3X [24]. Studies of the light neutralinos as LLPs decaying via RPV couplings in these experiments have been performed in Refs. [25–28]. In these references, two production mechanisms of the lightest neutralino have been taken into account: 1) single production from rare $B$– and $D$–meson decays via RPV couplings, 2) pair production from rare $Z$–boson decays via the Higgsino components. In this study, we focus on the latter in the context of future lepton colliders running at the $Z$–pole.

While the LHC is planned to be upgraded to high-luminosity LHC (HL-LHC) in the coming years, several next-generation new colliders have been proposed and are under development. Among them are the Circular Electron Positron Collider (CEPC) [29, 30] to be built in China and the Future Circular Collider (FCC) [31] at CERN as the successor of the LHC. The FCC would, as currently planned, start with an electron-positron collision mode, known as the FCC-ee [32]. Both the CEPC and the FCC-ee would operate at the $Z$–pole (with center-of-mass energy $\sqrt{s} = 91.2$ GeV) for 2-4 years, producing a terascale number of $Z$–bosons, exceeding the HL-LHC by approximately one order of magnitude and LEP by $\sim 5$ orders of magnitude. As LLPs are usually very feebly coupled to SM particles, their production cross sections at colliders are tiny. Such a large number of $Z$–bosons produced at the CEPC and the FCC-ee could therefore significantly enhance the discovery sensitivities of LLPs produced from rare $Z$–boson decays.
Studies have investigated the discovery potential of future lepton colliders for a variety of new-physics and SM scenarios related to $Z$–properties \cite{33–55}. In the present study we fill a gap by investigating the rare decays of the $Z$–bosons into a pair of neutralinos ($Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$) at future $Z$–factories at the CEPC and the FCC-ee. As the official parameters for $Z$–pole running are not released yet, another two proposed future $e^+e^-$ colliders, ILC (International Linear Collider) \cite{56} and CLIC (Compact Linear Collider) \cite{57} are not considered in this study.

This paper is organized as follows. We explain the physics accounting for the decay processes: $Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ and neutralino decays in Sec. II. In Sec. III we introduce the future $Z$–boson factories which we consider, i.e. the CEPC and the FCC-ee, and illustrate the fiducial volume of their detectors which we use. The simulation procedure with formulas which we use to estimate the number of neutralino decays in the detector is also presented in this section. In Sec. IV we show our numerical results and compare the sensitivity reaches at the CEPC and the FCC-ee with that of some proposed LHC experiments. We summarize in Sec. V.

II. PAIR PRODUCTION OF LIGHT NEUTRALINOS AND RPV SUPERSYMMETRY

In this section we explain the production and the decay mechanisms of the lightest neutralino which are considered in this paper. The lightest neutralino can be produced in a variety of physics processes. In this paper, we focus on their pair production from on-shell $Z$–boson decays, taking advantage of the large $Z$–boson production at the future high-luminosity lepton colliders. A $Z$–boson is coupled to two lightest neutralinos via the Higgsino components, leading to its decay to a pair of neutralinos, if $m_{\tilde{\chi}_1^0} < m_Z/2$. While light neutralinos are necessarily binolike and include only small Higgsino components, the sufficiently copious production of the $Z$–bosons may still compensate for it. In Ref. \cite{22}, it is discussed that the current lower limit on the Higgsino parameter $\mu$ in the supersymmetry models, obtained in LEP \cite{7} and ATLAS \cite{58} experiments, points to a calculated $\text{BR}(Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$ just below the experimental upper limit $\sim 0.1\%$ which is derived from the invisible width of the $Z$–boson measured at LEP \cite{7}. In this study, we treat $\text{BR}(Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$ hence as an independent parameter, disregarding the SUSY parameters affecting $\Gamma(Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$.

