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# The higgsino–singlino world at the large hadron collider

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**Abstract** We consider light higgsinos and singlinos in the next-to-minimal supersymmetric standard model at the large hadron collider. We assume that the singlino is the lightest supersymmetric particle and that the higgsino is the next-to-lightest supersymmetric particle with the remaining supersymmetric particles in the multi-TeV range. This scenario, which is motivated by the flavor and CP issues, provides a phenomenologically viable dark matter candidate and improved electroweak fit consistent with the measured Higgs mass. Here, the higgsinos decay into on (off)-shell gauge boson and the singlino. We consider the leptonic decay modes and the resulting signature is three isolated leptons and missing transverse energy which is known as the trilepton signal. We simulate the signal and the Standard Model backgrounds and present the exclusion region in the higgsino–singlino mass plane at the large hadron collider at $\sqrt{s} = 14$ TeV for an integrated luminosity of 300 fb$^{-1}$.

## 1 Introduction

Supersymmetric (SUSY) models are very popular among the numerous TeV extensions of the Standard Model (SM) [1, 2]. One of the main tasks of the LHC is the direct search for SUSY particles. After three years of running, both LHC experiments ATLAS and CMS have not revealed any new particles beyond the SM, but the absence of any excesses above the SM expectation can be translated into strict limits on the parameter space of low-energy SUSY. In particular, the first two generation squarks and gluinos with masses below 1.7 TeV are excluded if the squarks and gluinos are mass degenerate [3].

This result together with a relatively heavy Higgs [4,5] somewhat undermines the rationale for TeV scale SUSY, since heavy SUSY particles seem to reintroduce finetuning. However, electroweak finetuning arises from the minimization of the scalar potential. The matching condition for electroweak symmetry breaking is $1/2\, M_Z^2 \approx -\mu^2 - M_{H_u}^2$ [6],[1] where $M_Z$ is the mass of the Z boson and $M_{H_u}$ is the mass of the Higgs boson that couples to the top. A very large $\mu$ term is unnatural due to the required precise cancellation between the soft breaking terms and $\mu$. Thus, a supersymmetric model with heavy multi-TeV scalars, but sub-TeV $\mu$ values can still avoid large electroweak finetuning.

SUSY models with heavy multi-TeV matter scalars have the advantage that loop induced flavor changing neutral current and CP violating processes are suppressed [7–9] and help to ameliorate the late time gravitino decay problem [10,11]. Moreover, potential baryon number violating dimension five operators are suppressed and the resulting proton decay rate becomes very small [12]. Ref. [13] considers such a split scenario with light and degenerate higgsinos and decoupled gauginos and matter scalars (*higgsino world scenario*). However, in split scenarios with a light higgsino LSP the annihilation cross section is too large. Assuming standard cosmology, the thermal relic density is too small compared to the WMAP and Planck measurement [14,15] $\Omega h^2 \approx 0.1187$.

The simplest extension of the MSSM is the next-to-MSSM (NMSSM) with a scale invariant superpotential [16]. The supersymmetric Higgs mass term $\mu$ is dynamically generated by the vacuum expectation value (vev) of a gauge singlet chiral superfield $S$ and thus the NMSSM provides a weak scale solution of the $\mu$ problem in the MSSM. The singlet superfield leads to additional singlet-like CP-even and CP-odd Higgs states as well as a singlino-like neutralino state and thus the additional degrees of freedom can provide a solution to the dark matter issue of the *higgsino world scenario*. However, the resulting relic density is either too large or to small in large region of parameter space in the singlet extended *higgsino world scenario*. One solution is to demand a singlino-like neutralino LSP whose annihilation

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[1] Here, we assume $\tan\beta \geq 5$.

cross section is resonantly increased via Higgs bosons in the $s$-channel. Another solution is co-annihilation with a slightly heavier higgsino-like next-to-LSP (NLSP). Both mechanism lead to the desired relic density and hence the singlet extension of the *higgsino world scenario* is a phenomenologically viable model [17,18].

In this paper, we consider a *higgsino–singlino world scenario* with multi-TeV matter scalars and decoupled gauginos, but with a small $\mu$ term and a singlino-like LSP i.e. $m_{\rm singlino} < m_{\rm higgsino} \ll m_{\rm scalar}, m_{\rm gaugino}$. We want to explore the discovery reach of our scenario at the LHC at $\sqrt{s} = 14$ TeV in the production of a neutralino–chargino pair,

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_{2,3}^0 \ \text{with}\ \tilde{\chi}_1^{\pm} \to W^{\pm(*)}\tilde{\chi}_1^0 \ \text{and}\ \tilde{\chi}_{2,3}^0 \to Z^{0(*)}\tilde{\chi}_1^0.$$

The hadronic decays of the higgsinos lead to a final state signature with large QCD background and thus is not a viable signal at the LHC. However, the leptonic decay mode has particularly small QCD and SM background. The signature is three isolated leptons and missing transverse energy. This process is known as the trilepton signal and the corresponding searches has been performed by ATLAS and CMS [19–21]. Studies of the discovery potential at 14 TeV has been studied in [22,23] and in Ref. [24] the discovery potential of CP violation in the trilepton channel has been investigated. In this paper, we want to re-analyze the trilepton study. We simulate the signal and background at hadron level and we take into account the most important detector effect by performing a fast detector simulation. In particular, we derive limits for higgsino-like charginos and neutralinos with a singlino-like LSP at the LHC at 14 TeV which has not been considered in previous works.

