Pseudo-goldstino and electroweak gauginos at the LHC (Postprint)

Authors: Hikasa,K, Liu,T, Wang,L, Yang,JM

Date: 2016-12-28T00:00:00+00:00

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Full Text

Preamble

TTP14-010 Pseudo-goldstino and electroweak gauginos at the LHC

Ken-ichi Hikasa,[1] Tao Liu,[2] Lin Wang,[2] and Jin Min Yang[3]
[1]Department of Physics, Tohoku University, Sendai 980-8578, Japan
[2]Institut für Theoretische Teilchenphysik, Karlsruhe Institute of Technology (KIT), D-76128 Karlsruhe, Germany
[3]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Academia Sinica, Beijing 100190, China

Abstract

Multi-sector SUSY breaking predicts the existence of a pseudo-goldstino, which could couple more strongly to visible fields than the ordinary gravitino. In such scenarios, the lightest neutralino and chargino can decay into a pseudo-goldstino plus a Z-boson, Higgs boson, or W-boson. In this work we perform Monte Carlo simulations for the direct production of the lightest neutralino and chargino followed by their decays to a pseudo-goldstino. Considering scenarios with higgsino-like, bino-like, or wino-like lightest neutralinos, we find that the signal-to-background ratio at the high-luminosity LHC is between 6% and 25%, and the statistical significance can exceed 5σ.

PACS numbers: 14.80.Da, 14.80.Ly, 12.60.Jv

Introduction

Supersymmetry (SUSY) remains the most popular theory for solving the hierarchy problem, despite the recent discovery of a 125 GeV Higgs boson, which imposes some degree of fine-tuning on most low-energy SUSY models [1]. From a model-building perspective, the mechanism of SUSY breaking remains a puzzle. Typically, spontaneous SUSY breaking is assumed to occur in some hidden sector and is mediated to visible fields through a specific mechanism. This produces a massless fermion called the goldstino, which in the presence of local SUSY is absorbed into the longitudinal component of the gravitino. If SUSY is broken independently in multiple sectors, each sector yields a goldstino with SUSY breaking scale F . One linear combination of the is massless and eaten by the gravitino, while the orthogonal combination remains as a physical state called the pseudo-goldstino. The properties and phenomenology of the pseudo-goldstino have been investigated in the literature [2–16]. Compared to the gravitino, the interactions of the pseudo-goldstino are not completely constrained by the supercurrent, and thus some of its couplings could be large enough to produce intriguing phenomenology. In the framework of gauge-mediated SUSY breaking (GMSB), the pseudo-goldstino can make final states softer and more structured at colliders [14]. In GMSB with more than two hidden sectors, the multi-photon signature was discussed in [15] and the LHC detectability of Higgs boson decays into a pseudo-goldstino was examined in [16].

The non-observation of sparticles in the 7 TeV and 8 TeV runs of the LHC has set stringent bounds on colored sparticles. However, electroweak sparticles are less constrained due to their smaller production rates and can still have masses below 1 TeV. Theoretically, a light spectrum of electroweak sparticles is naturally predicted in frameworks such as anomaly mediation and non-minimal gauge mediation. Therefore, the study of electroweak sparticles, particularly light neutralinos and charginos, is crucial for testing SUSY at the LHC. At the LHC, neutralinos and charginos can be directly produced through the Drell-Yan process and vector boson fusion.

In many conventional scenarios with R-parity, the lightest neutralino is stable and simply leads to missing energy in experiments. However, in some low-scale gauge mediation scenarios, the lightest neutralino can decay into a photon plus a gravitino. In scenarios with SUSY breaking in two hidden sectors, the lightest neutralino can decay to a pseudo-goldstino plus a Z-boson or Higgs boson. In this work we focus on such a two-sector SUSY breaking scenario to study the LHC detectability of lightest neutralino and chargino production.

This paper is organized as follows. In Section II we briefly review the framework with a pseudo-goldstino and discuss its possible effects on neutralino and chargino decays. Then in Section III we study the corresponding signals at the LHC using an effective approach. Finally, we present our conclusions in Section IV.

