Searching for the Higgsino-Bino sector at the LHC

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ABSTRACT: We study the search for electroweakinos at the 13 TeV LHC in the case of heavy scalar superpartners. We consider both the direct production mode and the one associated with the decay of heavy Higgs bosons, and concentrate on the case of light Higgsinos and Binos. In this case, the direct production searches becomes more challenging than in the light Wino scenario. In the direct production mode, we use the current experimental searches to set the reach for these particles at larger luminosities, and we emphasize the relevance of considering both the neutral gauge boson and the neutral Higgs decay modes of the second and third lightest neutralino. We show the complementarity of these searches with the ones induced by the decay of the heavy Higgs bosons, which are dominated by the associated production of the lightest neutralino with the second and third lightest ones, with the latter decaying into gauge bosons. We show that, depending on the value of $\tan \beta$, the Higgs boson decay channel remains competitive with the direct production channel up to heavy Higgs boson masses of about 1 TeV. Moreover, this search is not limited by the same kinematic considerations as the ones in the direct production mode and can cover masses up to the kinematic threshold for the decay of the heavier electroweakinos into the lightest neutralino. This decay mode provides also an alternative way of looking for heavy Higgs bosons in this range of masses and hence should be a high priority for future LHC analyses.

KEYWORDS: Beyond Standard Model, Supersymmetric Standard Model

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1 Introduction

The Standard Model provides an excellent low energy effective theory describing the interaction of particles at energies similar to or smaller than the weak scale. Searches at the LHC are underway looking for the possible production of new particles with masses up to a few TeV. No clear signal of new physics has been found, leading to strong bounds on the presence of strongly interacting particles at the TeV scale (see, for instance, refs. [1, 2]). However, if the particles are weakly interacting, new physics searches may be hindered by small production cross sections and large backgrounds induced by the production of the weak gauge bosons and strongly interacting states, like the top and bottom quarks. Contrary to strongly interacting states, many weakly interacting particle search channels will become statistically significant only at high luminosities. For this reason, the LHC experimental collaborations are now starting to put stronger emphasis on the search for weakly interacting particles [3–13].

Among the many hypothetical weakly interacting particles, the electroweakinos, namely the superpartners of the Higgs and electroweak gauge bosons, are well motivated examples [14–16]. They are a natural consequence of supersymmetry at the TeV scale [17–21]. Weakly interacting supersymmetric particles are not subject to strong renormalization group effects in the evolution of their masses from high scales, and are therefore expected

to be lighter than strongly interacting ones. Moreover, this sector includes the Dark Matter candidates within these theories [22, 23]. Since Dark Matter is arguably one of the strongest reasons to expect new physics among the Standard Model, the search for these particles is particularly well justified. The superpartner of the hypercharge gauge boson, the Bino, places a special role beyond these particles, since it does not couple to any of the electroweak gauge bosons and therefore, after mixing with the heavier superpartners of the Higgs and the electroweak gauge bosons, can acquire the proper relic density for masses significantly lower than the TeV scale. The superpartners of the Higgs bosons, the Higgsinos, are very relevant in defining the light Dark Matter candidate interactions, since they mix with the Bininos through the Higgs vacuum expectation values. In this work, we shall assume, for simplicity, that the superpartners of the weak gauge bosons, the Winos, are significantly heavier than the two neutral Higgsino states, which therefore will become the second and third lightest neutralinos. Moreover, we shall assume that all scalar superpartners are sufficiently heavy, so that they do not participate in a relevant way in the decays of the Higgs bosons or electroweakinos.

Searches for electroweakinos at the LHC have so far been performed in direct production channels [3–6, 8–13]. The main production channel is mediated by charged and neutral electroweak gauge bosons, and can lead to hadronic, semi-leptonic and purely leptonic final states plus missing energy. Of particular relevance among these channels is the associated production of charged and neutral electroweakino states, with charged states decaying into $W^\pm$ bosons and the lightest neutralino state, and the second (and third) lightest neutralino states decaying into neutral gauge and Higgs bosons. The assumption of heavy Winos and scalar superpartners tend to weaken the reach of the LHC, since Winos have higher cross sections than the Higgsinos and light sleptons tend to contribute to the electroweakino decays increasing the total branching ratio into leptons, which are easier to distinguish from the large QCD background. Since the LHC limits are usually presented considering Wino direct production, e.g. [10], we shall recast these searches by studying the Higgsino cross sections and the proper decay branching ratios into SM Higgs and Z -boson final states.

Although well motivated, searches for electroweakinos proceeding from the decay of heavy Higgs bosons are in a preliminary state. There has so far been only a few relevant theoretical analyses of heavy Higgs bosons decaying into electroweakino states [24–43], concentrating mostly on the associated production of the lightest, and second and third lightest neutralinos, which then lead mostly to decay channels involving single production of the Z and Higgs bosons plus missing energy. Similar studies have been performed in the Next-to-Minimal-Supersymmetric-Standard-Model (NMSSM) [44–50]. These analyses show the relevance and the promising reach of these channels and serve as motivation for our work. For the comparison with the direct production channel, it is most relevant to understand the reach in the electroweakino mass parameter space, something not provided by these analyses.