The remainder of the paper is organized as follows. In Sect. 2, we discuss our scenario in more detail. In Sect. 3, we briefly review the main phenomenological features of the scenario. In Sect. 4, we first discuss the constraints from LEP2 and the LHC8 results and then the selection cuts before showing the numerical results for two benchmark points. Finally, we show the discovery reach in the higgsino–singlino mass plane at the LHC at $\sqrt{s} = 14$ TeV for an integrated luminosity of 300 fb$^{-1}$. We conclude in Sect. 5.

## 2 The spectrum

We consider the scale invariant NMSSM [16]. Assuming that the gauginos and the sfermions with masses in the multi-TeV scale are essentially decoupled from the low energy scale theory, we are left with the following particle spectrum beyond the SM fields : (i) neutralinos: a singlino-like LSP ($\tilde{\chi}_1^0$), two higgsino-like neutralinos ($\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$); (ii) charginos: higgsino-like state $\tilde{\chi}_1^{\pm}$; (iii) CP-even Higgs fields: the singlet like field ($H_1$), the SM like Higgs field ($h$) and the heavy doublet-like CP-even scalar field ($H_2$) and (iv) the CP-odd scalars: a singlet-like scalar ($a$) and a heavy CP-odd scalar ($A$). In this limit the entire effective theory of the *higgsino–singlino world scenario* essentially reduces to the following superpotential and the corresponding soft breaking part of the Lagrangian assuming a $Z_3$ symmetry

$$\begin{aligned} W_{(\mathcal{H}\mathcal{S})} &= \lambda \mathcal{S}\mathcal{H}_{\rm u}\cdot\mathcal{H}_{\rm d} + \frac{1}{3}\kappa\,\mathcal{S}^3, \\ -\mathcal{L}_{\rm soft}^{(HS)} &= m_{H_{\rm u}}^2|H_{\rm u}|^2 + m_{H_{\rm d}}^2|H_{\rm d}|^2 + m_S^2|S|^2 \\ &+ \left(\lambda A_\lambda H_{\rm u}\cdot H_{\rm d}S + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right), \end{aligned} \tag{1}$$

where $\mathcal{S}$, $\mathcal{H}_{\rm u}$ and $\mathcal{H}_{\rm d}$ denote the singlet, SU(2) doublet up-type and the doublet down-type Higgs superfields, respectively. $S$, $H_{\rm u}$ and $H_{\rm d}$ are the respective scalar fields. $\lambda$ and $\kappa$ are dimensionless Yukawa couplings, whereas the soft breaking terms for the scalar fields are given by $m_{H_{\rm u}}^2$, $m_{H_{\rm d}}^2$ and $m_S^2$. $A_\lambda$ and $A_\kappa$ are the trilinear soft breaking terms. Once the singlet gets a vev, the Higgs mixing term $\mu \equiv \lambda\langle s\rangle$ is generated. This can easily be at the weak scale, solving the usual $\mu$ problem of the MSSM. In the remainder of this section, we briefly sketch the masses of the relevant sub-TeV particles in the theory.

In the limit where $|\mu| \ll M_{\rm gauginos}$, the neutralino mixing matrix block diagonalizes into the predominantly heavy gaugino sector and the light higgsino–singlino sector. The mass matrix of the light higgsino–singlino sector can be written as,

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{bmatrix} 0 & -\mu & -\lambda v_u \\ -\mu & 0 & -\lambda v_d \\ -\lambda v_u & -\lambda v_d & 2\kappa\langle s\rangle \end{bmatrix}. \tag{2}$$

In this paper we only consider the parameter region with $2\kappa < \lambda \ll 1$. This choice ensures that the lightest neutralino is predominantly singlino-like and the chargino and neutralino masses are approximately given by,

$$\begin{aligned} M_{\tilde{\chi}_{2,3}^0} &= M_{\tilde{\chi}^{\pm}} \sim \mu = \lambda\langle s\rangle, \\ M_{\tilde{\chi}_1^0} &\sim 2\kappa\langle s\rangle = 2\frac{\kappa}{\lambda}M_{\tilde{\chi}_{2,3}^0}. \end{aligned} \tag{3}$$

The Higgs sector is composed of the usual CP-even scalar state that will be identified with the Higgs state observed at the LHC with a mass around $\sim 125$ GeV. The mass of this state can be written as,

$$m_h^2 = M_Z^2\left(\cos^2 2\beta + \frac{\lambda^2}{g^2}\sin^2 2\beta\right) + \delta, \tag{4}$$

with $\delta$ quantifying the radiative contributions from the sparticles, mainly from the stops. It will be assumed that the masses of the heavier sfermions will be set by fixing the Higgs mass at 125 GeV.[2] The masses of the other light singlet-like CP-even and CP-odd Higgs is given by,

$$m_{H_1}^2 \sim \kappa \frac{M_{\tilde{\chi}^0_{2,3}}}{\lambda}\left(A_\kappa + 4\kappa \frac{M_{\tilde{\chi}^0_{2/3}}}{\lambda}\right),$$
$$m_a^2 \sim -3\kappa \frac{M_{\tilde{\chi}^0_{1/2}}}{\lambda} A_\kappa. \tag{5}$$