II. Theoretical Review

Due to the non-renormalization theorem of the superpotential, spontaneous SUSY breaking is communicated to visible fields through the non-trivial Kähler potential K and gauge kinetic function f. After integrating out the hidden sector fields and parameterizing their information in a non-linear way [17] as X = 1 + √2   + ^{2} F , the following representative term that contributes to soft masses can be obtained:

$$K = \Phi^\dagger \Phi \sum_i \frac{X_i^\dagger X_i}{F_i^2} m_{\phi,i}^2$$

and

$$f_{ab} = \frac{1}{g_a^2} \left(1 - \sum_i \frac{X_i}{F_i} 2 m_{a,i} \right) \delta_{ab}.$$

In these equations,   is the so-called goldstino and m_{ϕ,a} are respectively the soft masses for chiral fields and gauginos. The trilinear A-terms and bilinear B could also be constructed easily but are omitted for simplicity. In the two-hidden-sector scenario with the definition F^{2} = F$_{1}^{2}$ + F$_{2}^{2}$ and tan   = F$_2$/F$_1$, the combination G = $_1$ cos   + $_2$ sin   is eaten by the super-Higgs mechanism, while one pseudo-goldstino G' = $_1$ sin   + $_2$ cos   remains. After substituting the expression for X and making some rotations, we obtain the interaction Lagrangian up to order 1/F :

$$\mathcal{L}_{\text{int}} = \sum_a \tilde{m}_a G' \sigma^{\mu\nu} \lambda_a F^a_{\mu\nu} + \sum_a m_a G \sigma^{\mu\nu} \lambda_a F^a_{\mu\nu} + \sum_a \tilde{m}_a G' \lambda_a D_a + \sum_a m_a G \lambda_a D_a.$$

Here the parameters m and $\tilde{m}$ are defined as:

$$m_a = m_{a,1} + m_{a,2}, \quad m_\phi^2 = m_{\phi,1}^2 + m_{\phi,2}^2,$$

$$\tilde{m}_a = m_{a,1} \tan\theta + m_{a,2} \cot\theta, \quad \tilde{m}_\phi^2 = m_{\phi,1}^2 \tan\theta + m_{\phi,2}^2 \cot\theta,$$

so that

$$\frac{\tilde{m}_a}{F} = \frac{m_{a,1}}{F_1} \sin\theta + \frac{m_{a,2}}{F_2} \cos\theta.$$

In our analysis we assume a large hierarchy between F$_1$ and F$_2$ (specifically, we assume F$_1$ F$_2$, so cot   is very large). In this case the pseudo-goldstino can couple more strongly to visible fields than the ordinary goldstino (gravitino).

Furthermore, we consider a small $\tilde{m}a$ *which occurs for a large cot (where* m{a,1} tan is suppressed) and a very small m_{a,2} (such a tiny gaugino mass is easily achieved if the SUSY breaking sector F_2 approximately preserves R-symmetry [18]).

In this special case, the pseudo-goldstino couplings with the photon or transverse Z-boson, which are proportional to $\tilde{m}$_a in Eq. (5), are suppressed. Therefore, in our following analysis we neglect the pseudo-goldstino couplings with the photon or transverse Z-boson.

Of course, a pseudo-goldstino should have a mass. At tree level its mass comes from the intrinsic property of supergravity, and it can also receive loop corrections that are very model-dependent. In our analysis we assume that the pseudo-goldstino is rather light so that a neutralino can decay into a pseudo-goldstino plus a Z-boson. Thus our numerical results are only applicable to a rather light pseudo-goldstino (for a very light pseudo-goldstino, say below 10 GeV, we can approximately neglect its mass in numerical calculations). The phenomenology of a rather massive pseudo-goldstino was considered in [14].

Now we examine the effects of the pseudo-goldstino in concrete models. In the minimal supersymmetric standard model (MSSM), the Lagrangian for neutralinos and charginos is given by:

$$\mathcal{L}_\chi = Y_{ij}\chi_i\chi_j h^0 + G_{ij}\chi_i^\dagger\bar{\sigma}^\mu\chi_j Z_\mu + (I_{ij}\chi_i^\dagger\bar{\sigma}^\mu\chi_j^+ + L_{ij}\chi_j^{-\dagger}\bar{\sigma}^\mu\chi_i)W_\mu^- + \text{h.c.}$$

Here , represent the four neutralinos in the gauge eigenbasis $\tilde{B}$, $\tilde{W}$^0, $\tilde{H}$_d^0, $\tilde{H}$_u^0 and their mass matrix is given by:

$$M_{\tilde{N}} = \begin{pmatrix} M_1\&0 & -c_\beta s_W m_Z\& s_\beta s_W m_Z & \\ 0\&M_2\&c_\beta c_W m_Z & -s_\beta c_W m_Z & \\ -c_\beta s_W m_Z\&c_\beta c_W m_Z\&0 & -\mu & \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu\&0 \end{pmatrix}.$$