In this work, we shall analyze the complementarity of the direct production and Higgs boson decay channels. The work is organized as follows: section 2 provides an analysis of the electroweakino and Higgs production cross sections. Section 3 provides the recast of existing searches to higgsino-like electroweakinos. In section 4, we concentrate on the

di-lepton plus missing energy channel for electroweakinos from the decay of heavy neutral Higgses and then present the complementarity of this search channel with the projected bounds for direct production. Section 5 is reserved for our conclusions.

2 Electroweakino productions

Scenarios where all strongly-interacting superpartners are decoupled from the rest of the MSSM are particularly well motivated both from the current status of direct searches at the LHC and the measurement of the Higgs boson mass. Indeed, within the MSSM, a 125 GeV SM-like Higgs boson mass may only be obtained for masses of the superpartners of the top quark of the order of 2 TeV or larger [51–55]. Disregarding sleptons for the moment, the remaining states of the MSSM then are the superpartners of the weak gauge bosons and Higgs doublets, and additional Higgs bosons. Assuming this low-energy spectrum leads to a particularly simple set of states, whose dynamics are determined by only a few parameters. The neutralinos appear as mixtures of the Bino, Wino, and the Higgsinos whose mass matrix is given by

$$M_N = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}, \quad (2.1)$$

where $c_W = \cos \theta_W$, $s_W = \sin \theta_W$, and θ_W is the weak-mixing angle, $c_\beta = \cos \beta$, $s_\beta = \sin \beta$, and $\tan \beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$ is the ratio of the vacuum expectation values of the Higgs doublets. The mass M_1 is the Bino mass parameter, M_2 and μ are the Wino and Higgsino mass parameters, respectively. Similarly, the chargino states appear as mixtures of charged Wino and Higgsino components with mass matrix

$$M_C = \begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}. \quad (2.2)$$

For a more detailed review of the resulting mass eigenstates and couplings see ref. [18] and references therein. Including the Higgs sector of the MSSM, the low energy theory results in a rich phenomenology where the relevant parameters are $\{M_1, M_2, \mu, \tan \beta\}$ and the masses of the heavy Higgs bosons, which are characterized with the CP-odd Higgs mass parameter m_A . In the case when the Wino is also decoupled the lightest electroweakinos are Bino-, and Higgsino-like. In this limit, the results we present in the following sections relies mainly on only four parameters $\{M_1, \mu, \tan \beta, M_A\}$.

2.1 Direct electroweakino production

The direct production of electroweakino states is governed by the interchange of $W^\pm$ and Z gauge bosons (see for instance, ref. [18]). Since the Bino does not couple to the gauge bosons, all production modes are controlled by the Higgsino couplings to gauge bosons, and the production of a particular mass eigenstate will depend on its component of the Higgsino

states. Assuming the lightest supersymmetric particle is mostly a Bino, its production, although kinematically favored, may only happen through its mixing with the neutral Higgsino states. Pair production of Bino states may be measured via its recoil against jets, in the jets plus missing energy channel. However, the production cross section tends to be too small to be competitive with other search channels. Binops may be hence mostly produced in association with the charged and neutral Higgsino states, leading after the decay of the heavier states to final states consisting of h , Z or $W^\pm$ plus missing energy. However, unless the Bino and Higgsino masses are close to each other, the cross sections are again too small to make these competitive search channels.

Much more promising is the search for electroweakinos via the production of the heavier, but mainly Higgsino states. Since it is not hampered by mixing, this search is only limited by the kinematic effects related to low production cross sections associated with high mass states. Also, in the limit of heavy superpartners, the Higgsino cross sections are smaller than the Wino cross sections, implying also a smaller reach than in the case of light Winos. Interestingly enough, since the scalar leptons couple to the Higgsino states in a way proportional to Yukawa couplings, the search for Higgsinos tends to be minimally affected by the presence of such states, which in this scenario will therefore mainly decay into leptons and missing energy and can be searched separately from the Higgsino states. This is relevant, since light sleptons may contribute to an explanation of the $g - 2$ anomaly [56–61]. Observe, however, that the contributions to the muon anomalous magnetic moment are highly reduced in the case of heavy Winos. In fact, even if the slepton masses were only a few hundreds of GeV, the contributions to $(g - 2)_\mu$ in the region of parameters we are considering, for moderate values of μ and $\tan\beta$, is only a few times 10^{-10} and not large enough to fit the Brookhaven experiment observation [62],

$$\delta a_\mu^{\text{exp}} \simeq (27 \pm 7 \pm 5) \times 10^{-10}, \quad (2.3)$$

where the errors are associated with experimental and theoretical uncertainties. Fitting the Brookhaven experiments would demand large values of $\tan\beta$ pushing the Higgs masses to values larger than 1 TeV [63, 64], for which the Higgs boson decay into electroweakinos ceases to be a competitive search channel.

Regarding the Higgsino being a Dark Matter candidate, if one assumes that the Dark Matter relic density comes from thermal annihilation, one needs to mix Higgsino and Bino appropriately to reach the right relic abundance. This is the so-called well tempered neutralino region [65], which tends to be in tension with direct detection experiments [66–71]. However, the relic density constraints can be easily evaded in the case of light Binops by the assumption of late entropy production (see, for instance, ref. [72]). Other ways to avoid the relic density constraints in the region of parameters we are concentrating on include coannihilation, Z -resonance annihilation, h -resonance annihilation (see, for instance, refs. [73–76]). Moreover, it is easy to weaken the spin-independent direct Dark Matter search constraints by simply concentrating on negative values of μ (see refs. [71, 77–83]). Though, it is worth noting that the constraints from spin-dependent Dark Matter searches will still apply [84, 85].