The sub-TeV spectrum will also include the usual doublet type CP-even ($M_{H_2}$) and CP-odd Higgs ($M_A$) which have nearly degenerate mass given by,

$$M_A = 2\mu(A_\lambda + \kappa\langle s\rangle)/\sin 2\beta, \tag{6}$$

and the charged Higgs with mass $M_{H_\pm}^2 = M_A^2 + M_W^2$. In the following, we choose $\lambda \ll 1$, so that the singlino and the singlet-like Higgs bosons only couple weakly to the other particles and thus possible light singlet-like Higgs bosons are not excluded by the LEP constraints. As we discuss below this is also the parameter range that is consistent with the Dark Matter constraints.

This framework is conceptually different from the split [25–27] or mini-split [28] models due to the existence of additional light scalar states. This necessarily includes additional sources of fine-tuning in the classical sense. However, in the paradigm where this notion of naturalness is disregarded [29,30] or reformulated [31–33], such proliferation of sources of fine-tuning may not be considered as conceptually inconsistent. Indeed, in models where the Higgs-Singlet sector is sequestered from the rest of the supermultiplets, this kind of spectrum can naturally arise. E.g., in 5d SUSY models where the Higgs-Singlet multiplets are usually confined to the brane and the rest of the multiplet can access the bulk [34].

## 3 Phenomenology of the higgsino–singlino world scenario

In this section we briefly comment on some phenomenological aspects of the *higgsino–singlino world scenario*:

1. With this split spectrum one can achieve a slightly better fit to the electroweak precision observables. Assuming $\lambda \ll 1$ one can neglect the effect of the singlet-doublet mixing. With this assumption there is negligible contribution to the S and T parameters[3] [35]. The non-zero contributions can be parametrized using the three observables $M_W$, $s_l^2$ and $\Gamma(Z \to l^+l^-)$. The latest experimental values are given in [37]. We utilize the SM prediction including all computed higher order corrections for $M_W$ [38], the leptonic weak mixing angle ($s_l^2$) [39] and $\Gamma(Z \to l^+l^-)$ [40]. The fit to the experimentally measured values is slightly improved in a large region of the parameter space as shown in Fig. 1.
2. In the limit $2\kappa < \lambda \ll 1$, that we explore in this paper, the singlino-like neutralino is the lightest supersymmetric particle, see Eq. (3). With conserved R-parity this can be the dark matter candidate in this class of models [18,41]. The higgsino-like neutralinos and charginos are the NLSPs. They are essentially degenerate with mass $\sim \mu$, except the electroweak corrections that lifts the degeneracy making the charginos slightly heavier by $\sim \mathcal{O}(10)$ MeV.
   We have performed a systematic scan to obtain the region of parameter space that is consistent with the dark matter relic density. Considering that the sfermions and the gauginos are decoupled, one finds that the entire parameter space of the theory, as expressed in Eq. 1, can be defined in terms of the following parameters, $[\lambda,\ \kappa,\ \tan\beta,\ \mu_{\text{eff}},\ A_\kappa,\ M_A]$. We utilize `NMSSMTools` [42,43] and `micrOmegas` [44] to perform a scan over in the range:

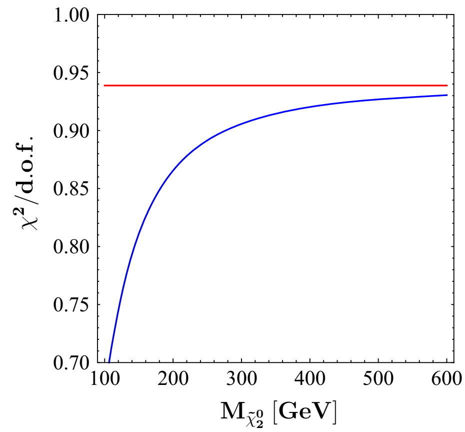


**Fig. 1** $\chi^2/d.o.f.$ fit for the *higgsino–singlino* world scenario using the three observable $M_W$, $s_l^2$ and $\Gamma(Z \to l^+l^-)$ is shown in *blue*. The *horizontal red line* represents the SM prediction

[2] The sfermion mass spectrum depend on the mixing in the stop sector and can be quite light. However in this paper we will focus on models where the mixing is negligible leading to a decoupled stop sector. Realistic origins of such spectrum will be given elsewhere in the discussion.

[3] There are however small corrections that arise due to the mixing with the singlino [36]. An analytical expression for the contribution is difficult. A perturbative expansion of the mass matrix given in Eq. (2) in terms of $\lambda$ gives us $\Delta T \sim \lambda^4 v^2/\mu^2 \cos 2\beta f(M_{\tilde{\chi}^0_1}/\mu)$. In the limit $\lambda \ll 1$ contributions of this order can be safely ignored.