The charginos ${}^+$, ${}^-$ in the gauge eigenbasis are $\tilde{W}$^±, $\tilde{H}$^± and their mass matrix is:

$$M_{\tilde{C}} = \begin{pmatrix} M_2 & \sqrt{2}s_\beta m_W \\ \sqrt{2}c_\beta m_W & \mu \end{pmatrix}.$$

The couplings to physical Higgs and gauge bosons are:

$$Y = \begin{pmatrix} g's_\alpha & g'c_\alpha \\ g's_\alpha & g'c_\alpha \end{pmatrix}, \quad G = g\begin{pmatrix} c_W^2 & -s_W c_W \\ -s_W c_W\&s_W^2 & \end{pmatrix},$$

$$I = g\begin{pmatrix} c_\beta \\ s_\beta \end{pmatrix}, \quad L = g\begin{pmatrix} s_\beta \\ c_\beta \end{pmatrix}.$$

Since the contribution in Eq. (5) is proportional to $\tilde{m}$_{ϕ}^2/F, there are two interaction terms that should be added to the above Lagrangian:

$$\mathcal{L}_{\text{pseudo}} = \sum_i \frac{\tilde{m}_\phi^2}{F} y_i G' \chi_i h^0 + \sum_{i,j} \frac{\tilde{m}_\phi^2}{F} \rho_i G' \chi_i Z_\mu,$$

with parameters y and   given by:

$$y_i = \frac{\tilde{B}_\mu s_\alpha}{\tilde{m}_\phi^2} N_{i3} c_\beta + \frac{\tilde{B}_\mu c_\alpha}{\tilde{m}_\phi^2} N_{i4} s_\beta,$$

$$\rho_i = \frac{\tilde{B}_\mu s_\beta}{\tilde{m}_\phi^2} N_{i3} + \frac{\tilde{B}_\mu c_\beta}{\tilde{m}_\phi^2} N_{i4}.$$

In the above matrices, α and β are the mixing angles in the Higgs sector with tan β = v_u/v_d, and s_β = sin β, c_β = cos β. We use the notations s_W = sin _W, c_W = cos _W (_W is the Weinberg angle).

[Figure 1: see original paper]

The linear terms induce a small mixing between neutralinos and the pseudo-goldstino, so we must rotate to the mass eigenstate basis for neutralinos, after which the small mass mixing can be treated perturbatively. For example, the vertex between the Z-boson and pseudo-goldstino G' appears after a mass insertion ', as shown in Fig. 1. The matrices ' and G' are defined as:

$$\rho'_i = \rho_j N_{ji}, \quad G'_{ij} = G_{\ell m} N_{\ell i} N_{mj},$$

where N is the rotation matrix that diagonalizes the neutralino mass matrix. Other interactions can be obtained in the same way, such as the interaction between charginos and the pseudo-goldstino.

Since in this scenario the couplings of the pseudo-goldstino with the photon or transverse component of the Z-boson are negligible, the two possible decay channels for the lightest neutralino are Z + G' or h + G'.

From the above analysis we can obtain the structure of the interactions for the pseudo-goldstino. However, many parameters are involved, particularly in the chargino and neutralino rotation matrices. Therefore we select only some representative interactions to study the corresponding phenomenology.

To study the phenomenology, we employ the effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \frac{\tilde{m}_\phi^2}{F}\left[g_{h\chi} h\chi^0 G' + g_{\chi Z}\bar{G}'\bar{\sigma}^\mu\chi^0 Z_\mu + g_{\chi W1}\bar{G}'\bar{\sigma}^\mu\chi^+ W_\mu^- + g_{\chi W2}\bar{G}'\bar{\sigma}^\mu\chi^- W_\mu^+ + \text{h.c.}\right].$$

