Higgsino Dark Matter or Not:
Role of Disappearing Track Searches at the LHC and Future Colliders

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Higgsino in supersymmetric standard models is known to be a promising candidate for dark matter in the Universe. Its phenomenological property is strongly affected by the gaugino fraction in the Higgsino-like state. If this is sizable, in other words, if gaugino masses are less than O(10) TeV, we may probe the Higgsino dark matter in future non-accelerator experiments such as dark matter direct searches and measurements of electric dipole moments. On the other hand, if gauginos are much heavier, then it is hard to search for Higgsino in these experiments. In this case, due to a lack of gaugino components, the mass difference between the neutral and charged Higgsinos is uniquely determined by electroweak interactions to be around 350 MeV, which makes the heavier charged state rather long-lived, with a decay length of about 1 cm. In this letter, we argue that a charged particle with a flight length of $O(1) \text{ cm}$ can be probed in disappearing-track searches if we require only two hits in the pixel detector. Even in this case, we can reduce background events with the help of the displaced-vertex reconstruction technique. We study the prospects of this search strategy at the LHC and future colliders for the Higgsino dark matter scenario. It is found that an almost pure Higgsino is indeed within the reach of the future 33 TeV collider experiments. We then discuss that the interplay among collider and non-accelerator experiments plays a crucial role in testing the Higgsino dark matter scenarios. Our strategy for disappearing-track searches can also enlarge the discovery potential of pure wino dark matter as well as other electroweak-charged dark matter candidates.

INTRODUCTION

The strongest motivation for new physics beyond the Standard Model (SM) is dark matter (DM) in the Universe. Among a variety of DM candidates, weakly-interacting massive particles (WIMPs) offer the most attractive paradigm to explain the observed DM density: $\Omega_{DM}h^2 \approx 0.12$ [1].

Higgsino in a supersymmetric (SUSY) extension of the SM, which is an SU(2) L doublet fermion with hypercharge 1/2, is a prime example of WIMP DM. The neutral component of Higgsino can mix with the neutral electroweak-inos, bino and wino, and if the dominant portion of the lightest state is Higgsino, then it is called a Higgsino-like state. The amount of the gaugino fractions in a Higgsino-like state strongly affects its phenomenological property. If the masses of SUSY particles other than Higgsino, especially those of the electroweak-inos, are in the multi-TeV region, then the gaugino fraction is quite suppressed and thus the lightest SUSY particle (LSP) can be regarded as an almost pure Higgsino. Such a “split” mass spectrum has various phenomenological and theoretical advantages [2, 3], and thus attracts wide attention [4–8] especially after the discovery of the 125 GeV Higgs boson [9]. The gaugino fraction may be small, but non-accelerator experiments such as DM direct searches and measurements of the electric dipole moments (EDMs) can probe it. As we discuss below, even the gauginos heavier than O(10) TeV can be probed in future experiments [10].

Another motivation for SU(2) L doublet DM is provided by a bottom-up approach. Classifying possible DM candidates in terms of their quantum numbers, we find that an SU(2) L doublet with hypercharge 1/2 or triplet with hypercharge zero has minimal non-zero electric charge to accommodate electrically neutral DM. Hence, SU(2) L doublet DM is a promising target even though we do not consider SUSY as new physics beyond the SM.

However, SU(2) L doublet fermion DM as it is, which corresponds to completely pure Higgsino DM, has already been excluded by DM direct detection experiments. In this case, the DM is a Dirac fermion, and thus has vector interactions with quarks via the Z-boson exchange, which results in a too large DM-nucleon spin-independent (SI) scattering cross section [11]. To avoid this constraint, we need some effects induced at higher energies that generate a mass split between the Dirac DM components, $\Delta m_0$, to divide it into two Majorana fermions $\tilde{\chi}_1^\pm$, which do not have vector interactions. To assure this, we need $\Delta m_0 \gtrsim O(100) \text{ keV}$ [10]; otherwise, the inelastic scattering process $\chi_1^+N \rightarrow \chi_1^0N$ ($N$ denotes a nucleon) instead gives a too large scattering cross section. Generically, the interactions that yield $\Delta m_0$ should be induced at a scale $\Lambda \lesssim 10^9 \text{ GeV}$ to give $\Delta m_0 \gtrsim O(100) \text{ keV}$ [10, 12]. Such effects are actually similar to the contribution of gaugino fractions to the property of the Higgsino DM. Thus, this SU(2) L DM can also be probed in future
non-accelerator experiments if the scale $\Lambda$ is relatively low. Notice that bounds from these experiments give a lower limit on $\Lambda$, while the inelastic-scattering bound gives an upper limit.