Figure 1. Representative decay topologies of electroweakino production at the LHC. *Left:* direct production channels resulting from pair producing a chargino and neutralino. *Right:* the Higgs portal channel resulting from the production of a heavy neutral Higgs boson decaying to neutralino pairs.

For the reasons discussed above, we will be mostly interested in the production of mainly Higgsino states with negative values of μ . The spectrum will consist of two neutral Majorana states, the second and third lightest neutralinos, and one charged Dirac state. The associated direct production of the charged and neutral states, mediated mostly by the charged gauge boson $W^\pm$ carries the largest cross section and it is represented in figure 1. Since the second and third lightest neutralinos are close in mass, provided it is kinematically allowed, they will mostly decay into either Z or light Higgs h final states plus missing energy. The chargino state, instead will decay into $W^\pm$ and missing energy

$$pp \rightarrow \chi_1^\pm + \chi_h^0 \rightarrow W^\pm + Z/h + \cancel{E}_T, \quad (2.4)$$

where $h = 2, 3$. We will concentrate in the region of parameters where the second and third lightest neutralino can decay into on-shell Z gauge bosons. Therefore, considering the decay of the $W^\pm$ into lepton states, the most interesting final states will be either tri-leptons plus missing energy or pairs of bottom quarks plus one lepton plus missing energy. Considering the decay of the $W^\pm$ into hadrons, the most interesting channel is two leptons (from Z) or two bottoms (from h) and missing energy.

In figure 2 we present the dependence of the associated production cross section as a function of the Higgsino mass parameter μ that we take to be negative for this consideration, and that represents the overall scale of the Higgsino masses (there is a small dependence of the Higgsino spectrum on the sign of μ , which is however, only significant for low values of μ , of the order of 100 GeV). We also represent, for comparison, the production of Winos, as a function of the Wino mass parameter M_2 , making evident the larger cross sections associated with these states.

The branching ratios also play an important role. The presence of two different Higgsino states imply that their decay branching ratios will not be equal. These two Higgsino states are close in mass, particularly for masses larger than Higgs mass, 125 GeV, for which also the dependence on the sign of μ becomes less significant. It is therefore useful to represent the sum of the branching ratios of the decay of the second and third lightest neutralinos into Z and Higgs final states. These are given in figure 3. In each case, we

Figure 2. Comparison of the LO direct production cross sections of electroweakinos in the pure Wino scenario (dashed lines) and the Bino-Higgsino scenario (solid lines) with $M_1 = 100$ GeV and $\tan \beta = 5$, assuming that scalar superpartners are decoupled. In the former case, $\mu = -2$ TeV and $m = M_2$ is varied. In the latter, $M_2 = 2$ TeV and $m = |\mu|$ is varied.

calculate the branching ratio using the code **Spheno** [86, 87] as functions of the parameters

$$M_1 \in [5, 500], \quad -\mu \in [100, 900], \quad (2.5)$$

assuming $M_2 = 2$ TeV, $\tan \beta = 5$, and $M_A = 1$ TeV.¹ For large values of $|\mu|$ the two neutralino Majorana states behave effectively like a single neutral Dirac state and, due to the Goldstone equivalent theorem, one expects that, approximately, the neutral states will decay 50 percent of the time into Z and 50 percent of the time into h final states, something that is evident from figure 3.

In the low mass range, provided both neutralinos become lighter than the Standard Model-like Higgs boson, they will decay into Z final states 100 percent of the time. However, we remark that for low values of $\tan \beta$ the splitting can be large enough so that whenever one neutralino is lighter than the Higgs the other becomes heavier, up to the point when the lightest neutralino can no longer decay into on-shell Z bosons. Apart from this, the total branching ratios of electroweakinos to the Z or Higgs boson display the same behavior for values of $\tan \beta$ that we consider.

¹Note that for lower values of the heavy Higgs mass, such that $M_A < m_{\chi_1^\pm} + m_{\chi_1^0}$, decay channels of electroweakinos to heavy Higgs bosons may become kinematically open. However, the corresponding branching ratios of these channels would be too small to be of any relevance.

Figure 3. *Left:* sum of the total branching ratio of Higgsinos to the Z boson, $\chi_{2,3}^0 \rightarrow Z + \chi_1^0$, normalized by 1/2. *Right:* sum of the total branching ratio of Higgsinos to the SM Higgs, $\chi_{2,3}^0 \rightarrow h + \chi_1^0$, normalized by 1/2. We show contours resulting from the scan in eq. (2.5), for $\tan\beta = 5$.

2.2 Electroweakinos from heavy Higgs production

The production of electroweakinos from the decay of heavy Higgs bosons has a different parametric dependence than the direct production. This is due to the fact that, contrary to the coupling to Z gauge bosons, pure Higgsino states do not couple to the heavy Higgs boson due to gauge invariance, and the coupling always involves mixed Higgsino and gaugino (Bino) components. Hence, the heavy Higgs decays into a mostly Higgsino and a mostly Bino state is preferred with respect to both the relevant couplings and kinematics.