Here we list all possible couplings, some of which may be turned off in specific cases. The decay widths of the lightest neutralino and chargino to the pseudo-goldstino are:

$$\Gamma(\chi^0 \to hG') = \frac{1}{16\pi m_\chi}\left(\frac{\tilde{m}_\phi^2}{F}\right)^2 g_{h\chi}^2 m_\chi^2 \left(1 - \frac{m_h^2}{m_\chi^2}\right)^2,$$

$$\Gamma(\chi^0 \to ZG') = \frac{1}{16\pi m_\chi}\left(\frac{\tilde{m}_\phi^2}{F}\right)^2 g_{\chi Z}^2 m_\chi^2 \left(1 - \frac{m_Z^2}{m_\chi^2}\right)^2 \left(1 + \frac{m_Z^2}{m_\chi^2} - 2\frac{m_Z^4}{m_\chi^4}\right),$$

$$\Gamma(\chi^\pm \to W^\pm G') = \frac{1}{16\pi m_\chi}\left(\frac{\tilde{m}_\phi^2}{F}\right)^2 (g_{\chi W1}^2 + g_{\chi W2}^2) m_\chi^2 \left(1 - \frac{m_W^2}{m_\chi^2}\right)^2 \left(1 + \frac{m_W^2}{m_\chi^2} - 2\frac{m_W^4}{m_\chi^4}\right).$$

The first two decay modes have been considered in [8] and we have verified that our results agree with theirs.

In our calculations we fix $\tilde{m}\_\{\phi\}/\sqrt{F} = 0.1$ and set all couplings g_X to unity. Under these assumptions, weak-scale neutralinos or charginos have decay widths of order 10^{-4} GeV and decay lengths $\Gamma^{-1}\quad 10^{-10}$ cm, so they will decay inside the detector. Note that these parameters have no effect on the production rates of neutralinos or charginos. As long as the neutralino and chargino only decay to the pseudo-goldstino, their signal rates are not sensitive to these parameters.

Regarding the parameter space in the neutralino/chargino sector, following the analysis in [19] we classify it according to the relative values of M_1, M_2, and : (i) $M_2 < M_1$, | |; (ii) | | < M_1, M_2; (iii) $M_1 < M_2$, | |. Each case corresponds to different properties of the lightest ordinary supersymmetric particle (LOSP). In the first case, the LOSP is higgsino-like, which can decay not only to Higgs but also to Z-boson through a mass insertion of . In the second and third cases the LOSP is wino-like and bino-like respectively, which only decays to a Higgs boson plus a goldstino through its mass mixing with the higgsino. For the lightest chargino, which is too light to decay into a neutralino plus an on-shell W-boson, it can now decay into a W-boson plus a pseudo-goldstino. Note that in the second case the interaction vertex requires more than one insertion, so the wino may mainly decay to the gravitino. Since the decay to gravitino has the same collider signature, we assume the lightest chargino decays entirely to the pseudo-goldstino.

Note that in addition to the above decays, the neutralino can also decay to a real goldstino (gravitino), which may be competitive and needs to be checked. The corresponding decay widths are given by [20, 21]:

$$\Gamma(\chi^0 \to \gamma G) = \frac{m_\chi^5}{16\pi F^2} |N_{11} c_W + N_{12} s_W|^2,$$

$$\Gamma(\chi^0 \to ZG) = \frac{m_\chi^5}{16\pi F^2} |N_{11} s_W - N_{12} c_W|^2 \left(1 - \frac{m_Z^2}{m_\chi^2}\right)^4 .$$

Here we see that the decay $^0 \to \gamma$G is suppressed for a higgsino-like neutralino. In the following we demonstrate results for a bino-like neutralino and compare with decays into a pseudo-goldstino. For numerical calculations, we fix the parameters tan $\beta = 10$, $M_1 = 200$ GeV, $M_2 = 500$ GeV, and = 1.0 TeV. The soft mass $\tilde{m}$_ϕ is a combination of Higgs soft parameters whose values can be obtained from SOFTSUSY [22] once tan β, , and the SM-like Higgs mass (taken as 125 GeV) are fixed. Note that these Higgs soft parameters receive contributions from two SUSY-breaking sectors, and we assume the two contributions are equal (B_ $_{,1}$ = B_ $_{,2}$) in the following numerical example.

[Figure 2: see original paper]

With the above fixed parameters, we vary cot and show the decay widths in Fig. 2. As expected, for small cot the decays into the real goldstino are important, while for large cot the decays into the pseudo-goldstino become dominant. The reason is clear: the couplings of the pseudo-goldstino are proportional to $\tilde{m}$_ϕ, which can be enhanced by a large cot , as shown in Eq. (6).

III. Phenomenological Study at the LHC

In this section we study the direct production of the lightest neutralino and chargino followed by their decays to a pseudo-goldstino at the LHC. We assume that other SUSY particles (such as squarks, sleptons, heavy Higgs bosons, and gluino) are heavy enough to be decoupled. The mass of the SM-like Higgs boson is fixed at m_h = 125 GeV. The parameters M_1, M_2, and are fixed to different values in the three cases listed in the preceding section. The sign of is assumed to be positive and tan β is fixed at 10 in the calculations. We use SOFTSUSY [22] to calculate the mass spectrum and mixing matrices.