In the Minimal Supersymmetric Standard Model (MSSM) \cite{3, 59}, an implicit ingredient is R-parity. R-parity conservation renders the lightest neutralino stable if it is the lightest supersymmetric particle (LSP) and it serves as a cold DM candidate. However, it is equally legitimate to consider the R-parity violating MSSM (RPV-MSSM) \cite{60} and study its implications in collider searches. With R-parity broken, the lightest neutralino decays to SM particles and cannot be considered as a DM candidate. In this paper, we assume R-parity violation and investigate the potential of detecting the lightest neutralino of $O(1-10 \text{ GeV})$ mass via its decay products. Since we will consider neutralinos decay to a kaon, we do not study neutralinos of mass below the kaon mass $\sim 500 \text{ MeV}$. The RPV part of the full superpotential in the RPV-MSSM, $W_{\text{RPV}}$, can be written as:

$$ W_{\text{RPV}} = \mu H_u \cdot L_i + \frac{1}{2} \lambda_{ijk} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k, $$

(1)

where the first three sets of operators violate lepton number and the last set of operators violate baryon number. Allowing all these terms to be nonvanishing would lead to a dangerous proton decay rate. Therefore, one may instead impose certain discrete symmetries, forbidding a subset of all terms and avoiding thus the proton decay rate problem \cite{61–64}. In this study, we focus on the $\lambda' L \cdot Q \bar{D}$ operators. For $m_{\tilde{\chi}_1^0} < m_Z/2$ and small $\lambda'$ couplings, the lightest neutralino becomes long-lived and decays after having travelled a macroscopic distance.

III. SIMULATION AND DETECTORS

In this section, we describe our simulation procedure and introduce the detector setups. The FCC-ee is planned to run at the $Z$–pole for a total of 4 years with the physics goal of $150 \text{ ab}^{-1}$ integrated luminosity with 2 interaction points (IPs), which would produce in total $5 \times 10^{12}$ $Z$–bosons \cite{32}. The 10-year operation plan of the CEPC includes two years of $Z$–pole period, expected to generate a total of $16 \text{ ab}^{-1}$ integrated luminosity with 2 IPs, projected to produce $7 \times 10^{11}$ $Z$–bosons \cite{65}. We express thus the total number of neutralinos produced as follows:

$$ N_{\tilde{\chi}_1^0} = 2 N_Z \cdot \text{BR}(Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0), $$

(2)

where $N_Z$ denotes the total number of produced $Z$–bosons and a factor of 2 accounts for the fact that each

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1 There is no tension with respect to the experimental bound on the Higgs invisible width \cite{25}, either.
Z-boson decays to two neutralinos. In order to determine the average decay probability of the neutralinos in the fiducial volume of the detectors, we make use of the Monte-Carlo (MC) simulation tool Pythia 8.205 [68, 67]. Pythia is implemented with the module “New-Gauge-Boson Processes” which allows to generate pure $Z'$-bosons from electron-positron scattering. By setting the mass of the $Z'$-bosons to be the same as the Standard Model (SM) $Z$-boson and setting it to decay solely to a pair of new fermions, we are able to extract the kinematics of the processes $e^+e^- \rightarrow Z, \ Z \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$ after simulating 10 thousand events for each point in the parameter space. The average decay probability in the fiducial volume can then be calculated as

$$\langle P[\tilde{\chi}^0_1 \text{ in f.v.}] \rangle = \frac{1}{N_{\text{MC}}^{\tilde{\chi}^0_1}} \sum_{i=1}^{N_{\text{MC}}^{\tilde{\chi}^0_1}} P[\tilde{\chi}^0_1; \text{in f.v.}],$$

where “f.v.” stands for “fiducial volume” and $N_{\text{MC}}^{\tilde{\chi}^0_1}$ is the total number of MC-simulated neutralinos. The computation of the individual decay probability $P[\tilde{\chi}^0_1; \text{in f.v.}]$ depends on the detector geometries and will hence be detailed later when we introduce the detector setups. We proceed to write the observed decays of the neutralinos in the fiducial volume as

$$N_{\text{obs}}^{\tilde{\chi}^0_1} = N_{\tilde{\chi}^0_1} \cdot \langle P[\tilde{\chi}^0_1 \text{ in f.v.}] \rangle \cdot \text{BR}(\tilde{\chi}^0_1 \rightarrow \text{final state}),$$

where BR$(\tilde{\chi}^0_1 \rightarrow \text{final state})$ is the branching ratio of the $\tilde{\chi}^0_1$ decays to the final states that we consider.