$\lambda = [0.001, 0.1],\ \kappa = [-0.05, -0.01],$
$\tan\beta = [1.5, 20],\ \mu_{\rm eff} = [100, 300]$ GeV,
$A_\kappa = [1, 1000]$ GeV.

A scatter plot for points consistent with observed relic density is shown in Fig. 2 for $M_A = 300$ GeV. The allowed parameter space can be divided into two distinct regions. In the region of the parameter space where $\kappa \sim \lambda/2$, the right dark matter relic density for LSP is achieved through co-annihilation with a relatively degenerate higgsino-like neutralino. The LSP can have a significant higgsino component in this scenario. In this case for effective reduction of the number density a mass difference of $\Delta M = M_{\tilde\chi_1^0} - M_{\tilde\chi_2^0} < 20$ GeV is required. The relative degeneracy of the chargino and the neutralino makes it relatively difficult to probe at the LHC. The collider phenomenology of this region of the parameter space closely resembles the *higgsino world scenario* and have better prospects of being probed at future colliders like the ILC [13]. For the possibility of probing this region at LHC with mono-jets + $\not\!\!E_T$, see [45–47]. A phenomenologically more promising region is obtained when $M_{\tilde\chi_1^0} = 1/2 M_A$, where $M_A$ is the mass of the heavy CP-odd Higgs. In this case the LSP can have efficient resonant annihilation with the heavy Higgs scalars in the $s$-channel. Actually we observe that the relative degeneracy of the CP-even and CP-odd heavy doublet-like Higgs implies a double resonance through the process $\tilde\chi_1^0\tilde\chi_1^0 \to$ on-shell $H_2/A \to b\bar b, aa^*$. In this case the LSP is predominantly singlino-like. In this case a relative separation between the higgsinos and the singlinos of the order of 100 GeV is possible. In the rest of this paper we will concentrate on the collider signal of this region of the parameter space.

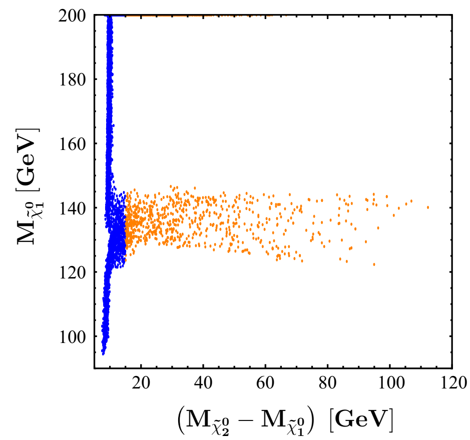


**Fig. 2** Scatter plot of allowed parameter points with $M_A = 300$ GeV is displayed. The *blue* (*darker*) points represent the co-annihilation region while the *red* (*lighter*) points represent regions in the parameter space where the relic abundance is obtained through resonant s channel annihilation of the singlino LSP

## 4 Discovery potential of higgsino–singlino world scenarios at the LHC at $\sqrt{s} = 14$ TeV

In this section, we want to discuss the phenomenological consequences of our *higgsino–singlino* world scenario at the LHC with a relatively simple collider study. The higgsinos and singlinos are the only kinematically accessible supersymmetric states at the hadron collider. Here, we consider associated chargino–neutralino pair production,

$$pp \to \tilde\chi_1^\pm \tilde\chi_2^0,\ \tilde\chi_1^\pm \tilde\chi_3^0. \tag{7}$$

The cross section for chargino–neutralino pair production is determined by $\tan\beta$, $\lambda$, the higgsino mass parameter and the singlino mass. Motivated by the LEP constraints on light singlet like scalars and the Dark Matter constraints discussed above we set $\tan\beta = 10$ and $\lambda = 0.01$ in our study. However the results presented here is relatively insensitive to the specific choice of these parameters. In particular, a different value of lambda only modify the branching ratio of the higgsino slightly as long as lambda is small. In Table 1, we show the total chargino–neutralino pair production cross section in picobarn at the LHC for $\sqrt{s} = 14$ TeV [48]. We assume that the gauginos and sfermions are decoupled and we set $M_{H_\pm} > M_{\tilde\chi_1^\pm} - M_{\tilde\chi_1^0}$, thus the $\tilde\chi_1^\pm$ decays into $W^{(*)}\tilde\chi_1^0$ with a branching ratio of 100%, where the asterisk denotes off-shell $W$ bosons. The heavier neutralino eigenstates $\tilde\chi_2^0$ and $\tilde\chi_3^0$ generally decay into $Z^{(*)}\tilde\chi_1^0$. However, $\tilde\chi_2^0$ and $\tilde\chi_3^0$ can also decay into the CP-even and CP-odd Higgs bosons. The explicit decay properties depend on the details of the Higgs sector. We set $M_A > M_{\tilde\chi_2^0} - M_{\tilde\chi_1^0}$, thus kinematically disallowing the $\tilde\chi_2^0$ and $\tilde\chi_3^0$ to decay into the heavy doublet like Higgs. The branching ratios of the $\tilde\chi_2^0$ and $\tilde\chi_3^0$ into singlet-like Higgs states are negligible, since we consider $\lambda \ll 1$. The branching ratio of the neutral higgsino states into the SM-like Higgs $h$ with a mass of $125 \pm 3$ GeV cannot be neglected, if the decay is kinematically possible. However, the branching ratio of $\tilde\chi_2^0$ and $\tilde\chi_3^0$ into $Z$ is still sizable.

