Hunting electroweakinos at future hadron colliders and direct detection experiments

Giovanni Grilli di Cortona

SISSA - International School for Advanced Studies,
Via Bonomea 265, I-34136 Trieste, Italy
INFN, Sezione di Trieste,
via Valerio 2, I-34127 Trieste, Italy

E-mail: ggrilli@sissa.it

ABSTRACT: We analyse the mass reach for electroweakinos at future hadron colliders and their interplay with direct detection experiments. Motivated by the LHC data, we focus on split supersymmetry models with different electroweakino spectra. We find for example that a 100 TeV collider may explore Winos up to $\sim 7$ TeV in low scale gauge mediation models or thermal Wino dark matter around 3 TeV in models of anomaly mediation with long-lived Winos. We show moreover how collider searches and direct detection experiments have the potential to cover large part of the parameter space even in scenarios where the lightest neutralino does not contribute to the whole dark matter relic density.

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1 Introduction

The LHC is getting ready to start its second run at a centre of mass energy of 13 TeV in 2015. In the first run ATLAS and CMS have discovered the Higgs boson [1, 2] and have put a huge effort into looking for new physics. Unluckily new phenomena pointing to beyond the standard model scenarios did not show up. However this fact is not discouraging: new physics may be within the reach of LHC or future colliders. The scientific community already started discussing collider physics beyond the LHC: in particular there are plans for hadron colliders with centre of mass energy up to 100 TeV. It is therefore very important to understand the physics potential of the next LHC runs and of future colliders.

The lack of discovery of new coloured states at the LHC is in tension with a natural implementation of supersymmetric (SUSY) models, favouring instead split SUSY models [3–6]. In split SUSY scalars are heavy and the low energy spectrum is characterised by gauginos and higgsinos. Split SUSY models give up on the idea that SUSY solves the hierarchy problem but it ameliorates other potential problems of ordinary SUSY such as flavour changing neutral currents, CP violation and fast proton decay. Moreover split scenarios maintain the successful unification of the gauge couplings and the lightest supersymmetric particle (LSP) as a viable candidate for dark matter. Indeed, if the lightest neutralino is stable, it may play the role of dark matter candidate. Pure higgsino (\(\tilde{h}\)) or Winos (\(\tilde{W}\)) states provide the full dark matter abundance if their mass is 1.1 or 3.2 TeV respectively. A pure Bino (\(\tilde{B}\)) is not a suitable candidate to be the whole dark matter because it would be overproduced in the early universe. However there are other suitable scenarios in which the dark matter particle is an admixture of two states: Bino/higgsino (\(\tilde{B}/\tilde{h}\)), Bino/Wino (\(\tilde{B}/\tilde{W}\)) and Wino/higgsino (\(\tilde{W}/\tilde{h}\)) [5–13].
Some simplified models where scalars are heavy and electroweakinos are the only accessible states were studied at the LHC by ATLAS and CMS [14, 15]. In particular cases they also studied the projection for the 14 TeV LHC [16, 17].

The WIMP (weakly interacting massive particle) nature of the lightest neutralino can be explored in collider searches, direct [18–22] and indirect [23, 24] detection experiments. In this paper we focus only on the first two types of searches because the latter is dominated by large astrophysical uncertainties (see for example [25–27]). Recently there has been a lot of effort in determining what could be the mass reach for the next generation colliders (100 TeV or so). Mass reach for coloured sparticles were analysed in simplified models assuming a 100 TeV collider [28, 29]. Pure Winos or higgsinos were studied in the mono-jet [30] and mono-photon, soft lepton and long lived particles searches [31, 32]. When this work was near completion [33, 34] came out with some overlap to this study. We discuss in the text differences and similarities whenever relevant. Direct detection for SUSY models was studied in the past (see for example [8–12, 35]) and recently looking for blind spots [36–40].

The paper is organised in two parts. In the first part (section 2) we introduce the method used for the determination of the future reach at hadron colliders and describe the searches analysed. We analysed the following simplified models:

• gravity or gauge mediation models with Bino LSP and Wino NLSP;
• anomaly mediated models with long lived Winos;
• low scale gauge mediation models with universal gaugino masses with Bino NLSP decaying in photons and gravitino;
• low scale gauge mediation models with higgsino NLSP.

In the second part we show the current bounds and future reach from direct detection experiments for split SUSY models with universal gaugino masses (in section 3.1) and models of anomaly mediation (in section 3.2). In those sections we also compare collider searches with direct detection experiments for the models studied.

