Exploring nearly degenerate higgsinos using mono-$Z/W$ signal

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Abstract

We propose a new search strategy for higgsinos. Assuming associated production of higgsino-like pairs with a $W$ or $Z$ boson, we search in the missing energy plus hadronically-tagged vector boson channel. We place sensitivity limits for (HL-)LHC searches assuming $\mathcal{O}(1\text{–}3.5 \text{ GeV})$ mass differences between the lightest neutral and charged states. We point out that using the $E_T^{\text{miss}}$ distribution significantly increases the sensitivity of this search. We find the higgsinos up to 110 (210) GeV can be excluded with 139 (300) fb$^{-1}$ data. The full data of the HL-LHC will exclude (discover) the higgsinos up to 520 (280) GeV.

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1 Introduction

Higgsinos, supersymmetric partners of the Higgs bosons, are important to understand the nature of electroweak (EW) symmetry breaking since it is closely related to the size of the EW breaking scale \[1-10\]. In addition, it is well known that the higgsino is a good candidate for dark matter (DM) \[11,12\], as it has not been excluded by the direct detection of the DM \[13\] if the mixing with the gauginos is sufficiently suppressed. Despite these important points, collider limits on higgsinos remain weak due to the mass degeneracy of higgsino-like charged and neutral states; in fact the limit on the higgsino mass is about 90 GeV, obtained in the LEP experiment \[23,24\]. In this letter, we point out that this limit can be raised by using the mono-$Z/W$ boson signal at the Large Hadron Collider (LHC).

The choice of collider searches for higgsinos depends on the mass splitting between $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_2$, i.e. $\Delta m_{\tilde{\chi}^\pm} := m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and $\Delta m_{\tilde{\chi}^0_2} := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. Here, $\tilde{\chi}^0_1$ ($\tilde{\chi}^0_2$) is the (second) lightest neutral higgsino, and $\tilde{\chi}^\pm_1$ are the charged higgsinos. If $\Delta m_{\tilde{\chi}^\pm} \lesssim O(0.1\text{ GeV})$ and $\tilde{\chi}^0_1$ is long-lived, the disappearing track search is available \[25-27\]. The current limit on the pure-higgsino is 210 GeV \[28,29\]. For larger mass splittings $\sim 0.3-1\text{ GeV}$, it is proposed in Ref. \[30\] that the higgsinos with shorter lifetime can be probed by a soft displaced track. On the other hand, soft leptons signals are available to search for higgsino pair production but generally require $\Delta m_{\tilde{\chi}^0_2} \gtrsim 5\text{ GeV}$ \[31-33\] to probe the 100 GeV range of higgsino masses. In these searches, one hard jet from initial state radiation is required to trigger on. The current LHC limit is 100 (190) GeV for $\Delta m_{\tilde{\chi}^0_2} = 2 (9)\text{ GeV}$ \[34\], but the limit is weaker than that from the LEP experiment for smaller mass differences. Thus there is a gap between the two search strategies at $\Delta m_{\tilde{\chi}^\pm} \sim 1-3.5\text{ GeV}$ where the current limit is about 90 GeV given only by the LEP result.

In this letter, we point out that this gap can be probed by using mono-$Z/W$ signals at the LHC \[35,36\], where an EW gauge boson $V := Z, W$ decays hadronically, and hence is reconstructed as a large radius jet. A similar idea using mono-$Z$ signal is studied in Ref. \[37\] where the $Z$ decays leptonically. Since the number of signal events is small due to the small branching fractions of leptonic decays of a $Z$ boson, the limit is less than 200 GeV with the 3 ab$^{-1}$ data at the HL-LHC. We find that although backgrounds increase, the search with a hadronically decaying $Z/W$ boson may have two advantages: a larger cross section due to the production in associated with a $W$ boson in addition to a $Z$ boson; and a larger branching fraction to quarks. By binning the missing energy distribution, we are further able to improve the analysis. In fact, we find that the limit will be tightened significantly in the future (HL-)LHC data.

This letter proceeds as follows. In Sec. 2 we briefly review the mass differences among the higgsinos. The hadronic mono-$V$ search is studied in Sec. 3. Section 4 concludes.