We focus on the leptonic decay modes of the gauge bosons which results in the trilepton and missing transverse energy final state configuration. The trilepton and missing transverse energy ($\not\!\!E_T$) signal at the LHC was first investigated in [22,23]. The ATLAS [19,20] and CMS [21] searches for trilepton and large missing transverse momentum at the LHC at $\sqrt{s} = 8$ TeV with an integrated luminosity of 20 fb$^{-1}$ put already strict constraints on gaugino pair production in a simplified MSSM model. They consider wino-like lightest chargino $\tilde\chi_1^\pm$, heavier wino-like neutralino $\tilde\chi_2^0$ and a bino-

**Table 1** The total $\tilde{\chi}_1^{\pm}\tilde{\chi}_{2,3}^0$ production cross section in picobarn at NLO at the LHC for $\sqrt{s} = 14$ TeV [48]

| $\mu$ (GeV) | 140 | 200 | 260 | 320 | 380 | 440 | 500 | 560 |
|---|---|---|---|---|---|---|---|---|
| $\sigma$ (pb) | 3.315 | 0.921 | 0.350 | 0.159 | 0.075 | 0.044 | 0.026 | 0.016 |

like LSP $\tilde{\chi}_1^0$ with decoupled sfermions and higgsinos. $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ masses up to 345 GeV are excluded. However, the mass limits on charginos and neutralinos are much weaker for the *higgsino–singlino* world scenarios, since the production cross section for higgsino-like charginos and neutralinos are much smaller than for the winos. Ref. [49] published a study with a light *higgsino–singlino* scenario. They derived constraints in the $M_{\tilde{\chi}_1^{\pm}} - M_{\tilde{\chi}_1^0}$ mass plane from the ATLAS trilepton and $\not{E}_T$ search [19]. They found that chargino masses up to 250 GeV are excluded. For small mass differences between the higgsino and the singlino, searches from LEP for $e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0$ are relevant [51,52]. As demonstrated in [49] the LEP bounds are stricter than the current LHC bounds for $M_{\tilde{\chi}_1^{\pm}} \leq 140$ GeV. In the following, we derive the exclusion limits in the *higgsino–singlino* mass plane at the LHC for an integrated luminosity of 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV.

The mass spectrum, couplings and decay widths are obtained with `NMSSMTools 4.1.0` [42–44]. The signal events are generated with `Herwig 2.7.0` [53]. The signal cross sections are normalized with the next-to-leading order (NLO) calculation from `Prospino2.1` [48]. The dominant SM backgrounds WZ, ZZ and $t\bar{t}$ are generated with `Herwig2.7.0`. The NLO cross sections for vector boson pair production and $t\bar{t}$ are taken from `MCFM 6.7` [54] and [55], respectively. We have generated $5 \times 10^5$ leptonic WZ, $5 \times 10^5$ leptonic ZZ events and $10^6$ leptonic $t\bar{t}$ events. The detector effects are estimated with the fast detector simulation `Delphes 3.0.12` [56]. We replaced the ATLAS detector card of `Delphes 3.0.12` with the `CheckMATE 1.1.4` card [57]. The detector tuning of `CheckMATE 1.1.4` has been validated with several ATLAS studies (in particular with [19]) and hence should be more accurate. Our event samples are then analyzed with the program package `ROOT` [58].

Jets are defined using the *anti-*$k_T$ algorithm [59] with $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2} = 0.4$. Here, $\Delta\Phi$ and $\Delta\eta$ are the difference in azimuthal angle and rapidity, respectively. We demand that all jets have $p_T > 20$ GeV and $|\eta| < 2.5$. The $b$-tagging efficiency is 85 %. ATLAS distinguishes between different *kinds* of electrons which have different reconstruction and identification efficiencies as a function of $\eta$ and $p_T$. We require “tight” electrons in our study [57]. All electrons must have $p_T > 7$ GeV and $|\eta| < 2.5$. The electrons must be isolated, i.e., the scalar sum of the transverse momenta of the tracks within $\Delta R = 0.3$ of the electron must be less than 16 % of the electron $p_T$ [19]. As for the electrons, ATLAS also have different types of muons with different efficiencies. We require “combined+standalone” muons in the following [57]. We also demand that all muons have to have $p_T > 7$ GeV and $|\eta| < 2.7$. The isolation requirements for the muons are similar to the electron case, but with a ratio of 12 % [19].

For the overlap removal we use the following procedure [19]. Any jet within $\Delta R \leq 0.2$ of an electron will be removed. This cut prevents double counting, since electrons are usually reconstructed as jets as well. Since we do not want to consider electrons and muons from heavy flavor decays within jets, all electrons and muons within $0.2 \leq \Delta R \leq 0.4$ of a jet will be removed.