2 Future reach at hadron colliders

In this section we will extrapolate the mass reach for future hadron colliders for several searches on electroweakinos relevant for split SUSY. In general it is quite difficult to estimate the mass reach for future colliders because cuts, acceptances ($a$), efficiencies ($\epsilon$) and type of analyses change and because of our ignorance on the details of the detector. In the following we will assume that cuts can be rescaled such that efficiencies and acceptances can be kept constant ($ea \simeq \text{const}$). We basically follow the same strategy outlined in Collider Reach [41, 42]. The energy dependence of the number of signal and background events ($S$ and $B$ respectively) is thus determined by the production cross section. In particular the energy dependence of $S$ and $B$ is the same since the parton level cross section has the same scaling $\sigma \sim 1/E^2$ at high energies and the pdf of both signal and background are evaluated at the
Table 1. Current experimental status and results of the analyses with rescaled background. All the numbers are in GeV. The models are explained in sections 2.1, 2.2, 2.3, 2.4 respectively.

| Model | 8 TeV $^{(3)}$ | 14 TeV [300(0) fb$^{-1}$] | 33 TeV [300(0) fb$^{-1}$] | 100 TeV [300(0) fb$^{-1}$] |
|-------|----------------|-------------------|----------------|----------------|
| Wino ($\chi^0_2 \rightarrow \chi^0_1 Z$) | 330 | 790 (1180) | 1280 (2050) | 2210 (3870) |
| Wino ($\chi^0_2 \rightarrow \chi^0_1 h$) | 287 | 700 (1080) | 1110 (1830) | 1890 (3380) |
| long-lived Wino | 250 | 600 (930) | 990 (1600) | 1750 (3080) |
| GM Wino | 660 | 1430 (1820) | 2590 (3510) | 5170 (7750) |
| GM higgsino | 350 | 880 (1260) | 1460 (2260) | 2610 (4400) |

same energy.$^{1}$ Therefore requiring that the significance at the new collider is the same as the one setting the current bounds gives

$$\sigma = S \sqrt{B} = S' \sqrt{B'} \Rightarrow \frac{S}{S'} = 1,$$

where $S'$ and $B'$ refer to the number of signal and background events at a future collider.

Given an existing LHC bound, the corresponding mass reach at the new collider can thus be obtained by simply computing the production cross section and requiring the same number of signal events needed to put the original bound. Since in the ratio $S'/S$ the main NLO effects cancel, the number of signal events is computed using the cross section of electroweakinos at leading order $^{[43]}$ convoluted$^{2}$ with the MSTW Parton Distribution Function $^{[44]}$.

We will show in the following that our analysis on electroweakino searches is in agreement with existing studies in the literature when available. Results are shown in figures 1–5 and in table 1 and refer to 95% CL mass reach.

### 2.1 Wino-Bino simplified model

The first search we consider is a Wino-Bino simplified model.$^{4}$ Charginos are mostly produced via the Drell-Yan process in $s$-channel through exchange of a $Z$ boson. They can also be produced in association with a neutralino via an $s$-channel $W$ boson. Production through squarks has been neglected because all the scalar super partners are assumed much heavier. This scenario can be realised both in gravity and in gauge mediation (GMSB) models. When the gaugino masses are universal ($M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$), the gluino is only

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$^{1}$This is true away from the squeezed limit, where most of the background come from softer SM particles.

$^{2}$Computing the signal, the cross section can be factorized out from the convolution with the Parton Distribution Function $S \sim \sigma \cdot pdf$ because the integral is dominated only by the threshold $\tau_0 \sim 4m^2$. We verified numerically the negligible effects of the tail of the distribution.

$^{3}$The limit for GM higgsino model was given for 19.5 fb$^{-1}$ of luminosity. All the other limits are given for 20.3 fb$^{-1}$.

$^{4}$The Wino-higgsino simplified model has been recently studied in $^{[33]}$. 

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Wino in the WZ channel

![Wino in the WZ channel](image)

**Figure 1.** Wino-Bino simplified model in the WZ channel. The left axis shows the luminosity for the method explained in the text, while on the right only five events were required. The grey shaded area is the current bound.

three times heavier than the Wino and we expect direct gluino searches to be stronger than direct Wino searches. However in non-universal gaugino models the gluino can be much heavier than the Wino and direct electroweak searches would be the best channel to explore this scenario. This channel is also sensitive to GMSB models where the Wino is the lightest neutralino, all the other gauginos are heavy and the gravitino is approximately massless. In this case Winos decay promptly through the same channel \( \tilde{W}^\pm \tilde{W}^0 \to W^\pm Z \tilde{G} \tilde{G} \).