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1 See recent discussions about the higgsino DM \[14,22\].
2 The CMS searches for mono-$Z$ boson \[38\].
2 Higgsino mass differences

The higgsino $\tilde{H}_u (\tilde{H}_d)$ is the $SU(2)_L$ doublet fermion which forms a chiral supermultiplet with the up-type (down-type) Higgs boson $H_u (H_d)$. The mass term for the higgsinos is given by $-\mu \tilde{H}_u \tilde{H}_d$, where $\mu$ is the so-called $\mu$-parameter which appears in the MSSM superpotential. The higgsinos are mixed with the bino $\tilde{B}$ and wino $\tilde{W}$ which form gauge supermultiplets with the $U(1)_Y$ and $SU(2)_L$ gauge bosons, respectively, after EW symmetry breaking. Diagonalizing the mass matrices, there are four neutralinos $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$) and two charginos $\tilde{\chi}_a^\pm$ ($a = 1, 2$), where the states are ordered by increasing mass. We shall study the case that the two lighter neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0$ and the lightest charginos $\tilde{\chi}_1^\pm$ are mostly higgsino-like. At the tree-level\footnote{The mass difference induced by radiative corrections is about 350 MeV\cite{39}, so it is sub-dominant in the case of $\Delta m_{\tilde{\chi}_1^\pm} \gtrsim 1$ GeV, which is our domain of interest.} the mass splittings of the higgsino-like states are approximately given by

\[
\Delta m_{\tilde{\chi}_1^0} := m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx m_Z^2 \left| \frac{c_W}{M_2} + \frac{s_W^2}{M_1} \right|, \\
\Delta m_{\tilde{\chi}_1^\pm} := m_{\tilde{\chi}_2^\pm} - m_{\tilde{\chi}_1^\pm} \approx \frac{\Delta m_{\tilde{\chi}_1^0}}{2} + \frac{m_Z^2}{2} \sin 2\beta \left( \frac{s_W^2}{M_1} - \frac{c_W^2}{M_2} \right),
\]

where $M_1$ ($M_2$) is the soft mass of the bino (wino), $m_Z$ is the Z boson mass, and $c_W (s_W) := \cos \theta_W (\sin \theta_W)$ with $\theta_W$ is the weak mixing angle. The angle $\beta$ is defined as $\tan \beta := \langle H_u \rangle / \langle H_d \rangle$. Assuming $M_1 = M_2$,

\[
\Delta m_{\tilde{\chi}_1^0} \sim 2 \Delta m_{\tilde{\chi}_1^\pm} \sim 2.1 \text{ GeV} \times \left( \frac{4 \text{ TeV}}{M_2} \right),
\]

where the second term in Eq. (2), which is typically sub-dominant due to the $\tan \beta$ suppression, is neglected. We see that $\Delta m_{\tilde{\chi}_1^\pm} \gtrsim 1$ GeV for $M_2 \lesssim 4$ TeV, while $\Delta m_{\tilde{\chi}_1^0} \lesssim 7$ GeV for $M_2 \gtrsim 1.2$ TeV. Hence, in a range of sub-TeV gaugino masses, neither is the chargino is long-lived nor do the neutralinos have sufficient mass gaps to leave detectable soft leptons. In this region of parameter space, we are thus justified in treating all the higgsino-like states $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$ as invisible particles assuming moderately small mass splittings $\Delta m_{\tilde{\chi}_1^\pm} \sim 1$–3.5 GeV.

3 Mono-Z/W search

We shall show that the mono-$V$ signals from higgsino pair production in association with an EW boson $V = Z, W$, i.e. $pp \rightarrow \tilde{\chi}\tilde{\chi}V$ with $\tilde{\chi} = \tilde{\chi}_{1,2}^0, \tilde{\chi}_1^\pm$, can probe higgsinos with sub-GeV mass differences in the future (HL-)LHC. We refer to the experimental analysis given by ATLAS\cite{36}. The left panel of Fig. 1 shows the production cross sections of the higgsino pair productions in association with $W^\pm, Z$ bosons and the SM Higgs boson $h$ at $\sqrt{s} = 13$ TeV when $M_1 = M_2 = 3$ TeV and $\tan \beta = 10$. All the other soft parameters are
Figure 1: The production cross sections for higgsino pair production in association with an EW gauge boson at $\sqrt{s} = 13$ TeV are shown on the left panel. The right panel shows the $E_T^{\text{miss}}$ distribution after the cut in the SR $0b$-HP when $\mu = 200$ and 500 GeV. $M_1 = M_2 = 3$ TeV and $\tan \beta = 10$ in both panels.