We however find that there is a range of $\Lambda$ which is high enough for the SU(2)$_L$ doublet fermion DM to be beyond the reach of these experiments but low enough to give $\Delta m_0 \gtrsim \mathcal{O}(100)$ keV [10,12]—correspondingly, we can find appropriately large gaugino masses with which the same situation is realized for Higgsino DM. This situation is completely viable, as the thermal relic abundance of pure Higgsino DM agrees with $\Omega_{\text{DM}} h^2 \sim 0.12$ if the Higgsino DM mass $m_{\text{DM}}$ is $\sim 1.1$ TeV [13]. A lighter mass region is also promising since there may be non-thermal contribution from high-energy physics, such as late-time decay of gravitinos. Therefore, it is quite important to consider an alternative strategy to probe such almost pure Higgsino DM.

It has been known that almost pure Higgsino is also difficult to probe at hadron colliders [14,15]. In this case, not only the neutral states $\tilde{\chi}^0_{1,2}$, but also the charged states $\tilde{\chi}^\pm$ are almost degenerate in mass at tree level. The charged states acquire a slightly heavier mass via the electroweak loop corrections, but still the mass splitting is as small as $\sim 350$ MeV. Due to this small mass splitting, the decay products of $\tilde{\chi}^\pm$ have soft momenta, which makes it hard to detect them. For this reason, the current LHC searches for Higgsinos rely only on mono-jet or mono-$X$ signals, which give poor constraints on Higgsinos due to large SM background (BG). Even a 100 TeV collider can test a small portion of parameter space in the Higgsino DM scenario [10].

However, this small mass splitting may offer a different strategy to probe Higgsinos at colliders. Because of the small mass splitting, the charged Higgsino has rather long lifetime—as it turns out, a mass difference of $\sim 350$ MeV results in a decay length of $\sim 1$ cm. It is therefore interesting to ask whether charged tracks with an $\mathcal{O}(1)$ cm length can be detected at collider experiments. In this letter, we address this question by taking into account potential improvements in disappearing track searches with fully optimized inner detectors at the LHC and a future 33 TeV collider. Such an improvement may also increase the discovery potential of pure wino DM; thus, we also consider the wino DM case for comparison.

**HIGGSINO PHENOMENOLOGY**

To begin with, we discuss the mass spectrum of Higgsino components, paying particular attention to the gaugino mass effects on it. The masses of these components split after the electroweak symmetry is broken. These mass splittings are induced by the tree-level mixing with the electroweak-inos, as well as the electroweak radiative corrections. We here assume that the masses of the electroweak-inos are much larger than the TeV scale. At one-loop level, the electroweak-loop contribution to the charged-neutral mass splitting is given by

$$\Delta m_{\text{rad}} \simeq \frac{1}{2} \alpha_2 m_Z \sin^2 \theta_w \left( 1 - \frac{3m_Z}{2m_{\tilde{\chi}^\pm}} \right),$$