We use MadGraph5 [23] to perform Monte Carlo simulations for signals and SM backgrounds. The effective Lagrangian in Eq. (15) for the pseudo-goldstino interaction is implemented in FeynRules [24] and passed to MadGraph5 as a UFO model file [25]. Signal and background samples are generated at parton level by MadGraph5 and then passed to Pythia [26] for parton showering and hadronization. The signal cross section is normalized to next-to-leading order (NLO) using Prospino2 [27]. Fast detector simulations are performed using Delphes [28] with the ATLAS detector configuration. For jet clustering we use the anti-k algorithm [29] with radius parameter ΔR = 0.5 in the FastJet package [30]. Sample analysis is performed with MadAnalysis5 [31].

A. Higgsino-like LOSP (| | < M_1, M_2)

In this case the neutralinos and charginos are produced mainly through the pairs $^0{}_1{}^0{}_2$, $^0{}_1{}^+{}_1$, and $^+{}_1{}^-{}_1$. (Note that if   is much smaller than M_1 and M_2, then the higgsino-like $^0{}_1$, $^0{}_2$ and $^+{}_1$, $^-{}_1$ are nearly degenerate, and such pair productions give no visible final states in the conventional MSSM with $^0{}_1$ being the LSP. In this case, to detect such productions at the LHC, an extra jet or photon is needed [32]). Their cross sections at NLO can be found in [19]. Among these channels, the production of $^0{}_1{}^+{}_1$ has the largest rate. In the two-hidden-sector SUSY breaking scenario, the neutralino decays to a Z-boson or Higgs plus a pseudo-goldstino G', as discussed in Section II. Due to the large systematic uncertainty for Higgs hadronic decays at the LHC, we focus on the Z-boson mode and assume its branching ratio to be 0.5. With leptonic decays of Z/W±, the signal is:

$$pp \to \chi_1^0\chi_1^\pm \to ZG'W^\pm G' \to \ell^+\ell^-\ell^\pm\nu G'G' \quad (3\ell + E_T^{\rm miss},\ \ell = e,\mu,\tau).$$

The relevant Feynman diagram is displayed in Fig. 3 [Figure 3: see original paper]. The three leptons in the final state contain an oppositely charged lepton pair with the same flavor. The tau lepton can be partially reconstructed from its hadronic decays. Note that the neutralino pair $^0{}_1{}^0{}_2$ can also contribute to the signal. We have verified that its contribution is very small and can be safely neglected. The relevant mass parameters are fixed to   = 200 GeV, M_1 = 1.0 TeV, and M_2 = 1.5 TeV as a benchmark scenario.

For the 3 + E_T^{miss} final state, the dominant irreducible SM background is WZ diboson production. We also consider other SM backgrounds including top quark pair production, ZZ diboson production, and Z-boson production in association with jets. Top pair production with dileptonic decays may fake the signal since b-jets and light jets can be misidentified as charged leptons. This contribution can be suppressed by applying b-jet and light-jet vetoes. For the ZZ background process with both Z bosons decaying to leptons, it can mimic our signal when one lepton is missing in the detector. In the case of Z + j background, it may fake our signal if a light jet is misidentified as a charged lepton. These processes can be suppressed by requiring large E_T^{miss}. We do not consider multi-lepton (n ≥ 3) final states from the production of three gauge bosons due to their small cross sections compared to other backgrounds.

[Figure 4: see original paper]

To efficiently cut the SM backgrounds, we plot in Fig. 4 some kinematic distributions for the signal and backgrounds at the LHC with $\sqrt{s}$ = 14 TeV. In the left panel of Fig. 4, we show the normalized transverse mass M_T($_1$, E_T^{miss}) distribution, where this variable is defined as:

$$M_T(\ell, E_T^{\rm miss}) = \sqrt{2p_T^\ell E_T^{\rm miss}[1-\cos\Delta\phi(\ell, E_T^{\rm miss})]},$$

with $\Delta\phi$(, E_T^{miss}) being the azimuthal angle difference between the lepton and the missing energy. We use the lepton with the largest transverse momentum to construct M_T. The right panel of Fig. 4 shows the normalized E_T^{miss} distribution. It is clear that a lower cut of about 120 GeV on M_T and 100 GeV on E_T^{miss} can improve the statistical significance of the signal. Based on these distributions, we apply the following event selection:

- **Basic selection**: Three leptons with p_T^{ $_1$, $_2$, $_3$} > 60, 40, 20 GeV, following isolation criteria for electrons and muons: the scalar sum of transverse momenta of all charged particles with p_T > 0.5 GeV within a cone ΔR = 0.5 around the electron or muon should be less than 10% of the lepton's transverse momentum. We assume a τ-tagging efficiency of 40% and also include QCD jet mis-tags in Delphes.
- M_T($_1$, E_T^{miss}) > 120 GeV.
- E_T^{miss} > 100 GeV.
- The invariant mass of the oppositely charged lepton pair with same flavor must satisfy |m_{ } - m_Z| < 20 GeV.
- Veto on tagged b-jets with p_T > 20 GeV and | | < 2.5. We use the b-jet tagging and c-jet mis-tagging efficiency parametrization from [33]. Delphes also includes the misidentification rate for light jets.
- Veto events with p_T(j) > 60 GeV and | | < 5.0.

[TABLE:I]

In Table I we present the numbers of signal and background events for the LHC with √s = 14 TeV and 100 fb^{-1} of integrated luminosity. We have normalized the WZ production cross section to NLO [34] and the t$\bar{t}$ production cross section to next-to-next-to-leading order (NNLO) [35]. The table shows that the signal is overwhelmed by backgrounds after basic selection. As expected, the cut on transverse mass M_T can suppress all background processes significantly, especially electroweak processes. They are further reduced by requiring large missing transverse energy. The dominant irreducible SM background WZ is suppressed by about one order of magnitude. The large Z+j background has been completely removed. The other important background t$\bar{t}$ is also reduced by about a factor of seven, while the signal is decreased by only half. Although the invariant mass cut on the charged lepton pair reduces both signal and backgrounds, it efficiently improves the statistical significance of the signal. The final two cuts vetoing b-jets and light jets are crucial for further suppressing the t$\bar{t}$ background. Note that the veto on light jets also has a small effect on the signal due to tau jets in the final state. After all cuts, the signal-to-background ratio is 11%.

[TABLE:II]

Table II shows the number of signal events and its significance before and after cuts for different luminosities at the 14 TeV LHC. Although the signal is reduced by applying cuts, its statistical significance is efficiently increased. With an integrated luminosity of 200–300 fb^{-1}, the sensitivity can reach 5σ.

B. Wino-like LOSP ($M_2 < M_1$, | |)

In this case, among the direct productions of neutralinos and charginos at the LHC, the pair production of ${}^{0}{}_{1}$ ${}^{+}{}_{1}$ is dominant and we consider this process. As discussed previously, the LOSP ${}^{0}{}_{1}$ can only decay to a Higgs boson and a pseudo-goldstino G' in this scenario. Thus the signal is a single lepton and two bottom quarks with large missing transverse energy:

$$pp \to \chi_1^0\chi_1^\pm \to hG'W^\pm G' \to \ell^\pm b\bar{b}\nu G'G' \quad (\ell + 2b + E_T^{\text{miss}},\ \ell = e, \mu, \tau).$$

In our calculations we fix the relevant parameters as $M_2 = 200$ GeV, $= 1.0$ TeV, and $M_1 = 1.5$ TeV. Other parameters are assumed to take the same values as in the higgsino-like LOSP case.

The dominant SM backgrounds for this signal are diboson productions, Wb$\bar{b}$, top pair, and single top productions. For diboson productions, we only consider WZ production where Z decays to b$\bar{b}$ and W decays leptonically. Contributions from other diboson productions should be very small. For Wb$\bar{b}$ production, its contribution can be suppressed by requiring large missing transverse energy. Top pair production can mimic the signal if one of the W bosons decays leptonically. Single top production can also fake the signal when a light quark is misidentified as a b-quark or when there is missing transverse energy.

[Figure 5: see original paper]

Figure 5 presents the normalized M_T and E_T^{miss} distributions for the signal and backgrounds at the 14 TeV LHC. The peak of the transverse mass distribution for backgrounds with a single W is expected around m_W. Including dileptonic channels, the shape of the curves for top pair production should be slightly different. We observe that the transverse mass cut should be effective for suppressing backgrounds. In the missing transverse energy distribution, the signal has a slightly harder E_T^{miss} spectrum due to the contribution from the pseudo-goldstino. Thus a hard cut on E_T^{miss} will further reduce backgrounds. We employ the following selections for this signal:

- **Basic selection**: One isolated lepton with p_T > 40 GeV, two tagged b-jets with p_T^{b$_1$,b$_2$} > 60, 40 GeV, | | < 2.5.
- The invariant mass of the b-jets must satisfy |m_{bb} - m_h| < 25 GeV.
- M_T > 100 GeV.
- E_T^{miss} > 120 GeV.