chosen at 5 TeV and $\text{sgn}(\mu) = +1$. We shall fix these values of the soft parameters and vary $\mu$ in our analysis. With these parameters, $\Delta m_{\tilde{\chi}^\pm_1} \sim 1.5$ GeV nearly independent of $\mu$ (for $\mu$ up to about 1 TeV). Cross sections are calculated by using MadGraph-5.2.8.2 [40] based on the sparticle spectrum calculated by softsusy-4.1.9 [41]. The associated production cross section with the Higgs boson is shown for comparison, and it is more than $10^3$ smaller than those with the EW gauge bosons. We see that the associated production with a $W$ boson is dominant and production with a $Z$ boson is sub-dominant. This fact motivates us to study the hadronic decays of the EW gauge bosons instead of the leptonic decays of the $Z$ boson.

We simulate events $pp \to \tilde{\chi}\tilde{\chi}V (\rightarrow q\bar{q})$, with $q$ light-flavor quarks, using MadGraph5. The events are showered and hadronized by Pythia8 [42], and then run through the fast detector simulator Delphes3.4.2 [43]. We used the default ATLAS card for the detector simulation, but we added the large-$R$ jet with $R = 1.0$ on top of the small-$R$ jet with $R = 0.4$ using the anti-$k_T$ jet clustering algorithm [44,45]. The trimming algorithm [46] is applied and sub-jets with radius parameter $R = 0.2$ whose transverse momenta ($p_T$) is below 5% of the original jet $p_T$ are removed from the large-$R$ jet in order to remove the energy deposits from pile-up. We also modified the $p_T$ thresholds to reconstruction efficiencies of electrons and muons to be 7 GeV. Further, the energy fractions of the higgsino-like chargino tracks to both ECAL and HCAL are set to zero, the chargino tracks do not deposit energy in the calorimeters as in our parameter space they decay before encountering the tracker.

Among the signal regions (SRs) defined in Ref. [36], we find that the mono-$W/Z$
SR with 0b-tagged jet and high-purity (HP), namely 0b-HP, is the most relevant for the higgsino signal. The SRs with b-tagged jet(s) are not very sensitive to our signal, because the dominant production is from $\tilde{\chi}\tilde{\chi}W^{\pm}$ which does not have bottom quarks in the final state. 0b-HP has the smallest backgrounds among the 0b-tagged jet SRs. In 0b-HP, $E_T^{\text{miss}} > 250$ GeV and one large-$R$ jet is required, where the large $R$-jet must have $p_T > 200$ GeV and $|\eta| < 2.0$. Since the selection criteria for a $W/Z$ boson tagger in Ref. [36] is adjusted such that the efficiency is constantly 50% [47], we simply assume that the half of the events passing the other cuts of 0b-HP are classified into the HP region.

An event is rejected if it includes any reconstructed electron (muon) with $p_T > 7$ GeV and $|\eta| < 2.47$ (2.7). In order to suppress the multi-jet backgrounds, the events are required to be $\Delta \phi(E_{T}^{\text{miss}}, \vec{p}_{T}^{j}) > 3\pi/2$, $\min_{i\in\{1,2,3\}}\Delta \phi(E_{T}^{\text{miss}}, \vec{p}_{T}^{j_i}) > \pi/9$, $\vec{p}_{T}^{\text{miss}} > 30$ GeV and $\Delta \phi(E_{T}^{\text{miss}}, \vec{p}_{T}^{\text{miss}}) < \pi/2$, where $\Delta \phi$ is the azimuthal angle separation between two transverse vectors. Here, $E_{T}^{\text{miss}}$, $\vec{p}_{T}^{\text{miss}}$, $\vec{p}_{T}^{j}$ and $\vec{p}_{T}^{j_i}$ are transverse momentum vectors of $E_T^{\text{miss}}$ reconstructed by Delphes which is calorimeter-based, track-based missing transverse momentum, large-$R$ jet and the $i$-th small-$R$ jet, respectively. The track-based $\vec{p}_{T}^{\text{miss}}$ is the negative sum of the transverse momenta of tracks with $p_T > 0.5$ GeV and $|\eta| < 2.5$ except those of the charginos. The small-$R$ jets are ordered by their $p_T$. Our treatment of the cuts in the other SRs are explained in Ref. [48] which studies limits on sneutrinos using the same signal, and hence we do not repeat them here. We found that these give weaker bounds than those from 0b-HP.