We consider the two different extreme cases, where the neutral Wino decays with \( BR = 1 \) either to \( Z \) and LSP or to Higgs and LSP. The charged Wino decays always to \( W \) and LSP. In the first case the dominant signature is three leptons and missing energy and the main background comes from the SM WZ production. A Wino NLSP for \( m \gtrsim 350 \) GeV is excluded for Bino masses less than 100 GeV [14, 15]. In the second case the final states are one charged lepton (electron or muon), missing transverse energy (from the LSP and the neutrino coming from the \( W \) decay) and two \( b \)-jets (from the Higgs). For a massless Bino, Winos between 125 and 141 GeV and between 166 and 287 GeV are excluded [45].

The mass reach in the Wino-Bino simplified model are shown in figure 1 and figure 2 for the WZ and the Wh channel respectively. In the WZ scenario, we find that the LHC14 may extend the mass reach to 1.2 TeV for a luminosity of 3000 fb\(^{-1}\) and it will increase up to \( \sim 4 \) TeV at a 100 TeV collider. The first result is in agreement with the 1.1 TeV mass reach given by ATLAS [16]. The latter can be compared with results by [34], although the two analyses differ for the treatment of the branching ratios: we assume 100% decay in \( Z \) or \( h \), while they keep into account the fact that the branching ratios of Winos depend on the choice of \( \tan \beta \) and on the choice of the relative sign between gauginos and higgsinos.
Moreover, in [34] only the lepton channels have been considered, however the $b$-jet channel has a higher sensitivity in the Higgs mediated scenario, due to the enhanced branching ratio $\text{BR}(h \rightarrow b\bar{b}) \gg \text{BR}(h \rightarrow WW/ZZ)$. So we find that a 100 TeV collider with 3000 fb$^{-1}$ of luminosity may reach 3.4 TeV in the $b$-jets channel as opposed to the only 1.3 TeV reach found in [34] considering only the lepton channel. As a reference point the figures also show the "ultimate reach" in the right axis obtained by requiring $S' = 5$ assuming that the background can be reduced to zero and the efficiencies and the acceptances can be made 100%. (A more realistic result can be simply obtained by rescaling the required luminosity by $\epsilon$, $a$ and the $\sqrt{B}$.) The plots can also be used to compare the performance of different colliders. For example, in figure 1 and 2, we notice that, for the EW searches described in this section, the sensitivity of the LHC14 with 3000 fb$^{-1}$ is approximately the same as a 33 TeV collider with a luminosity ten times smaller.

2.2 Long-lived Wino

Long-lived chargino searches can be used to probe models with Wino LSP such as anomaly mediation models (AMSB) or high scale GMSB with non universal gaugino masses. In these models the neutral Wino states are highly degenerate with the charged Wino. For heavy higgsino the mass splitting at tree level is suppressed and it is dominated by the radiative generated contribution, which is around 160-170 MeV at one-loop level [46–48]. This small mass splitting imply that the charged Wino has a considerable lifetime (of order $c\tau = \mathcal{O}(10) \text{ cm}$) and it decays mainly into the neutral Wino and a soft charged pion.

The signature for this search is one hard jet from initial state radiation (ISR), large missing transverse energy and a disappearing track (the chargino eventually decays to a
soft not reconstructed pion). The jet must not be too close to the missing energy direction because it usually denotes jet mismeasurement. Chargino pair ($\tilde{\chi}^+_{1}\tilde{\chi}^-_{1}$) and chargino neutralino ($\tilde{\chi}^0_{1}\tilde{\chi}^0_{1}$) associated production with initial state radiation are the relevant processes for this search. The relevant background originates from unidentified leptons and charged particles with high mis-reconstructed transverse momentum ($p_T$) as well as charged hadrons interacting with the inner detector. ATLAS excludes charginos with mass below 250 GeV in the AMSB model [49].

We model the relevant cross section through the process $q\bar{q} \rightarrow Zj \rightarrow e^+e^-j$ using the program MCFM [50] and rescaling the partonic cross section with the electroweakino one. This is a good approximation within the method used because the cross section depends only on the energy and on the different pdfs and the process with the exchange of a photon is negligible with respect of the $Z$ exchange diagrams. We derived the mass reach in two ways: by conservatively rescaling the cut on the transverse momentum of the jet with the mass of the final state, in such a way that $p_T/m_W = const$, or keeping the cut fixed to the value the ATLAS experiment used in its study ($p_T > 80$ GeV), if feasible.