[TABLE:III]

Table III displays the cut flow for signal and backgrounds at the LHC with $\sqrt{s}$ = 14 TeV and 100 fb^{-1} integrated luminosity. We have normalized the dominant t$\bar{t}$ background to NNLO [35]. The signal is overwhelmed by backgrounds at the basic selection level. As expected, the M_T cut suppresses backgrounds while keeping most of the signal. This cut is extremely effective for suppressing the Wb$\bar{b}$ background. The Wb$\bar{b}$ background is further suppressed by a hard cut on E_T^{miss}. The WZ and ZZ backgrounds with two leptons from Z decay are removed by requiring a large invariant mass of leptons. The dominant reducible backgrounds t$\bar{t}$ and tW are strongly suppressed by vetoing b-jets and light jets. After all cuts, the signal-to-background ratio is about 6%.

[TABLE:IV]

Table IV presents the number of signal events and its statistical significance for different luminosities at the 14 TeV LHC. As expected, these optimization cuts efficiently improve the signal significance. The significance can reach 5σ for an integrated luminosity of about 300 fb^{-1}. We also note that the signal-to-background ratio is only about 6%, implying that systematic uncertainties must be controlled at the percent level to detect the signal in this case.

C. Bino-like LOSP ($M_1 < M_2$, | |)

In this case the lightest neutralino is bino-like and its pair production cross section at the LHC is small (10^{-6}–10^{-7} pb). For the next-to-lightest ordinary supersymmetric particle (NLOSP), its composition depends on the relative values of M_2 and . We investigate different scenarios: (i) | | < M_2, where the next-to-lightest neutralino $^0{}_2$ and chargino $^+{}_1$ are higgsino-like; (ii) M_2 < | |, where the next-to-lightest neutralino $^0{}_2$ and chargino $^+{}_1$ are wino-like. In both scenarios, the leading production channels are NLOSP pair production. Since the decay of the neutral NLOSP is more sensitive to SUSY parameters than the charged NLOSP, we explore only the charged NLOSP pair ($^+{}_1$ $^-{}_1$) production. Here the chargino dominantly decays to a W boson plus a bino-like LOSP $^0{}_1$ or pseudo-goldstino G'.

In the case of a higgsino-like $^+{}_1$, due to the relatively large higgsino-bino mixing, $^+{}_1$ decays to $^0{}_1$$W^+$ $^0{}_1$ and pseudo-goldstino G'. The channel is pp → $^+{}_1$ $^-{}_1$ → W^+G'W^-G' → hhW^+W^-G'G' with a cross section of 6.7 fb, which is too small to be detected at the LHC.

In the case of a wino-like $^+{}_1$, there is little mixing between bino and wino. Then $^+{}_1$ will decay to pseudo-goldstino G' and a W boson. Thus the signal is:

$$pp \to \chi_1^+\chi_1^- \to W^+G'W^-G' \to \ell^+\ell^-\nu\nu G'G' \quad (2\ell + E_T^{\text{miss}},\ \ell = e, \mu, \tau).$$

The characteristic of this signal is two highly boosted leptons and large missing transverse energy in the final state. This feature helps distinguish the signal from backgrounds.

In our analysis the bino-like LOSP neutralino mass is set to M_1 = 200 GeV. We also set M_2 = 500 GeV and   = 1.0 TeV, with other parameters the same as in the higgsino-like LOSP case.

The SM backgrounds come from diboson productions of WW, ZZ, and WZ, as well as top pair and single top productions. The WW background can be suppressed by requiring large missing transverse energy. For the ZZ background, when one Z boson decays to leptons and the other to neutrinos, it can resemble our signal. However, these two leptons differ from the signal's highly boosted leptons, so a high invariant mass cut on the two leptons could reduce this background. For the WZ background, it fakes the signal only if one of the three final-state leptons is missed in detection. The two W bosons produced in $t\bar{t}$ and tW processes can decay to leptons and thus fake our signal. These processes can be suppressed by applying b-jet and light-jet vetoes. Since we require large transverse energy, W/Z production associated with a jet or photon is not considered.