There are hence two main possibilities. Either the lightest neutralino is produced from the decay of neutral Higgs bosons, in association with the second and third lightest neutralinos, or it is produced in association with the chargino states, coming from the decay of the charged Higgs boson. In the case of neutral Higgs bosons, which is diagrammatically represented in figure 1, where the second and third lightest neutralino can decay into either a Z or a Higgs boson h (the heavier Higgs bosons are highly degenerate in mass), leading to interesting mono-Higgs and mono-Z final states. Among the mono-Z final states, the decay into two leptons becomes particularly interesting as has already been emphasized in refs. [39]–[50].

Figure 4. The production cross-section for the process $H/A \rightarrow \chi_{2,3}^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ for higgsino-like electroweakinos, with heavy scalar mass $m_A = 600$ GeV and $\tan\beta = 2, 5, 8, 10$ respectively.

The charged Higgs production mode is also interesting. Charged Higgs, however, can only be produced at sufficiently high rates in association with top and bottom quarks, implying significantly smaller cross sections than the ones associated with neutral gauge bosons. Also, the final state is similar to the top-quark pair production mode, albeit with significant missing energy. Hence the reach is hampered by the large $t\bar{t}$ background. For these reasons, in this work we shall not concentrate on this mode, but we plan to come back to it in an independent analysis.

3 Reach of direct production searches of higgsino states at higher luminosities

In order to compute the reach for Higgsino states in the direct production mode, we have considered a number of recent ATLAS studies, refs. [7, 9, 10, 12], in which they present bounds on the masses of charginos and neutralinos at the 13 TeV LHC for luminosities ranging from 36 fb^{-1} to 139 fb^{-1} .² The bounds presented in these studies assume that the electroweakino spectrum results from parameters aligned with the pure Wino scenarios and that the corresponding branching ratios of neutralinos into either the Z boson or SM h are 100 percent, depending on the study. We have recasted each bound including the cross sections associated with the production of Higgsino-like states, and incorporated the branching

²The CMS study shows similar sensitivities when luminosity is the same, see [5].

ratios of the neutralino states for a given chargino mass (which is also degenerate in mass with the neutral Higgsino states for large values of μ) resulting from the scan of eq. (2.5).

To obtain the relevant cross section starting from the parameters M_1, μ and $\tan \beta$, mass eigenstates, mixings, and branching ratios are calculated with **FeynHiggs** [55, 88–94] linked with **SPheno**. The branching ratios of EW-inos to SM gauge bosons have also been checked with **SUSY-HIT** [95]. When presenting bounds on direct search channels we consider fixed $\tan \beta = 5$. In the Higgsino-Bino limit, the $\tan \beta$ dependence on the relevant branching ratios follows as $\text{BR}(\chi_2^0 \rightarrow Z/h + \chi_1^0) \sim \frac{1}{2}(1 \mp \sin(2\beta))$ and $\text{BR}(\chi_3^0 \rightarrow Z/h + \chi_1^0) \sim \frac{1}{2}(1 \pm \sin(2\beta))$, when $|\mu| - M_1$ is significantly larger than m_h [96]. Thus, since we sum both contributions from χ_2^0 and χ_3^0 in the production channels, the overall dependence of the total cross is dominated by kinematics rather than the coupling, as expected by the Goldstone Boson Equivalence theorem. In contrast, the Higgs production channel will depend strongly on $\tan \beta$. We will explore this complementarity of the parameter space further in the following section.

LO cross sections were generated and cross checked between **MadGraph5** [97] and **Prospino2.1** [98]. For chargino masses ~ 100 GeV the K-factors between LO and NLO electroweakino cross sections are about $K \simeq 1.3$ [99]. We find that the K-factors decrease to $K \simeq 1.1$, once the mass of the chargino reaches ~ 500 GeV. As this variation occurs in a region which is relevant to the current bounds, we have used the NLO cross sections from **Prospino2.1** in our results. For each chargino-neutralino pair in the scan we then compare the cross section to the corresponding 95% CL upper limit, $\sigma_{\text{limit}}^{\text{up}}$, taken from **HEP-Data**

$$N_{\text{sig}}(N_{\text{bkg}}, 95\%) = \sigma_{\text{limit}}^{\text{up}} \epsilon_{\text{eff}} L. \quad (3.1)$$

Assuming that the background efficiencies remain the same, we then find the bound for Higgsino-Bino masses via

$$\sigma(pp \rightarrow \chi_1^\pm \chi_{2,3}^0) \text{BR}(\chi_1^\pm \rightarrow W^\pm + \chi_1^0) \text{BR}(\chi_{2,3}^0 \rightarrow Z/h + \chi_1^0) = \sigma_{\text{limit}}^{\text{up}}. \quad (3.2)$$

Finally, we extrapolate the existing bounds for the 13 TeV LHC to luminosities of 300 fb^{-1} and 3 ab^{-1}

$$\sigma_{\text{limit}}^{\text{up}; L'} = \sqrt{\frac{L^{\text{exp}}}{L'}} \sigma_{\text{limit}}^{\text{up}}, \quad (3.3)$$

where L^{exp} is the corresponding luminosity for each analysis that we have considered.

Inspection of the LHC experiment analyses reveal that the most powerful searches are associated with the tri-lepton final states and the Higgs final state. In the following subsection, we review the status of the different search channels for Higgsino-like states. We note that since the efficiencies tend to be improved with further analyses and the energy will be eventually upgraded to values of order of 14 TeV our analysis should be considered as a conservative one.