This scenario is relevant for dark matter searches. Indeed a Wino LSP is expected to thermally saturate the relic density for a mass $m_\chi \simeq 3.2$ TeV. LHC14 has the potential to explore long lived chargino scenarios for masses around 600 GeV for a luminosity of 300 fb$^{-1}$. This result is in agreement with the study in [51]. By exploiting the new tracker installed at ATLAS, the reach for this kind of search may increase up to 800 GeV at the LHC14 with 100 fb$^{-1}$. We find that a 100 TeV collider would reach a Wino mass around 3.1 TeV for 3000 fb$^{-1}$. In the literature there are similar results for the disappearing track of long-lived Wino searches [31, 32]. In order to be sure to reach the thermal dark matter mass range we should either increase the luminosity or the collider energy: for example with

![Figure 3. Long-lived Wino. Refer to the first figure or to the text for further explanation.](image)
a 200 TeV collider and 1000 fb$^{-1}$ of luminosity the Wino reach would comfortably extend over 3 TeV. In addition it seems that without stronger cuts than the one used by ATLAS the reach could be extended up to 5 TeV for a 100 TeV collider with a luminosity of 3000 fb$^{-1}$. This channel is particularly important in models such as anomaly mediation, where the ratio between the gluino and the Wino is large ($M_3 \simeq 7 M_2$), because it could be more powerful than the gluino searches \cite{28}.

2.3 GMSB Wino-Bino simplified model

In gauge mediated supersymmetric models usually the gravitino and the Bino are the LSP and the NLSP respectively and the latter decays to the former via emission of one hard photon. The search discussed in this section describes the production of Winos decaying into Binos that subsequently decay into photons and gravitinos. This channel leads to events with two final state photons, large missing energy and a moderate amount of visible transverse energy. The relevant background is given by QCD processes involving photons and jets, where a photon or a jet is mis-measured, EW processes like $W + X$, where $X$ is mis-reconstructed as a photon, and $W$ and $Z$ production in association with photons. ATLAS set limits on a Wino mass of 570 GeV for any Bino above 50 GeV \cite{52}. For models with universal gaugino masses the limit increases to 660 GeV.

In figure 4 we show the reach for the GMSB Wino-Bino scenario. Already the LHC14 will probe Winos up to 1.8 TeV with 3000 fb$^{-1}$, corresponding to a gluino $\sim 5.4$ TeV. At 100 TeV it is possible to exclude $\sim 7.8$ TeV Wino. This has a strong impact in GM models with universal gaugino masses in which $\tan \beta$ is large. In these models the $\sim 125$ GeV Higgs mass fix the squark masses to be around 10 TeV or below. Gluinos are expected at the same scale or below, which means a Wino around $\sim 3.3$ TeV or below. Such Wino could be
probed already at a 33 TeV collider with 3000 fb$^{-1}$. Like in the previous case also in this scenario the Wino reach is stronger than the gluino one.

### 2.4 GMSB higgsino simplified model

In the last search the gravitino is assumed to be the LSP with higgsinos NLSP. This channel is relevant, for example, in lopsided gauge mediation models [53], where scalars and gauginos are in the multi-TeV range and the production of electroweakinos in the cascade of coloured sparticles is suppressed with respect to the direct production of light higgsinos.

Higgsinos NLSPs decay to gravitino and $Z$ or $W$ bosons. The branching fraction of higgsino to $Z$ can be enhanced (with respect to the decay to Higgs) in the so called Z-enriched GM model [54, 55]. The signature for this search is three or four leptons plus missing transverse momentum or two leptons, two jets and missing transverse momentum. The background is given mainly by the Standard Model $WZ$ production. CMS set a limit of 350 GeV to this type of higgsinos [15]. We consider only the channel with two leptons, two jets and missing transverse momentum since it is the one that dominate the search. In figure 5 we show the results. The bounds on this search is expected to grow above 1 TeV by the end of the LHC lifetime and reach 4.4 TeV at a 100 TeV machine with 3 ab$^{-1}$.

### 3 Interplay with Direct Dark Matter searches

In split SUSY dark matter searches depend on the low energy electroweakino spectrum. We focus on two representative scenarios: models with universal gaugino masses and models of anomaly mediation SUSY breaking. These scenarios cover all the relevant dark matter candidates in split SUSY, i.e. pure higgsino, pure Wino, $\tilde{h}/\tilde{W}$, $\tilde{h}/\tilde{B}$ and $\tilde{B}/\tilde{W}$.
Figure 6. Diagrams that contribute to the neutralino nucleon cross section. The diagrams with Z exchange are relevant only for the Spin Dependent cross section.