We have implemented the lepton triggers from [19]. The single electron or single muon triggers require at least one electron or one muon with $p_T \geq 25$ GeV. The symmetric di-muon trigger demands at least two muons with each $p_T \geq 14$ GeV, while the asymmetric trigger requires $p_T \geq 18$ GeV and $p_T \geq 10$ GeV. For the symmetric di-electron trigger, at least two signal electrons are required to have $p_T \geq 14$ GeV, while for the asymmetric electron trigger, we demand $p_T \geq 25$ GeV and $p_T \geq 10$ GeV. Finally, the mixed electron–muon (muon–electron) trigger requires one electron with $p_T > 14$ GeV (10 GeV) and one muon with $p_T \geq 10$ GeV (18 GeV). In the following, we assume an overall trigger efficiency of 100 %.

All events in the signal regions must contain three isolated leptons (electrons and muons). We demand at least one same flavour opposite sign (SFOS) lepton pair with an invariant mass above 20 GeV to suppress low mass resonances. We have defined three signal regions with one $Z$ depleted region and two $Z$ enriched regions.

For the $Z$ depleted signal region **SRnoZ**, we demand that the SFOS pair closest to the $Z$ mass satisfies $m_{\mathrm{SFOS}} \leq 81.2$ GeV or $m_{\mathrm{SFOS}} \geq 101.2$ GeV. Events with jets with $p_T \geq 20$ GeV are vetoed. Finally, we require $E_T^{\mathrm{miss}} \geq 30$ GeV. This signal region is very similar to the trilepton study presented in [60].

Both $Z$ enriched regions are defined as follows. We require for the invariant mass $m_{\mathrm{SFOS}}$ closest to the $Z$ mass: $81.2\,\mathrm{GeV} \leq m_{\mathrm{SFOS}} \leq 101.2\,\mathrm{GeV}$. We veto all events with $b$-jets with $p_T \geq 20$ GeV. We demand large missing transverse energy with $E_T^{\mathrm{miss}} > 75$ and 150 GeV corresponding to signal regions **SRZ1** and **SRZ2**, respectively. The transverse mass is given by

$$m_T = \sqrt{2 \cdot E_T^{\mathrm{miss}} \cdot p_T^{\ell} \cdot (1 - \cos\Delta\phi_{l,E_T^{\mathrm{miss}}})}, \qquad (8)$$

**Table 2** Number of background and signal events for benchmark point **BP1** with $M_{\tilde{\chi}_2^0} = 160$ GeV and $M_{\tilde{\chi}_1^0} = 100$ GeV after each cut for signal region **SRnoZ**. In the last three columns, we present the ratio between the number of signal and background events, the statistical significance and the significance including systematic errors. All numbers are normalized to 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV

| | WZ | ZZ | $t\bar{t}$ | **BP1** | S/B | $\mathcal{S}_{\text{stat}}$ | $\mathcal{S}_{\text{stat+sys}}$ |
|---|---|---|---|---|---|---|---|
| 3 leptons | 111,143 | 15,282 | 156,210 | 4,675 | 0.02 | 8.8 | 0.2 |
| SFOS | 109,093 | 15,102 | 116,521 | 4,614 | 0.02 | 9.4 | 0.3 |
| $Z$ veto | 15,606 | 1,969 | 99,826 | 4,384 | 0.04 | 12.8 | 0.4 |
| $\not{E}_T$ | 11,507 | 871 | 87,069 | 3,448 | 0.03 | 10.9 | 0.4 |
| Jet veto | 5,812 | 298 | 8,426 | 1,640 | 0.11 | 13.6 | 1.6 |

**Table 3** Number of background and signal events for benchmark point **BP2** with $M_{\tilde{\chi}_2^0} = 400$ GeV and $M_{\tilde{\chi}_1^0} = 20$ GeV after each cut for signal region **SRZ2**. In the last three columns, we present the ratio between the number of signal and background events, the statistical significance and the significance including systematic errors. All numbers are normalized to 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV

| | WZ | ZZ | $t\bar{t}$ | **BP2** | S/B | $\mathcal{S}_{\text{stat}}$ | $\mathcal{S}_{\text{stat+sys}}$ |
|---|---|---|---|---|---|---|---|
| 3 leptons | 111,143 | 15,282 | 156,210 | 132 | 0 | 0.25 | 0.01 |
| SFOS | 109,093 | 15,102 | 116,521 | 129 | 0 | 0.26 | 0.01 |
| $Z$ request | 93,487 | 13,133 | 16,694 | 106 | 0 | 0.3 | 0.01 |
| $b$-jet veto | 89,233 | 12,184 | 6,457 | 97 | 0 | 0.3 | 0.01 |
| $\not{E}_T$ | 1,872 | 102 | 288 | 68 | 0.03 | 1.43 | 0.34 |
| $m_T$ | 47 | 5 | 52 | 50 | 0.48 | 4.9 | 4.03 |

where $\Delta\phi_{l,E_T^{\text{miss}}}$ corresponds to the azimuthal angle between the lepton and the missing transverse momentum vector. The lepton in the $m_T$ calculation is the one which is not the lepton of the SFOS pair. $p_T^\ell$ is the transverse momentum of the lepton. We demand $m_T \geq 110$ GeV in order to suppress the WZ background. **SRnoZ** considers scenarios with small mass splitting between the singlino and the higgsino, which is generally smaller than the $Z$ mass. **SRZ1** and **SRZ2** target scenarios with larger mass differences between the singlino and the higgsino. The difference between **SRZ1** and **SRZ2** is the missing transverse energy cut which is larger for **SRZ2** and thus it is more sensitive for heavy higgsinos and large mass differences between the higgsino and the singlino.