For calculating the individual decay probability, i.e. $P[\tilde{\chi}^0_1; \text{in f.v.}]$, we need to take into account the detector setups. The CEPC is equipped with a baseline detector concept [30]. In its inner region, there are a silicon pixel vertex detector, a silicon inner tracker, and a Time Projection Chamber (TPC) which reconstructs the tracks of objects. For the FCC-ee, two detector designs have been proposed, namely the “CLIC-Like Detector” (CLD) [65] and the “International Detector for Electron-positron Accelerators” (IDEA) [2]. As the name says, the CLD design is modified from the CLIC detector after taking into account the FCC-ee specificities. Both detector designs of the FCC-ee employ a setup similar to that of the CEPC baseline detector. In this paper, we consider the fiducial volume of the detectors as consisting of the vertex detector and the tracker. This choice is conservative and ensures that a potential electron produced from a neutralino decay could still be reconstructed. Since all of these three designs are cylindrically symmetric around the beam axis with the IP at the center, we show in Fig. 1 a general side-view sketch of the detector fiducial volume, where $R_I$ is the inner radius of the vertex detector, and $R_O$ and $L_d$ are respectively the outer radius and the half length of the tracker. Although the various detectors share the same topology, they are designed with different geometrical parameters ($R_I, R_O, L_d$) and they have different integrated luminosities of $Z$-boson production as discussed above. We summarize the relevant information in Table I.

The individual decay probability of the neutralinos inside the fiducial volume of detectors is estimated with the following formulas:

$$P[\tilde{\chi}^0_1; \text{in f.v.}] = e^{-L_i/\lambda^r_i} \cdot (1 - e^{-L'_i/\lambda^r_i}),$$

$$L_i = \text{min}(L_d, |R_O/\tan \theta_i|),$$

$$L'_i = \text{min}(L_d, |R_O/\tan \theta_i| - L_i),$$

$$\lambda^r_i = \beta^r_i \gamma_i / \Gamma_{\text{tot}}(\tilde{\chi}^0_1),$$

where $\theta_i$ is the polar angle of an individual neutralino.

![FIG. 1. General side-view sketch of the fiducial volumes of detector designs for the CEPC and the FCC-ee, with definition of distances and angles used in text. The detectors are cylindrically symmetric around the beam axis. IP denotes the interaction point at the CEPC or the FCC-ee. The dashed line depicts an example neutralino track, with polar angle $\theta_i$.](image-url)

| Detector        | $R_I$ [mm] | $R_O$ [mm] | $L_d$ [mm] | $N_Z$    |
|-----------------|-----------|-----------|-----------|----------|
| CEPC            | 16        | 1.8       | 2.35      | $7 \times 10^{11}$ |
| FCC-ee CLD      | 17        | 2.1       | 2.2       | $5 \times 10^{12}$ |
| FCC-ee IDEA     | 17        | 2.0       | 2.0       | $5 \times 10^{12}$ |

TABLE I. Summary of parameters of the fiducial volume of each detector. $N_Z$ is the total number of $Z$-bosons expected to be produced. The parameters of the CEPC baseline detector are extracted from Refs. [30, 65] while the geometries of the CLD and the IDEA detectors of the FCC-ee are reproduced from Ref. [32].

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2 The CEPC also takes IDEA as an alternative detector concept. [30]
\( (\chi_0^0) \), \( \Gamma_{tot}(\chi_0^0) \) is the total decay width of the neutralino, \( \beta_i^e \) is the velocity of \( (\chi_0^0) \), along the beam axis, and \( \gamma_i \) is its Lorentz boost factor.