(1)

where $\alpha_2 \equiv g_2^2/4\pi$ with $g_2$ the SU(2)$_L$ gauge coupling constant, $m_Z$ is the Z-boson mass, $\theta_w$ is the Weinberg angle, and $m_{\tilde{\chi}^\pm}$ is the charged Higgsino mass. We find $\alpha_2 m_Z \sin^2 \theta_w/2 \simeq 355$ MeV. After all, the mass difference between the neutral components, $\Delta m_0$, and that between the charged component and the Higgsino LSP, $\Delta m_+$, are respectively given by

$$\Delta m_0 \simeq \frac{v^2}{4|\mu|} |X| \Delta X,$$

(2)

$$\Delta m_+ = \Delta m_{\text{tree}} + \Delta m_{\text{rad}},$$

(3)

with

$$\Delta m_{\text{tree}} \simeq \frac{v^2}{8|\mu|} \left[ |X| \Delta X + \sin 2\beta \Re(Y) \right],$$

(4)

where $v \simeq 246$ GeV is the Higgs VEV, $\mu$ is the Higgsino mass, and $\tan \beta \equiv (H_u)/(H_d)$ with $H_u$ and $H_d$ being the up- and down-type Higgs fields, respectively,

$$X \equiv \mu^* \left( \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2} \right), \quad Y \equiv \mu^* \left( \frac{g_1^2}{M_1} - \frac{g_2^2}{M_2} \right).$$

(5)

$\Delta X \equiv \sqrt{1 - \sin^2 \theta_X \sin^2 \theta_W} - 2\beta$, where $\Delta X \equiv \arg(X)$, $M_1$ ($M_2$) is the bino (wino) mass, and $g_1$ is the U(1) gauge coupling. As we discussed above, $\Delta m_0 \gtrsim \mathcal{O}(100)$ keV is required to suppress the SI inelastic DM-nucleon scattering via the Z-boson exchange.

Even in this case, the Higgsino-nucleon SI scattering occurs via the Higgs-boson exchange process induced by the electroweak-ino mixing. The resultant SI scattering cross section with a proton, for instance, is evaluated as

$$\sigma_{\text{SI}}^{(p)} \simeq \frac{4m^2_{\text{SI}} m_p^2}{\pi v^2 m_h^4} F^2 \Delta m_{\text{tree}}^2 F(X,Y)^2,$$

(6)

with

$$F(X,Y) = \frac{|X| \Delta X + \sin 2\beta \Re(X)}{|X| \Delta X + \sin 2\beta \Re(Y)},$$

(7)

where $m_p$ is the proton mass, $m_h \simeq 125$ GeV is the Higgs mass, $m_{\text{DM}} \equiv m_p m_{\text{DM}}/(m_p + m_{\text{DM}})$, $F_{\text{mat}} \equiv \sum_{q=u,d,s} f_T q + 2f_T c/9$, $f_T c \equiv 1 - \sum_{q=u,d,s} f_T q$, and the mass fractions $f_T$ are computed with a QCD lattice simulation as $f_T = 0.0149$, $f_T = 0.0234$, and $f_T = 0.0440$ [17]. In the derivation of Eq. (6), we have dropped the electroweak-loop contribution to the SI scattering cross section, which is found to be negligible for almost pure
Higgsino DM [18]. Using this expression, we find a relation between the SI scattering cross section and the tree-level charged-neutral mass splitting $\Delta m_{\text{tree}}$:

$$\Delta m_{\text{tree}} \approx \frac{170 \text{ MeV}}{F(X,Y)} \left( \frac{m_p}{m_{\text{red}}} \right) \left( \frac{\sigma_{SI}^{(p)}}{10^{-48} \text{ cm}^2} \right)^{\frac{1}{3}} .$$  

(8)

This equation shows that for a value of $\sigma_{SI}^{(p)}$ that exceeds the neutrino floor [19], which lies around $10^{-48} \text{ cm}^2$ for a DM mass of $O(100) \text{ GeV}$, the charged-neutral mass splitting is expected to be larger than a few hundred MeV.