We present the cutflows for the SM backgrounds as well as for two benchmark points for an integrated luminosity of 300 fb$^{-1}$ at the LHC with $\sqrt{s} = 14$ TeV in Tables 2 and 3. The statistical significance is estimated with

$$\mathcal{S}_{\text{stat}} = S/\sqrt{B}, \qquad (9)$$

where $S$ and $B$ correspond to the number of signal events and background events after each cut. We also show the significance taking into account the systematical errors. We assume an overall systematic uncertainty of 10 % for all SM backgrounds. Our estimate of the significance is then given by

$$\mathcal{S}_{\text{stat+sys}} = \frac{S}{\sqrt{B + (0.1 \cdot B)^2}}. \qquad (10)$$

First, we choose a light chargino with $M_{\tilde{\chi}_1^\pm} = 160$ GeV and a singlino with $M_{\tilde{\chi}_1^0} = 100$ GeV for benchmark point **BP1**. Here both $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ decay via off-shell $Z$ bosons. The first cut already provides a statistical significance of 8.8 due to the large production cross section. The dominant backgrounds are WZ and $t\bar{t}$. After the SFOS cut, we veto $Z$ bosons and thus heavily suppress the WZ and ZZ background. We apply a mild $\not{E}_T$ cut which reduces SM backgrounds containing a $Z$. However, nearly 20 % of the signal events do not pass the cut due to the small mass splitting between the higgsino and the singlino. We keep this cut, since it removes the $Zb$ background which we did not simulate [60]. The jet veto heavily suppresses the $t\bar{t}$ background and we obtain a good statistical significance of 13.6. Finally, if we account for systematic errors, the significance reduces to 1.6 owing to the large systematic uncertainty of the WZ and $t\bar{t}$ backgrounds. $t\bar{t}$ remains as one of the dominant background in **SRnoZ**. Note that our $t\bar{t}$ background is larger than in [60], partly because they did not normalise their $t\bar{t}$ sample to the NLO cross section. We rescaled their cross section to NLO, but their $t\bar{t}$ background is still smaller than our estimate, because they further reduced the $t\bar{t}$ background by imposing different isolation criteria for the leptons. In addition, they demand a larger minimal transverse momentum of 10 GeV on the leptons. However, we keep our isolation requirements, since we validated our analysis with [19]. In any case, we believe that our background estimate for $t\bar{t}$ is sufficiently conservative.

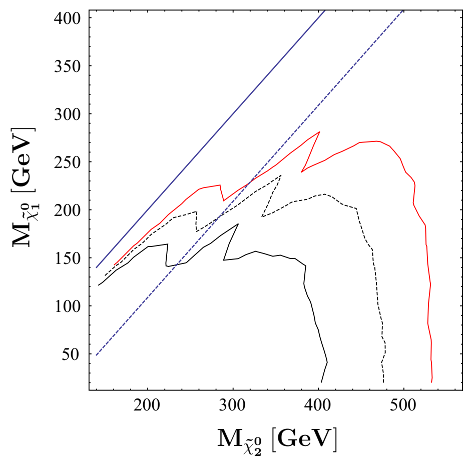


**Fig. 3** Signal significance (only statistical errors) in the $\tilde{\chi}_2^0$-$\tilde{\chi}_1^0$ mass plane assuming an integrated luminosity of 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV. The *red, black dashed and black solid curve* corresponds to 2, 3 and 5$\sigma$, respectively. The *blue dashed line* indicates $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} = m_Z$ whereas the *blue solid curve* delimits the region with a singlino LSP

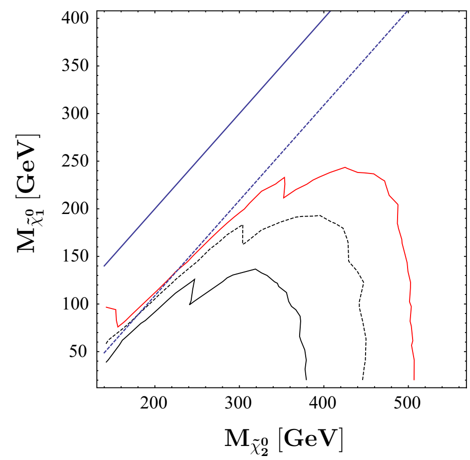


**Fig. 4** Signal significance including systematic errors. Everything else is the same as in Fig. 3

In scenario **BP2**, the neutralino and chargino masses are set to $M_{\tilde{\chi}_1^\pm} = 400$ GeV and $M_{\tilde{\chi}_1^0} = 20$ GeV. On-shell decays of $\tilde{\chi}_{2,3}^0$ into $Z$ are still dominant even though decays into the SM Higgs are kinematically allowed. The branching ratios are BR$(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + Z) = 65\,\%$ and BR$(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 + Z) = 43\,\%$. The first two cuts are identical as for **BP1**. The SFOS and the $Z$ requirement suppress the $t\bar{t}$ background. We apply a $b$-jet veto which further reduces the $t\bar{t}$ background while the other backgrounds are still sizable. However, the strict cut on the missing transverse energy heavily suppresses the di-gauge boson backgrounds. The final cut on $m_T$ further reduces the WZ background and we obtain a statistical significance of about 4.9. Taking into account the systematic uncertainty, we still obtain a significance of 4.