The $E_{T}^{\text{miss}}$ distributions of the observed data, fitted SM background and higgsino pair production in 0b-HP are shown in the right-panel of Fig. 1[4]. The main backgrounds are from $V + \text{jets}$ production where an EW gauge boson decays leptonically and contributes to $E_T^{\text{miss}}$. Hence, much background is rejected by the requirement for the large-$R$ jet in the HP region, since the $Z/W$-tagged jet would be accidentally reconstructed from the multi-jet background. This gives an advantage to the mono-$V$ search compared with mono-jet [35,49] and mono-photon [50,51] searches in which a jet (photon) is also expected in $V + \text{jets}$ ($V\gamma$) backgrounds and are irreducibly indistinguishable from the signals. The red (blue) histogram shows the higgsino signal with $\mu = 200$ (500) GeV, assuming the cross section calculated by MadGraph5 and the integrated luminosity of 36.1 fb$^{-1}$. The total signal number of events passing the cuts is 51.0 (9.63) for $\mu = 200$ (500) GeV, and the number of events in the last bin $E_T^{\text{miss}} \in [800, 1500]$ GeV is 1.75 (0.82). Although the total number of events is about 5 times different at these two points, those in the last bin are about two times over a steeply falling background. Thus, a tighter cut for $E_T^{\text{miss}}$ will give stronger search sensitivity for higgsinos with heavier masses.

We calculate experimental limits based on the test statistics [52],

$$q^{n}_{\mu} := -2 \log \frac{L(n|\mu, \hat{b})}{L(n|\hat{\mu}, \hat{b})},$$

4The values in the $E_T^{\text{miss}}$ bins of the fitted backgrounds and errors can be found at https://www.hepdata.net/record/83180.
Figure 2: The efficiencies of $\tilde{\chi}\tilde{\chi}V$ production of each bin of $E_T^{\text{miss}}$ in the SR 0b-HP (left) and the future sensitivities at the LHC (right). On the left panel, the efficiency to the SR 0b-HP with $E_T^{\text{miss}} > 250$ GeV is divided by 5 and is represented by the black line.

where the likelihood function is defined as

$$L(n|\mu, b) := \prod_i^{N_{\text{bin}}} \frac{\lambda_i^{n_i}}{n_i!} e^{-\lambda_i} \times \frac{1}{\sqrt{2\pi \Delta b_i}} \exp \left( -\frac{(b_i - b_i^0)^2}{2(\Delta b_i)^2} \right), \quad (5)$$

with $\lambda_i := \mu s_i + b_i$. Here, we assume a Gaussian distribution of the number of background events centered at $b_i^0$ with uncertainty $\Delta b_i$ in the $i$-th bin of the analysis. $n_i$ ($s_i$) are the number of observed (signal) events in the $i$-th bin. $(\mu, \{b_i\})$ is a set of values of $(\mu, \{b_i\})$ which maximizes $L$, and $(\hat{b}_i)$ is that of $\{b_i\}$ which maximizes $L$ for a given $\mu$. Assuming the asymptotic distribution of $q_\mu$ [53], $\text{CL}_s$, $Z_{\text{excl}}$ and $Z_{\text{disc}}$ are respectively given by

$$\text{CL}_s = \frac{1 - \Phi \left( \sqrt{q_1^{\text{obs}}} \right)}{\Phi \left( \sqrt{q_1^{b_0} - \sqrt{q_1^{\text{obs}}}} \right)}, \quad Z_{\text{excl}} = \sqrt{q_1^{b_0}}, \quad \text{and} \quad Z_{\text{disc}} = \sqrt{q_1^{b_0} + b_0}, \quad (6)$$

where $n_{\text{obs}}$ is the number of events observed by an experiment, and $\Phi$ is the cumulative distribution function of the normal distribution. The 95% C.L. limit is where $\text{CL}_s = 0.05$ and the exclusion (discovery) potential corresponds to $Z_{\text{excl}} = 2$ ($Z_{\text{disc}} = 5$). We assume that the number of background events and its error are simply rescaled by $R_L := \mathcal{L}/36.1$ fb$^{-1}$ and $\sqrt{R_L}$, respectively, with the integrated luminosities $\mathcal{L} = 139, 300$ and 3000 fb$^{-1}$. These luminosities correspond to the amounts of data at the Run-2, Run-3 and HL-LHC respectively.