3.1 ZW channels

This is the traditional search channel for electroweakinos and leads to very powerful results at high luminosities. The ATLAS collaboration has explored this channel using a variety of techniques and final states. As mentioned, final states with three leptons [12] or two

Figure 5. Constraints on the Bino-Higgsino scenario projected to 300 and 3000 fb⁻¹ at 95% confidence level in the top panel, 139 fb⁻¹ at 95% confidence level and 3000 fb⁻¹ at 5 σ in the lower panel. We choose $\tan \beta = 5$, but the results depend very weakly on this choice for the range of parameters that we explore. The $0lbb$ (gray) [9] and $1lbb$ (magenta, cyan) [10] come from the $\chi_{2,3}^0 \chi_1^\pm \rightarrow hW + 2\chi_1^0$ channel, with $h \rightarrow \bar{b}b$ and W decay to hadronic or leptonic final states. The 3ℓ (dark yellow) [12] and $3\ell/2\ell + j$ (orange) [8] come from the $\chi_{2,3}^0 \chi_1^\pm \rightarrow ZW + 2\chi_1^0$ channel, with $Z \rightarrow 2\ell$. For the gray and orange shaded region, there are dotted lines cutting off the high mass region because σ_{limit} is not provided from HEP-Data.

leptons with jets [7] provide the strongest reach. After recasting the LHC analyses for the case of Higgsinos and using both the Recursive Jigsaw reconstruction method as well as the standard ones, we observe the sensitivity for Higgsino-like electroweakinos at a luminosity of 300 fb^{-1} in the top left panel of figure 5. The LHC should be capable of reaching Higgsino masses of about 500 GeV, but only for lightest neutralino masses that are lower than 200 GeV, and far from the kinematic threshold for the decay of the second and third lightest neutralino into Z states. This is due to the fact that, for masses close to this kinematic threshold, the leptons carry low p_T values. This is one of the main advantages of the Higgs production mode, where the leptons will receive higher p_T contributions due to the high p_T of the electroweakinos proceeding from the decay of the heavy Higgs bosons.

In the top right panel of figure 5, at higher luminosity of 3000 fb^{-1} , the situation is highly improved. On one hand, Higgsino masses up to 750 GeV could be reached in this case, for lightest neutralino masses up to about 300 GeV. The reach for 3ℓ (dark yellow line) stops at the dotted lines. In this case, $\sigma_{\text{limit}}^{\text{up}}$ is not provided for the higher mass region in the current searches. However, it is expected that updated searches would be sensitive to this region. In general, this is a highly interesting reach, that covers the region of Higgsino masses one would associate with a natural low energy supersymmetry scenario. But the kinematic limitations close to threshold are still present, although only for higher lightest neutralino masses.

3.2 hW channels

A secondary channel to probe the production of charginos and neutralinos occurs when the neutralinos decay to a SM Higgs boson. The ATLAS collaboration has studied this channel for electroweakino pair production of $\chi_1^\pm \chi_2^0$. Similarly, the production cross sections assumed couplings associated to Wino-like couplings and the decay branching ratio of $\chi_1^\pm \rightarrow W^\pm \chi_1^0$ and $\chi_2^0 \rightarrow h \chi_1^0$ are both 100% [9, 10]. The final states considered in these studies are $0\ell + \bar{b}b$, $1\ell + \bar{b}b$, $1\ell + \gamma\gamma$ and $\ell^\pm \ell^\pm$, which arise from a combination of leptonic and hadronic decays of the $W^\pm$, and SM Higgs decay into $\bar{b}b$, $\gamma\gamma$ and 2ℓ . From their results we find that the $0\ell + \bar{b}b$ and $1\ell + \bar{b}b$ channels provide the strongest bound, therefore to explore the ultimate reach for Higgsino-like electroweakinos we only recast these channels.

We find that these channels provide a 95% CL reach for larger chargino masses almost up to 600 (750) GeV for luminosity of 300 (3000) fb^{-1} , as shown in the top panel of figure 5. For luminosity of 300 fb^{-1} , only the $0\ell + \bar{b}b$ channel provides constraints, for $m_{\chi_1^\pm}$ between 400–600 GeV and very light χ_1^0 , while the bound from the $1\ell + \bar{b}b$ channel vanishes. This already shows the need for higher luminosities to search for higgsino-like electroweakinos in this decay channel. For luminosity of 3000 fb^{-1} , we see a dramatic enhancement of the constrained region for both $0\ell + \bar{b}b$ and $1\ell + \bar{b}b$ channels.

Moreover, in the bottom right panel of figure 5 we show the 5σ reach for direct production of Higgsino-like states at HL-LHC both for the ZW and hW channels. Comparing with the bottom left panel of figure 5, we see that it is still possible to discover light electroweakinos in the HL-LHC era in regions of parameters not already probed at current collected luminosity of 139 fb^{-1} . Our results are consistent with other projections to future upgrades at the LHC [96, 100, 101].³

³For other theoretical studies in this direction see [74].

4 Reach of the Higgs decay production mode at higher luminosities

Although there are already a few theoretical analyses of this mode [39]–[50], there is to our knowledge no dedicated search for electroweakinos in this production mode. Therefore we performed our own analysis of the background and production rates.⁴ We concentrated only on the gluon fusion mode, and on the lepton decays of the Z bosons proceeding from the decay of the second and lightest neutralinos in the lepton plus missing energy analysis. Thus, the relevant signal results in two opposite-sign, same flavor leptons with significant missing energy

$$gg \rightarrow H/A \rightarrow \chi_h^0 + \chi_1^0 \rightarrow \ell^+ \ell^- + \cancel{E}_T, \quad (4.1)$$

where we sum the channels from heavy neutral scalar H and pseudoscalar A production, and $h = 2, 3$.