In Fig. 3, we present the exclusion limits in the $\tilde{\chi}_2^0$–$\tilde{\chi}_1^0$ mass plane at the LHC at $\sqrt{s} = 14$ TeV with 300 fb$^{-1}$. The statistical significance is estimated with Eq. (9). The best signal region is chosen for each point in the mass plane. The red, black dashed and black solid curve correspond to $2\sigma$, $3\sigma$ and $5\sigma$, respectively. Above the blue solid line, the decay of the higgsino into a singlino + $X$ is not allowed. The blue dashed line corresponds to $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} = m_Z$. Below the blue dashed line, the $\tilde{\chi}_2^0$ decays in a 2-body decay with $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$. Here, the selection cuts of the $Z$ enriched signal regions provide the best sensitivity for our signal. Above the blue dashed curve, the $\tilde{\chi}_2^0$ decays via off-shell $Z^*$ in a three body final state which is sensitive to the $Z$ depleted signal region. We are sensitive for higgsino masses up to 540 GeV for massless singlinos. With decreasing mass difference between the higgsino and the singlino, the significance drops sharply. Decreasing the mass splitting reduces the average $p_T$ of the leptons. Thus, the final state leptons becomes too soft which does not allow to separate our signal from the SM background. However, these region can be probed in higgsino pair production in association with a hard jet [45–47] or a trilepton search with a relatively hard initial state radiation jet [61].

In Fig. 4, we included the systematical errors for the calculation of the significance, see Eq. (10). Higgsino masses up to 500 GeV can be excluded for massless singlinos. We are not sensitive to small mass differences between the higgsinos and singlinos due to the large systematic errors of the WZ and $t\bar{t}$ backgrounds. However, our estimate of 10 % is quite conservative and hence Fig. 4 is a rather pessimistic estimate of the exclusion limit for small mass differences. As more data is collected, the systematic uncertainties will be much smaller and one can expect to cover a substantial portion of the DM allowed region through the trilepton channel.

## 5 Conclusion

In this paper, we considered a light *higgsino–singlino world scenario* with decoupled matter scalars and gauginos in the NMSSM. There are phenomenological reasons to consider such a split scenario. The non-observation of supersymmetric particles with a relatively heavy Higgs provides strict limits on the soft breaking scale of supersymmetry. However, finetuning arguments favor relatively light higgsinos. But a light higgsino LSP with multi TeV scalars and gauginos typically results in a too small relic density in standard cosmology. On the other hand, a supersymmetric model with a light higgsino–singlino sector can provide a viable DM candidate. If the higgsino is the NLSP with a small splitting to the singlino LSP, co-annihilation between both sparticles can lead to the correct relict density. However, for a relative degeneracy between the higgsino and the singlino, the production of higgsinos is difficult to detect at the LHC since the decay products of the higgsinos are very soft. On the other hand, the right amount of the relic density can be obtained via resonant annihilation with heavy Higgs scalars while allowing for a large mass splitting between the higgsino and the singlino. Another advantage to consider a *higgsino–singlino world scenario* is that flavor changing neutral current CP violating processes are suppressed and that the gravitino problem is solved. Thus motivated, we focused on the production of a higgsino-like chargino neutralino pair at the LHC. In particular, we considered the leptonic decay modes which results in the trilepton and missing transverse energy final state. In this work, we present a collider study of the *higgsino–singlino world scenario* at the LHC at $\sqrt{s} = 14$ TeV for an integrated luminosity of 300 fb$^{-1}$. We simulated the signal and the most important SM backgrounds with recent MC simulations and we also estimated the detector response with a fast detector simulation. We considered three signal regions corresponding to a $Z$ depleted region (for small mass differences between the higgsino and the singlino) and two $Z$ enriched signal region. We discussed in detail the cuts for two benchmark scenarios. We examined the discovery reach in the higgsino–singlino mass plane. For massless singlinos, higgsinos with masses up to 500 GeV can be excluded for an integrated luminosity of 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV. However, the discovery reach is severely constrained in the small splitting region due to the low efficiency of the selection cuts and the assumptions on the systematic errors. Higgsino masses with a mass splitting of the order of the $Z$ mass boson can be excluded with 200 (300) GeV assuming a systematic error of 0 % (10 %). However, the region of small splitting would require more involved search strategies [45–47,61] to be accessible at the LHC. Finally, our results of the discovery reach are also true if we allow for non-split scenarios, e.g. if matter scalars are kinematically accessible at the LHC, but do not alter our assumptions of the decay chain.

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