In general, the electroweak-ino contribution yields CP violation, which then induces EDMs of the SM particles. Currently, the electron EDM, $d_e$, is most stringently restricted: $|d_e| < 8.7 \times 10^{-29} \text{ cm}$ [20]. The Higgsino contribution to the electron EDM is induced by the two-loop Barr–Zee diagrams [21, 22] and given by the sum $d_e = d_e^{\gamma\gamma} + d_e^{hZ} + d_e^{WW}$, where $d_e^{\gamma\gamma}$, $d_e^{hZ}$, and $d_e^{WW}$ are the Higgs-γ, Higgs-Z, and WW loop contributions, respectively. We find [10]

$$d_e^{\gamma\gamma} \approx \frac{e g_2^2 m_e}{(4\pi)^4 4\mu l_1} \cdot \frac{8 \sin^2 \theta_w f_0^h}{X|X + \sin 2\beta \Re(Y)} \Delta m_{\text{tree}} ,$$

$$d_e^{hZ} \approx \frac{e g_2^2 m_e}{(4\pi)^4 4\mu l_2} \cdot \frac{f_0^W \Im(Y)}{X|X + \sin 2\beta \Re(Y)} \Delta m_{\text{tree}} ,$$

$$d_e^{WW} \approx \frac{e g_2^2 m_e}{(4\pi)^4 4\mu l_3} \cdot \frac{f_0^W \Im(Y)}{X|X + \sin 2\beta \Re(Y)} \Delta m_{\text{tree}} ,$$

(9)

with $f_0^{h,W} = f_0(|\mu|^2/m_{h,W}^2)$ and

$$f_0(r) = r \int_0^1 \frac{dx}{r-x(1-x)} \ln \left( \frac{r}{x(1-x)} \right) ,$$  

(10)

where $m_e$ is the electron mass, $m_W$ is the W-boson mass, and $e$ is the positron charge. For the electron EDM, $d_e^{hZ}$ is always subdominant due to an accidentally small numerical factor [10]. Using this expression, we can again relate $d_e$ with the mass splitting $\Delta m_{\text{tree}}$ as

$$d_e \approx 3 \times 10^{-31} \cdot \sin(2\beta) \cdot \frac{1 \text{ TeV}}{|\mu|} \left( \frac{\Delta m_{\text{tree}}}{100 \text{ MeV}} \right) F_{ph} \text{ ecm} ,$$

(11)

where $F_{ph}$ is the sum of the factors in the parentheses in Eq. (9). By noting that future experiments may probe $d_e \sim 10^{-31} \text{ ecm}$ [23, 24], we find that a Higgsino with $\Delta m_{\text{tree}} \gtrsim 100 \text{ MeV}$ can be tested in EDM experiments.

As we have seen above, a Higgsino with $\Delta m_{\text{tree}} > O(100) \text{ MeV}$ can be tested in future non-accelerator experiments. On the other hand, an almost pure Higgsino with $\Delta m_{\text{tree}}$ (much) smaller than $\sim 100 \text{ MeV}$ is beyond the reach of these experiments. It is also challenging to probe such Higgsinos in DM indirect searches, or mono-jet/X searches at the LHC. However, as we mentioned above, in this case we may search for Higgsinos using disappearing tracks at the LHC, since $\tilde{\chi}^\pm$ becomes rather long-lived due to the small mass difference $\Delta m_+$. The decay length of $\tilde{\chi}^\pm$ is approximately [20]

$$c\tau \approx 0.7 \text{ cm} \times \left( \frac{\Delta m_+}{340 \text{ MeV}} \right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m_+^2}} .$$  

(12)

where $m_\pi$ is the pion mass. Hence, we expect that a pure charged Higgsino leaves an O(1) cm track in the detector. We will see below that it is indeed possible to detect an $O(1)$ cm disappearing track at colliders.

### DISAPPEARING TRACK SEARCHES

Disappearing track searches highly rely on the performance of silicon pixel detectors. The CMS detector has three barrel layers of pixel detectors in a magnetic field of 3.8 T at radii of 4.4 cm, 7.3 cm, and 10.2 cm with a pixel size of $100 \times 150 \mu \text{m}^2$ [26]. The ATLAS Pixel detector is located in a magnetic field of 2 T and consists of four barrel layers at radii of 3.3 cm, 5.05 cm, 8.85 cm, and 12.25 cm [23]. The innermost layer in the ATLAS Pixel detector system called Insertable B-Layer (IBL) [27], which was installed before the LHC Run 2 started, has a pixel size of 50 × 250 $\mu \text{m}^2$, while the other layers have a pixel size of 50 × 400 $\mu \text{m}^2$. For concreteness, we mainly consider the ATLAS setup in this section.