The production of Higgs bosons become significant at either small or large values of $\tan \beta$, for which the gluon fusion cross section is proportional to the large top and bottom-quark Yukawa couplings, respectively. The main couplings governing the production cross section are given by

$$g_{Ht\bar{t}} \simeq g_{At\bar{t}} \simeq \frac{m_t}{v \tan \beta} \quad (4.2)$$

and

$$g_{Hb\bar{b}} \simeq g_{Ab\bar{b}} \simeq \frac{m_b \tan \beta}{v(1 + \Delta_b)}, \quad (4.3)$$

where m_t , m_b and v are the running top-quark and bottom-quark masses and the Higgs vacuum expectation value $v \simeq 174$ GeV, respectively. The factor Δ_b is associated with a threshold correction [102, 103], induced by the decoupling of the supersymmetric particles [104–106], which tends to be suppressed for low values of the Higgsino mass parameter compared to the heavy colored particles. Moreover, Δ_b becomes significant in this case only for very large values of $\tan \beta$, for which the heavy Higgs bosons are heavily constrained via their decay into τ leptons [63, 64].

Regarding branching ratios, it is important to remark that the same couplings that control the production cross sections also control the branching ratios into top and bottom quarks. Hence, assuming Higgs masses above the top quark pair production threshold, the gain in production cross section at low and large values of $\tan \beta$ is compensated by the reduction of the branching ratio of the decay into electroweakinos. Overall, considering both the Higgs production and decay branching ratios while concentrating on the gluon fusion analysis, we find that the total production rate coming from the decay into electroweakinos is enhanced for lower values of $\tan \beta$ and decreases slowly for larger values of $\tan \beta$.

In the MSSM, for moderate values of the Higgsino mass parameter μ , low values of m_A lead to a modification of the Higgs couplings which therefore affect the agreement between the theoretical predictions and the Higgs precision measurements [107, 108]. The modifications of the Higgs couplings are approximately independent of $\tan \beta$ and lead to a bound of about 600 GeV on m_A [38]. Observe, however, that these bounds may be modified

⁴We have closely followed the analysis strategy given in ref. [39], where the same signature has been studied exclusively in the compressed region, $m_{\chi_{2,3}^0} - m_{\chi_1^0} \simeq m_Z$ and we find a similar reach.

considering the low energy theory to proceed from, for instance, the NMSSM in the limit of heavy singlet [109], that may arise dynamically from the renormalization group evolution at low energies [110, 111]. In this article, we have mainly focused on the region of masses higher than 600 GeV, since they allow to avoid the precision measurement constraints in the MSSM, but also enhance the reach for heavier electroweakinos.

Beyond the precision measurement constraints, other relevant constraints come from the search for heavy Higgs bosons decaying into SM final states. As discussed before, in the MSSM, the decays of the heavy Higgs to bottom quarks and tau leptons are enhanced by large $\tan\beta$. The $H/A \rightarrow \tau^+\tau^-$ decay channel has been studied in the ATLAS Run-II search (139 fb^{-1}) [64] in the case where at least one tau lepton decays hadronically and assuming that all superpartners are heavy enough that the H/A Higgs bosons can not decay into them. In this case, the current bounds would exclude values of $\tan\beta \gtrsim 8$ for $m_A = 600 \text{ GeV}$. However, in the present case the heavy neutral Higgses can decay into a Higgsino-Bino pair with branching ratios close to 30% which, for given m_A , alleviates the upper limit on $\tan\beta$.

Recently, the comparison of the current and projected bounds between these two scenarios has been studied in [112]. They find that for scenarios with light electroweakinos the bound from $H/A \rightarrow \tau^+\tau^-$ excludes $\tan\beta \gtrsim 15$, for $m_A = 600 \text{ GeV}$ and luminosity of 36 fb^{-1} . While for the HL-LHC at 14 TeV and luminosity of 3 ab^{-1} , they project this bound to be $\tan\beta \gtrsim 8$. Additionally, constraints for the $H/A \rightarrow \bar{b}b$ decay have been presented in [113]. However, the bound is quite weak and only excludes values of $\tan\beta > 20$, for the same region of heavy Higgs masses. As we shall see, irrespectively of these bounds, the sensitivity of the search for electroweakinos proceeding from the decay of heavy Higgs bosons is highly reduced for values of $\tan\beta > 10$, even for low masses of the heavy Higgs.

For lower $\tan\beta$, there exist constraints from the decays of the charged Higgs bosons, $H^\pm \rightarrow t\bar{b}$, and also the neutral Higgs channel, $H/A \rightarrow \bar{t}t$. In the case of the charged Higgs the bounds become weak in the region of parameters we are considering, as can be seen from the results of ref. [114]. For instance, for $\tan\beta = 0.5$ the mass of the charged Higgs should satisfy $m_{H^\pm} > 1.2 \text{ TeV}$, while for $\tan\beta = 1$ there are no constraints for $m_{H^\pm}$. For the decay of the neutral Higgs bosons to $\bar{t}t$, the projected HL-LHC sensitivity is $\tan\beta \lesssim 2$ for a heavy Higgs mass $m_A = 600 \text{ GeV}$ [103]. However, considering top associated production can mildly increase this sensitivity to $\tan\beta \lesssim 3$. The current limits for the $\bar{t}t$ channel for $m_A = 600 \text{ GeV}$ is about $\tan\beta \lesssim 1.5$, coming from the analysis of the CMS 13 TeV 36 fb^{-1} data [115]. In our analysis, we shall limit our analysis to values of $\tan\beta \geq 2$. Also, unless the stop masses are larger than 10^5 GeV , it is impossible to obtain the proper Higgs mass in the MSSM for values of $\tan\beta$ lower than 2 [51–55].