In this study, we assume 100% detector efficiency with no background event. We consider 3 signal events are sufficient for discovery of a long-lived neutralino.

Before we present sensitivity estimates of long-lived neutralinos, we first present the average decay probabilities for 1 GeV neutralinos at future lepton colliders and compare them with that of AL3X and MATHUSLA given in Ref. [27] for the same physics process \( Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \) and neutralino mass. The average decay probability in the fiducial volume \( \langle P[\chi_1^0 \text{ in f.v.}] \rangle \) is also known as fiducial efficiency, following the convention used in Refs. [24, 27].

We denote the fiducial efficiency for neutralinos pair produced from \( Z \)–decays as \( \epsilon_{\text{fid}}^{Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0} \) and show its values at various experiments in Table 11.

| \( Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \), ct [m] | CEPC | FCC-ee CLD | FCC-ee IDEA |
|-------------------------------------------------|------|-------------|-------------|
| \( \epsilon_{\text{fid}}^{Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0} \) | 4.78 \times 10^{-2} | 5.16 \times 10^{-2} | 4.83 \times 10^{-2} |
| \( \epsilon_{\text{fid}}^{Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0} \) | AL3X | MATHUSLA | 8.0 \times 10^{-4} |

TABLE II. List of the fiducial efficiencies \( \epsilon_{\text{fid}}^{Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0} \) multiplied by ct in the unit of meter for neutralinos of mass 1 GeV pair produced from \( Z \)–boson decays in the AL3X, MATHUSLA, CEPC and FCC-ee detectors, for the boosted decay length much larger than the distance between the detector and the IP. The numbers for the cases of AL3X and MATHUSLA are reproduced from Ref. [27].

We work in the limit that the boosted decay length \( \beta \gamma c t \) of the neutralino is much larger than the distance from the IP to the detector, such that we are allowed to present \( \epsilon_{\text{fid}}^{Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0} \) with a linear dependence on ct, though in the calculation we use the exact formula. The typical values of \( \beta \gamma \) of 1 GeV neutralinos produced from \( Z \)–bosons at the CEPC and the FCC-ee are \( \sim 45 \). Therefore, our results are legitimate for \( ct \geq 1 \) m for both the CEPC and the FCC-ee. We find that for large decay length of neutralinos, the detectors of the future lepton colliders show a similar fiducial efficiency that is larger than that of AL3X and MATHUSLA in this benchmark scenario. This better efficiency is partly due to the almost full coverage of polar and azimuthal angle of the detectors at lepton colliders, and partly due to the fact that the \( Z \)–pole center-of-mass energy leads to the produced \( Z \)–bosons almost stationary and hence their decay products, i.e. the neutralinos, less boosted in the forward direction. The similarity of the fiducial efficiency between the CEPC baseline detector and the FCC-ee CLD/IDEA, is consistent with the closeness of their geometrical parameters listed in Table 11.

IV. NUMERICAL RESULTS

In this section, we present our numerical results. Following the choice made in Refs. [23, 27], we consider two benchmark values for \( \text{BR}(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \) the experimental upper limit \( 10^{-3} \) and a more conservative choice \( 10^{-5} \). We choose to require \( \lambda'_{112} L_1 \cdot Q_1 D_2 \) as the only nonvanishing RPV operator, which leads to the lightest neutralino decays to SM particles via a sfermion exchange. The decay mode depends on the neutralino mass. For \( m_{\chi_1^0} \) of \( \mathcal{O}(\text{GeV}) \) mass, the hadronization effects are important and

\[
\chi_1^0 \rightarrow \begin{cases} (K_L^0, K_S^0, K^*) \ (\nu_e, \bar{\nu}_e) \ , \ \text{invisible mode}, \\ (K^\pm, K^{* \pm}) + e^\mp \ , \ \text{visible mode}, \end{cases}
\]  