The current disappearing track searches by the ATLAS collaboration [28] whose main target is a long-lived charged wino, require four hits in the silicon detectors. Thus, at the LHC Run 1, a target charged particle needs to fly at least 29.9 cm, which corresponds to the location of the innermost layer of the silicon strip detector called SemiConductor Track (SCT), to pass this selection. This Run-1 analysis excludes a pure charged wino with a mass of less than 270 GeV [31]. Thanks to the IBL, the required minimum flight length of target particles was shortened (12.25 cm) at the Run 2, giving much better sensitivity to a pure charged wino, which has a decay length of $\sim 6$ cm. The current mass limit on a pure charged wino is 430 GeV [32].

A similar strategy may be adopted for charged Higgsino searches. As shown in Eq. (12), an almost pure charged Higgsino has a decay length of $\sim 1$ cm, which suggests us to focus on shorter tracks. To optimize the search strategy for this case, we here require only two hits in the Pixel detector. In addition to these two hits, a reconstructed primary vertex may be utilized to determine the momentum of a disappearing track. Note that the resolution of the position of a primary vertex is $O(10) \mu \text{m}$ [33], which is the same order as that of the

1. Recently, the CMS collaboration has replaced the pixel detectors with four layers at radii 2.9 cm, 6.8 cm, 10.9 cm and 16.0 cm [27].
2. The CMS Run-1 study can be found in Ref. [30].
PIXEL DETECTOR. FIG. 1 illustrates the configuration of the ATLAS inner tracker, where required numbers of hits in the detector are shown by red blobs for the analyses of the ATLAS Run-1&2 and ours. As shown in this figure, our search strategy allows the ATLAS detector to probe a disappearing track with a length of \( \gtrsim 5 \) cm.

According to the ATLAS Run-2 analysis [32], there are three classes of BG events in this search: hadrons that scatter with the detector, leptons whose flight direction is bent with Bremsstrahlung, and fake tracks due to mis-identification of hit points. The total number of remaining BG events after the selection cut is expected to be \( 11.8 \pm 3.1 \) in the electroweak production channel in the Run-2 study [32].

As we have reduced the number of hits in the silicon detector, the resolution of the transverse momentum of a disappearing track (\( P_T^{\text{dis}} \)) may be worse than the current one, \( \Delta(1/P_T^{\text{dis}}) \sim 10 \text{ TeV}^{-1} \). Since \( \Delta(1/P_T^{\text{dis}}) \propto L^{-2} \) with \( L \) the track length, we expect \( \Delta(1/P_T^{\text{dis}}) \sim 30 \text{ TeV}^{-1} \) for our two-hit method. This means that if a disappearing track has \( P_T^{\text{dis}} \gtrsim 30 \) GeV, its momentum can no longer be measured accurately. This poor momentum resolution may increase the number of BG events significantly.

Meanwhile, these BG events may be reduced with the help of reconstruction of displaced tracks. This technique has already been established in the long-lived particle searches with displaced vertices (DVs) [34] with the current reconstruction efficiency of displaced tracks from a radius of 5 cm being about 80% [35]. As the hadronic scattering and lepton Bremsstrahlung BG events generally yield a kink signature, these events may be removed efficiently if a DV having a disappearing track and a displaced track is reconstructed. Notice that this requirement scarcely reduces the signal events, since the emitted pion in the charged Higgsino decay is too soft to be reconstructed as a kink signature. The fake-track events may also be resolved with the DV reconstruction, especially those caused by displaced tracks from additional \( pp \) interactions, i.e., pile-up events. Moreover, a pixel detector with a reduced pixel size of \( 25 \times 100 \) \( \mu m^2 \) is being developed [36], which may improve the momentum resolution for a disappearing track in future colliders.