Another possible search channel for the heavy Higgs follows from the same production mechanism but followed by the heavier neutralinos decaying instead to the SM Higgs boson, $\chi_{2,3}^0 \rightarrow h + \chi_1^0$, followed by the Higgs decay to bottom quarks. Despite the fact that this decay chain can have a sizable rate, depending on m_A and $\tan\beta$, this signal suffers from multiple QCD backgrounds. We have estimated the signal significance of this channel using the background and analysis of ref. [116]. We find that the reach of this channel will not be competitive in comparison to direct searches or the dilepton Higgs channel. Thus, we will not explore this possibility in this work.

Figure 6. 95 % CL bounds on the heavy neutral Higgs decay into electroweakinos $H/A \rightarrow \chi_h^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$, with $Z \rightarrow \ell^+ \ell^-$. With integrated luminosity of 300 fb^{-1} and $m_{H/A} = 400$ & 600 GeV , the sensitivities for electroweakinos are shown as contours in the $m_{\chi_1^\pm} - m_{\chi_1^0}$ plane for $\tan \beta = 2, 5, 8$, & 10 . For $m_{H/A} = 600 \text{ GeV}$ the bounds vanish for values of $\tan \beta \gtrsim 5$.

To compute the resulting bounds, requiring that events contain a significant amount of missing energy drastically reduces the contribution from QCD backgrounds. The relevant backgrounds then come from di-boson production, $pp \rightarrow VV$, with $V = W, Z$. Further requiring that one pair of opposite-sign, same flavor leptons reconstruct the Z -boson mass, $85 \text{ GeV} < m_{\ell\ell} < 95 \text{ GeV}$, leaves the ZZ channel as the most relevant source of background. Apart from large $\cancel{E}_T$ in the events, the signal significance can be further improved by using the modified clustered transverse mass introduced in ref. [39],

$$m_{cT}^2(\ell\ell, \cancel{E}_T) = 2 \times \left((|\vec{p}_T^{\ell\ell}| + |\vec{p}_T|)^2 - |\vec{p}_T^{\ell\ell} + \vec{p}_T|^2 \right), \quad (4.4)$$

where $\vec{p}_T^{\ell\ell}$ is the transverse momentum of the di-lepton system, and $\vec{p}_T$ is the two-vector of the missing transverse energy. For more details of the kinematics and impact of the cuts see ref. [39]. We generate background and signal using **MadGraph5** followed by shower and detector simulation with **Pythia8** [117, 118] and **Delphes** [119] respectively. For a given heavy Higgs mass and $\tan \beta$, we calculate the signal significance in the chargino-neutralino plane, calculated from eq. (2.5), by optimizing lower and upper cuts on $\cancel{E}_T$ and m_{cT}^2 , respectively.

Our results for 300 fb^{-1} are presented in figure 6 in the $m_{\chi_1^\pm} - m_{\chi_1^0}$ plane. Viewing the bounds in this way allows for a straightforward comparison with the direct production search channels in the same parameter space. For 300 fb^{-1} , the LHC sensitivity for heavy Higgs bosons decaying into electroweakinos is limited to relatively low values of m_A , that as argued before would lead to tension with Higgs precision measurements, unless one goes beyond the pure MSSM description. In the left panel, we show the bounds for $m_A = 400 \text{ GeV}$. For $\tan \beta = 2$, the sensitivity covers almost the entire region that is kinematically allowed. Whereas for $\tan \beta = 10$, the sensitivity reaches to chargino masses of almost 300 GeV , and slightly above 100 GeV for the lightest neutralino mass. In the

Figure 7. 95 % CL bounds on the heavy neutral Higgs decay into electroweakinos $H/A \rightarrow \chi_h^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$, with $Z \rightarrow \ell^+ \ell^-$. With integrated luminosity of 3000 fb^{-1} and $m_{H/A} = 600, 700, 800, 900 \text{ GeV}$, the sensitivities for electroweakinos are shown as contours in the $m_{\chi_1^\pm} - m_{\chi_1^0}$ plane for $\tan\beta = 2 - 10$.

right panel, in the case of $m_A = 600 \text{ GeV}$, we see that the sensitivity is limited to low values of $\tan\beta = 2$ and 5 . For larger values of the Higgs masses the bounds become even weaker and vanish for $m_A \gtrsim 700 \text{ GeV}$, due to the decrease in the production cross-section $\sigma(gg \rightarrow H/A \rightarrow \chi_h^0 \chi_1^0 \rightarrow Z + 2\chi_1^0)$.