while heavier neutralinos would decay to two jets and an electron/missing energy (visible/invisible mode). For neutralinos lighter than \( \sim 3.5 \) GeV we calculate the neutralino decay width via modes given in Eq. 7 with two-body decay formulas given in Ref. [28] while for larger masses we use the three-body decay \( (\chi_1^0 \rightarrow e^\mp / \nu_e + jj) \) results given by SPheno 4.0.3 [39, 70]. In this study, when calculating \( N_{\text{obs}}^{\tilde{\chi}_1^0 \tilde{\chi}_1^0} \) with Eq. 4 we consider two cases for the \( \tilde{\chi}_1^0 \) decays: (i) all the final states of decays can be identified so that \( \text{BR}(\tilde{\chi}_1^0 \rightarrow \text{final state}) = 100\% \); (ii) only the visible/charged final states of decays can be identified so that \( \text{BR}(\tilde{\chi}_1^0 \rightarrow \text{final state}) = \text{BR}(\tilde{\chi}_1^0 \rightarrow \text{visible mode only}). \) Since the visible/charged products are usually easier to be reconstructed in the detectors, the latter is more conservative.

In Fig. 2, we present two plots of 3-event contour curves in the \( \chi_1^0 / m_{\chi_1^0} \) plane for the two benchmark values of \( \text{BR}(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \), respectively. For simplicity, we assume all the sfermions are degenerate in mass during the evaluation. We show with three hashed horizontal lines the current upper limit on \( \lambda'_{112} \) for three benchmark sfermion mass values: 250 GeV, 1 TeV and 5 TeV, extracted from Ref. [71]:

\[
\lambda'_{112} < 0.03 \frac{m_{\tilde{\chi}_1^0}}{100 \text{ GeV}}.
\]  

\( ^3 \) The numbers of \( \text{BR}(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \) refer to the case when \( m_{\chi_1^0} \ll m_Z \). For larger neutralino masses, we have taken into account the phase space suppression effect in our evaluation.
Since the various detectors of the $e^+e^-$ colliders possess a similar fiducial efficiency, we show isocurves of the CEPC baseline detector and the FCC-ee IDEA detector only. The green (grey) solid lines show the limits at the FCC-ee (CEPC) with the IDEA (baseline) detector design and 150 (16) ab$^{-1}$ integrated luminosity when including all decay modes of the lightest neutralinos, while the dashed curves are limits when including only the visible/charged decay modes. We overlap the plots with estimates from other experiments at the LHC: AL3X, CODEX-b, FASER and MATHUSLA, extracted from Refs. [25, 27]. We observe that all detectors may have a sensitivity reach in $\frac{\lambda_{112}}{m_f^{1/2}}$ for the whole range of the neutralino mass orders of magnitude smaller than the current RPV upper bounds. While at the LHC, MATHUSLA has the smallest lower reach in $\frac{\lambda_{112}}{m_f^{1/2}}$ and AL3X has the largest upper reach, the future lepton colliders may enclose all the sensitive parameter space covered by the future LHC experiments. This is mainly because a terascale number of $Z-$bosons can be produced at the future lepton colliders and also because the detector setup of lepton colliders covers almost the full solid angles. At the small-value regime, when $m_{\chi_1^0} \sim 40$ GeV and $\text{BR}(Z \to \chi_{1/0}^0) = 10^{-3}$, the FCC-ee can reach as low as $1.5 \times 10^{-14}$ in $\frac{\lambda_{112}}{m_f^{1/2}}$ with 150 ab$^{-1}$ luminosity, while the CEPC reaches $3.9 \times 10^{-14}$ with luminosity of 16 ab$^{-1}$. Since their fiducial efficiencies are similar, this difference in sensitivities is almost fully due to the difference in luminosities. For $\text{BR}(Z \to \chi_{1/0}^0) = 10^{-5}$, the FCC-ee’s lower reach in $\frac{\lambda_{112}}{m_f^{1/2}}$ can still be down to $1.5 \times 10^{-13}$, and the upper reach of the FCC-ee and the CEPC does not change much compared to the larger $\text{BR}(Z \to \chi_{1/0}^0)$ case. Note in both plots, the lower bound of the CEPC/FCC-ee dashed curves, which indicates the limits when including only visible/charged decay modes of $\chi_0^0$, is only slightly worse than the solid isocurves. This is because in almost the whole kinematically allowed angles. At the small-value regime, when $m_{\chi_1^0} \sim 40$ GeV and $\text{BR}(Z \to \chi_{1/0}^0) = 10^{-3}$, the FCC-ee can reach as low as $1.5 \times 10^{-14}$ in $\frac{\lambda_{112}}{m_f^{1/2}}$ with 150 ab$^{-1}$ luminosity, while the CEPC reaches $3.9 \times 10^{-14}$ with luminosity of 16 ab$^{-1}$. Since their fiducial efficiencies are similar, this difference in sensitivities is almost fully due to the difference in luminosities. For $\text{BR}(Z \to \chi_{1/0}^0) = 10^{-5}$, the FCC-ee’s lower reach in $\frac{\lambda_{112}}{m_f^{1/2}}$ can still be down to $1.5 \times 10^{-13}$, and the upper reach of the FCC-ee and the CEPC does not change much compared to the larger $\text{BR}(Z \to \chi_{1/0}^0)$ case. Note in both plots, the lower bound of the CEPC/FCC-ee dashed curves, which indicates the limits when including only visible/charged decay modes of $\chi_0^0$, is only slightly worse than the solid isocurves. This is because in almost the whole kinematically allowed mass range (except when $m_{K^+} < m_{\chi_0^0} < m_{K^0_{l\ell\nu}}$), the visible decay branching ratio of the $\chi_0^0$ is approximately 0.5.