Taking these potential improvements into account, in the following analysis, we use a momentum cut of \( P_T^{\text{dis}} > 100 \) GeV and assume that the number of BG events is not so much increased due to deterioration in the momentum resolution.

RESULT

Now we discuss the prospects of our two-hit method for the long-lived charged Higgsino searches. We use MADGRAPH5 [37], PYTHIA6 [38], and DELPHES3 [39] for collider simulations and estimate the production cross sections of SUSY particles with PROSPINO2 [40]. We consider the 8 TeV LHC with 20.3 fb\(^{-1} \) data [31], the 13 TeV run with 36.1 fb\(^{-1} \) data [32], and the 14-TeV LHC and a future 33 TeV run with an integrated luminosity of 3 ab\(^{-1} \). We adopt the same set of kinematic selection criteria as in the Run-1 analysis [31], except for the missing energy cut, \( E_T^{\text{miss}} > 140 \) GeV, and the leading-jet transverse momentum cut, \( P_T^{\text{lead}} > 140 \) GeV for the 8 and 13 TeV cases. For the 14 and 33 TeV cases, we require \( E_T^{\text{miss}}, P_T^{\text{lead}} > 400 \) GeV and 600 GeV, respectively. As mentioned above, for the selection of disappearing track candidates, we require two hits in the silicon tracker with \( P_T^{\text{dis}} > 100 \) GeV. To estimate the number of BG events for each case, we rescale the observed number of BG events in the ATLAS Run-2 study [32] according to the event rates of the \( W + \text{jets} \) and

FIG. 2: Expected limits on Higgsino from disappearing track searches at the LHC and a 33 TeV collider.


\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{The current [31, 32] and expected limits on wino at the LHC and a 33 TeV collider.}
\end{figure}

\section*{CONCLUSION AND DISCUSSION}

In this letter, we have discussed the testability of the Higgsino DM scenario. We have seen that a wide region of parameter space for the Higgsino DM scenario can be probed in future non-accelerator experiments. However, if the electroweak-inos are so heavy that the tree-level charged-neutral Higgsino mass difference is less than $O(100)$ MeV, Higgsinos may escape from these non-accelerator searches. To probe such cases, in this paper, we propose a new collider search strategy for almost pure Higgsinos based on the first two layers of the Pixel detector, which is sensitive to $O(1)$ cm disappearing tracks.

We have found that using this two-hit search method we can probe 1 TeV pure Higgsino, whose thermal relic abundance agrees with $\Omega_{\text{DM}} h^2 \approx 0.12$, at a 33 TeV collider. As a consequence, the non-accelerator experiments and the disappearing track searches play a complementary role in probing Higgsinos, and thus the interplay among these experiments is of great importance to test the Higgsino DM scenario experimentally.

This method can also improve the disappearing track searches for long-lived charged winos. In fact, since pure charged winos have relatively long decay length, $\sim 6$ cm, we expect a number of signal events with the two-hit search strategy. In this case, we may even require two disappearing tracks, which can reduce the SM BG significantly. We also note that this two-hit strategy is useful for the search of other electroweak-charged DM candidates. A detailed study of these searches, as well as the reduction of BG by means of DVs, will be discussed elsewhere [42].

As we have seen, our proposal for the detection of disappearing tracks extends the LHC reach of the Higgsino and wino DM searches significantly. Nonetheless, the mass values favored by thermal relic are beyond the LHC reach, and thus we need a new hadron collider to cover the entire region for the DM scenario. It is worth emphasizing that to maximize the potential of such a collider, not only an increase in the beam energy and luminosity, but also an improvement in the tracker system is of crucial importance, which should be considered seriously when we discuss proposals for future colliders.

\textit{Note Added:} During the completion of this paper, a related study [43] was submitted to arXiv where pure Higgsino searches based on disappearing tracks at the LHC and a future 100 TeV collider were discussed on the assumption that a charged track with a length of 10 cm is detectable. We also noticed that the ATLAS collaboration started to study a possibility of using a two-hit strategy to search for long-lived charged winos [44].

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