In figure 7, we show the reach for 3000 fb^{-1} . We find that for heavy Higgs masses of $600\text{--}700 \text{ GeV}$, the reach can explore a broad range of values of $\tan\beta$. Further, for larger masses of the heavy Higgses the reach of the Higgs decay channel generally improves in the region of the kinematic limit of the $\chi_{2,3}^0 \rightarrow Z + \chi_1^0$ decay. This is expected as the

Figure 8. Comparison between the $H/A \rightarrow \chi_h^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ electroweakino search and the existing direct production constraints for the higgsino-like electroweakinos at HL-LHC. In the case of the resonant Higgs channel we present the bounds for $m_A = 600$ (700) GeV for luminosity of 300 (3000) fb^{-1} .

cut efficiency of the kinematics resulting from high p_T leptons compensates the decrease in cross sections. For Higgs masses above 1 TeV, we find no reach for any values of $\tan \beta$, since beyond this point the efficiency gain cannot compete with the drop in the production cross section.

In figure 8, we compare the $H/A \rightarrow \chi_h^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ search to existing direct production constraints interpreted for higgsino-like electroweakinos, as presented in the top right panel of figure 5. The sensitivities are nicely complementary to each other. We find that there is a significant overlap in the parameter space that can be covered between the proposed Higgs decay search and the direct production searches. We note that since there is still a chance to obtain a 5σ discovery at HL-LHC, as we show in the bottom right panel of figure 5, the search for electroweakinos will become an alternative way of probing the existence of a heavy Higgs boson beyond the traditional decay channels to τ -leptons, and top and bottom quarks. As emphasized before, the proposed Higgs decay channel also has better sensitivity close to the compressed mass region $m_{\chi_1^\pm, \chi_h^0} \simeq m_{\chi_1^0} + Z$ compared with the direct production case, offering a unique channel to explore this region of electroweakino masses.

5 Conclusions

In this article we have analyzed the search for electroweakinos at the LHC, putting emphasis on the complementarity of direct and Higgs decay production modes. We have considered the case of heavy scalar superpartners and concentrated on the well motivated case of light Higgsinos and Binos. We have shown that the LHC reach in this case remains weak in

both production channels at a luminosity of 300 fb^{-1} but becomes very promising at higher luminosities.

In the direct production mode, the high luminosity LHC, with a total integrated luminosity of 3000 fb^{-1} will be able to cover up to masses of the lightest chargino and second and third lightest neutralino states up to the order of 800 GeV for lightest neutralinos lower than about 300 GeV. This is comparable to the current reach at the LHC for the case of light Winos and significantly larger than the reach for light Higgsinos at 300 fb^{-1} , that go up to chargino masses of about 600 GeV for lightest neutralinos not heavier than 150 GeV. In spite of the considerable reach, a large gap is open when the mass differences between the heavier electroweakino states and the lightest neutralino state become small.

The reach in the heavy Higgs decay mode depends strongly on the Higgs boson masses, and cannot go up to chargino masses as large as in the direct production mode. However, for heavy Higgs boson masses larger than 500 GeV and smaller than about 900 GeV, and moderate values of $\tan\beta$, it can go up to chargino masses of about 500 GeV for lightest neutralino masses not heavier than 300 GeV. Interestingly, although the coverage is not as strong as the direct production case, this search is not limited by the same kinematic considerations as the ones in the direct production mode and can cover masses up to the kinematic threshold for the decay of the heavier electroweakinos into the lightest neutralino. Moreover, this mode provides also an alternative way of looking for heavy Higgs bosons in this range of masses and hence should be a high priority for future LHC analyses.

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A Auxiliary figures

In figure 4, we have shown the production cross-section for the process $H/A \rightarrow \chi_{2,3}^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ for higgsino-like electroweakinos in the case of $m_A = 600 \text{ GeV}$ and $\tan\beta = 2, 5, 8, 10$. For reader's convenience, we also show the comparison of the production cross section for $m_A = 600, 700, \text{ GeV}$ and $800, 900 \text{ GeV}$ in figure 9, and figure 10 respectively.

B Results for $\text{sgn}(\mu) = +1$

In the main results presented in this paper we have assumed that $\text{sgn}(\mu) = -1$. Apart from the motivations given in the introduction for this choice, it is of interest to also explore the

Figure 9. The production cross-section for the process $H/A \rightarrow \chi_{2,3}^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ for higgsino-like electroweakinos, with heavy scalar mass $m_A = 600, 700$ GeV and $\tan \beta = 2, 5, 8, 10$.

Figure 10. The production cross-section for the process $H/A \rightarrow \chi_{2,3}^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ for higgsino-like electroweakinos, with heavy scalar mass $m_A = 800, 900$ GeV and $\tan \beta = 2, 5, 8, 10$.

possibility of $\text{sgn}(\mu) = +1$. We have studied the corresponding production cross sections in this case and find only minor qualitative differences to the main results. However, for completeness in figure 11 we show the comparison between $H/A \rightarrow \chi_h^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ electroweakino search and the existing direct production constraints for the higgsino-like electroweakinos at HL-LHC assuming $\text{sgn}(\mu) = +1$. In the case of the resonant Higgs channel we present the bounds for $m_A = 600$ (700) GeV for 300 (3000) fb^{-1} luminosity.

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Figure 11. Comparison between the $H/A \rightarrow \chi_h^0 \chi_1^0 \rightarrow Z + 2\chi_1^0$ electroweakino search and the existing direct production constraints for the higgsino-like electroweakinos at HL-LHC assuming $\text{sgn}(\mu) = +1$. In the case of the resonant Higgs channel we present the bounds for $m_A = 600$ (700) GeV for luminosity of 300 (3000) fb^{-1} .

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