[Figure 6: see original paper]

Figure 6 shows the normalized M_T distributions of the hard and soft charged leptons for the signal and backgrounds at the 14 TeV LHC. Since both leptons in the signal come from decays of heavy particles, the signal has a harder spectrum than backgrounds in the M_T distributions. We notice that backgrounds in the M_T($_2$, E_T^{miss}) distribution fall faster than in the M_T($_1$, E_T^{miss}) distribution. Thus we require a cut on M_T($_2$, E_T^{miss}) to suppress backgrounds. The normalized E_T^{miss} distribution for signal and backgrounds is also presented in Fig. 6. The E_T^{miss} distribution for the signal is much harder than backgrounds due to the extra pseudo-goldstino contribution to missing energy. We apply a large missing transverse energy cut to improve signal significance. Based on this analysis, we apply the following selection:

- **Basic selection**: Two opposite-sign leptons with p_T^{ $_1$, $_2$} > 60, 40 GeV, | | < 2.5.
- M_T($_2$, E_T^{miss}) > 120 GeV.
- E_T^{miss} > 120 GeV.
- M_{ $^+$ $^-$} > 140 GeV.
- Veto on tagged b-jets with p_T > 20 GeV and | | < 2.5.
- Veto events with p_T(j) > 50 GeV and | | < 5.0.

[TABLE:V]

Table V presents the cut flow for signal and background events at the LHC with $\sqrt{s}$ = 14 TeV and 100 fb^{-1} integrated luminosity. We have normalized the dominant $t\bar{t}$ background to NNLO [35]. The signal is overwhelmed by backgrounds at the basic selection level. As expected, the M_T cut on the soft lepton can suppress backgrounds while keeping most of the signal. This cut is extremely effective for suppressing the WW background, which is further reduced by a hard cut on E_T^{miss}. The WZ and ZZ backgrounds with two leptons from Z decay are removed by requiring a large invariant mass of leptons. The dominant reducible backgrounds $t\bar{t}$ and tW are strongly suppressed by vetoing b-jets and light jets. After all cuts, the signal-to-background ratio is about 25%.

[TABLE:VI]

Table VI displays the number of signal events and its significance before and after cuts for different luminosities at the 14 TeV LHC. The significance is efficiently improved by these cuts and can reach 5σ for a luminosity of 300–400 fb^{-1}.

[TABLE:VII]

Finally, we note that the LHC has searched for neutralinos and charginos with leptons plus missing E_T at 7 and 8 TeV, and the observed events agree with SM backgrounds (no excess), giving some limits on the relevant parameter space [36]. Since our signals are quite rare compared to the huge SM backgrounds (as our results show, only at 14 TeV LHC with rather high luminosity can our signals be accessible), the current LHC limits at 7 and 8 TeV with limited luminosities cannot yet constrain our scenario. We have verified this numerically, and the results for the 8 TeV LHC are shown in Table VII (since the kinematic distributions of signals and backgrounds for 8 TeV LHC are similar to those for 14 TeV LHC, we use the same cuts as for the 14 TeV LHC in each case). The statistical significances are below 2σ for a luminosity of 21 fb^{-1}.

IV. Conclusion

The pseudo-goldstino is predicted in multi-sector SUSY breaking scenarios. Compared to the ordinary gravitino, it can couple more strongly to the visible sector and thus lead to intriguing collider phenomenology. In this scenario the lightest neutralino (chargino) can decay into a pseudo-goldstino plus a Z-boson or Higgs boson (W-boson). We have performed Monte Carlo simulations for the direct production of the lightest neutralino and chargino followed by their decays to a pseudo-goldstino. Considering higgsino-like, bino-like, or wino-like lightest neutralinos, we found that the signal-to-background ratio (S/B) is 6%–25% and the statistical significance S/√(S+B) exceeds 5σ at the high-luminosity LHC. Therefore, it is feasible to explore such multi-sector SUSY breaking scenarios at the high-luminosity LHC if backgrounds are known to percent-level precision.

Acknowledgments

Lin Wang acknowledges Prof. Johann H. Kühn and Prof. Matthias Steinhauser for their warm hospitality. This work is supported by the Grant-in-Aid for Scientific Research (No. 24540246) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, by the DFG through SFB/TR 9

“Computational Particle Physics,” and by the National Natural Science Foundation of China under grant Nos. 11275245, 10821504, and 11135003.

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