The left panel of Fig. 2 shows efficiencies, rates to pass the cuts per a generated event, of the higgsino production $pp \rightarrow \tilde{\chi}\tilde{\chi}V$ in the each bin of $E_T^{\text{miss}}$ of 0b-HP. We generated
50,000 events at each point. The black line represents the total efficiency to \(0b-\text{HP}\) with \(E_T^{\text{miss}} > 250\) GeV divided by 5. We see that the efficiency to \(0b-\text{HP}\) is about 10\% and it is dominated by the lowest \(E_T^{\text{miss}}\) bin for the light higgsinos, while the total efficiency slightly increases to about 20\% with the higher efficiencies in the last three bins for the heavier higgsinos. Since the number of signal events decreases more slowly than that of the backgrounds as \(E_T^{\text{miss}}\) increases because of the efficiency increase, the large \(E_T^{\text{miss}}\) bins will be able to discriminate the signal from the background more efficiently. Using the SM background (and its error) in each bin of the \(E_T^{\text{miss}}\) distribution, we calculate \(Z_{\text{excl}}\) and \(Z_{\text{disc}}\).

The result of our analysis is shown in the right panel of Fig. 2. We plot both \(Z_{\text{excl}}\) and \(Z_{\text{disc}}\), but the values are so close that we can not find visible differences. We see that the Run-2 (Run-3) data will put the limit about 110 (210) GeV. However, the current data can not constrain the higgsinos heavier than the LEP bound, i.e. \(\text{CL}_s > 0.05\) for \(m_{\tilde{\chi}_0^1} \gtrsim 90\) GeV. With the full-data of the HL-LHC, we can exclude (discover) higgsinos up to about 520 (280) GeV. It is remarkable that the Run-2 data may constrain the higgsino heavier than the LEP bound. For comparison, if we apply the inclusive 250 GeV \(E_T^{\text{miss}}\) cut without the \(E_T^{\text{miss}}\) distribution binning technique can only exclude a 110 GeV higgsino with \(L = 300\) fb\(^{-1}\) and the exclusion (discovery) potential is 300 (150) GeV with \(L = 3000\) fb\(^{-1}\). Thus using the high-\(E_T^{\text{miss}}\) bins are crucial to raise the sensitivity.

4 Conclusion

In this letter, we point out that the mono-W/Z search can explore the higgsinos with \(\Delta m_{\tilde{\chi}_1^{\pm}} \sim 1\text{–}3.5\) GeV, where the decay products of the heavier states are invisible. Higgsinos in this parameter range can not be covered by searches using disappearing tracks or soft leptons. Since the \(E_T^{\text{miss}}\) distribution of the signal is different from that of the background, the sensitivity can be tightened by using the \(E_T^{\text{miss}}\) distribution to obtain limits. We showed that the full data of the Run-2 (Run-3) at the LHC can exclude the higgsinos up to 110 (210) GeV, and that of the HL-LHC can exclude (discover) higgsinos up to about 520 (280) GeV. Therefore, the mono-W/Z search indeed has sensitivity to light higgsinos. This search could be applicable to higgsinos with smaller mass differences, \(\Delta m_{\tilde{\chi}_1^{\pm}} \lesssim 1\) GeV in which a charged track can be detected, since the search relies only on the existences of the large-\(R\) jet and a large \(E_T^{\text{miss}}\), and hence the signals with charged (disappearing) tracks would pass the cuts. Our result also suggests that sensitivities of searches using disappearing tracks and/or soft leptons could be improved by using a large-\(R\) jet from hadronic decays of a EW gauge boson to trigger instead of a small-\(R\) jet.

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