V. CONCLUSIONS

In this study, we estimate the sensitivity reach of future high-luminosity $Z-$factories when detecting the lightest neutralinos pair produced from on-shell $Z-$bosons via their Higgsino components. The results are shown in Fig. 2. The two plots in the $\frac{\lambda_{112}}{m_f^{1/2}}$ vs. $m_{\chi_1^0}$ plane correspond to two benchmark values of $\text{BR}(Z \to \chi_{1/0}^0)$: the experimental upper constraint $10^{-3}$ and a more conservative choice $10^{-5}$. We find that the $Z$-pole running mode at future lepton colliders has a sensitivity reach in $\frac{\lambda_{112}}{m_f^{1/2}}$ orders of magnitude smaller than the current RPV upper limits for the mass range $1$ GeV $\lesssim m_{\chi_1^0} \lesssim m_Z/2$. When

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{The sensitivity estimate of the CEPC (grey) and the FCC-ee (green) presented in the 2D plane of $\Lambda_{112}/m_f^{1/2}$ vs. $m_{\chi_1^0}$ for two different benchmark values of $\text{BR}(Z \to \chi_{1/0}^0)$, respectively. The solid contour curves correspond to three decay events in the fiducial volume when considering all decay modes of $\chi_1^0$, while the dashed lines include only visible/charged decay modes ($K^{\pm}\to x^\pm, e^\pm u\bar{u}$). The estimates for experiments at the LHC: AL3X, CODEX-b, FASER and MATHUSLA, are reproduced from Refs. [25, 27]. The hashed horizontal lines correspond to the current RPV bounds on the single coupling $\lambda_{112}$ [71] for three different degenerate sfermion masses.}
\end{figure}
Our results show that the unprecedentedly large number of $Z^0$-bosons expected to be produced at the future $Z^0$-factories may serve as a very sensitive probe of exotic decays of $Z^0$-bosons. Our work on the lightest neutralinos in the context of the RPV-SUSY complements the other studies in the literature on rare $Z^0$-decays. In this particular physics case, we find that the next-generation $e^+e^-$-colliders may outperform the future detectors at the LHC.

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