Direct detection experiments are based on the idea of [56] that exploits the recoil energy from dark matter particles scattering on nuclei. The scattering cross section of the neutralino with nucleons is calculated from the effective lagrangian for the scattering between neutralino, quarks and gluons in the limit of low relative velocity [57–59]. The spin independent scattering cross section of the neutralino with a nucleon \( N \) can be expressed in a simple way as

\[
\sigma_{SI}^N = |Higgs + gluon + twist-2|^2. \tag{3.1}
\]

\( Higgs, \) \( twist-2 \) and \( gluon \) refer to the diagrams in figure 6. The \( Higgs \) diagrams (figure 6(a)) are generated by the scalar-type effective operators \( \tilde{\chi}^0 \tilde{\chi}^0 \bar{q}q \) and \( \tilde{\chi}^0 \tilde{\chi}^0 G_{\mu\nu}G^{\mu\nu} \) and their contribution to the amplitude is proportional to the \( \tilde{\chi}^0 \tilde{\chi}^0 h \) coupling:

\[
c_{h\tilde{\chi}\tilde{\chi}} = (N_{12} - N_{11} \tan \theta_W)(N_{13} \cos \beta - N_{14} \sin \beta), \tag{3.2}
\]

where \( N_{1i} \) are the elements of the matrix that diagonalise the neutralino mass matrix in the basis \( (\tilde{B}, \tilde{W}, H_u, H_d) \). The \( twist-2 \) diagram (figure 6(b)) plays an important role in the computation of the cross section because it contributes to the amplitude with opposite sign with respect to the other diagrams. This will lead to some accidental cancellation. The \( gluon \) contributions (figure 6(c)) are of the same order of the one-loop diagrams because of the presence of a factor \( 1/\alpha_s \) that comes from the calculation of the gluon matrix element. Therefore the gluon contribution is comparable to the one-loop diagrams, although the dark matter interaction with nucleons is induced by two-loop diagrams.
Figure 7. Spin independent neutralino-nucleon scattering cross section requiring $\Omega h^2 = 0.1196$ in the universal gaugino masses model (red is Bino-like, yellow is higgsino-like LSP). The magenta area is the actual bound by LUX, the dashed magenta line is the projected reach of LZ. The neutrino background is shaded in light blue. The numbers are explained in the legend on the right panel.

For the computation of the cross section we used leading order formulae [57–59]. The uncertainty has been estimated by taking into account the uncertainties from hadronic matrix elements and those from known 1-loop QCD corrections. The order of magnitude of the latter is comparable with [60–63].

In the rest of the section we only focus on neutralino dark matter that is thermally produced. The relic density was computed with DarkSusy [64, 65] and the package DarkSE [66] to compute the Sommerfeld effect. For the value of the relic density we used the Planck result, $\Omega h^2 = 0.1196 \pm 0.0031$ [67].

3.1 Gauge Mediation with universal gaugino masses

The first scenario we consider is split SUSY with universal gaugino masses. Higgsinos can be either light or heavy and are left as free parameters. In general we have two free parameters, $\mu$ and $M_0$ ($M_i \propto \alpha_i M_0$) which are further constrained to one by requiring $\Omega_{DM} = \Omega_{\text{exp}}$. This leads to a phenomenology in which the LSP can be either the higgsino (when $|\mu| < M_1$) or the Bino (when $|\mu| > M_1$).

In figure 7 we show the spin independent cross section for the scattering of neutralinos on nucleons. The magenta shaded area shows the region excluded by LUX [20]. The dashed magenta curve set the projected reach for LZ [68, 69]. The light blue area represents the irreducible neutrino background [70]. The three red/yellow curves represent the spin independent cross section requiring the correct relic density for $\mu > 0$, large $\tan \beta$ and $\mu < 0$ from top to bottom respectively (in the following we set the gaugino masses positive). For large $\tan \beta$ the sign of $\mu$ is irrelevant: the curve in the middle is the limit for both positive and negative scenario. The red colour of each curve represents a bino-like LSP, while the yellow a higgsino-like LSP. A Bino needs to mix with an higgsino in order to have sizeable
GM with universal gaugino masses

Figure 8. Region in the $(\mu, M_2)$ allowed by direct chargino searches at LEP (excluded in red) and by the requirement that the neutralino does not exceed the CDM relic density (excluded in blue). The colour shading for actual bounds, future reach and background for direct detection are the same as in the previous figure.

annihilation cross section and therefore the correct relic density. In this region the cross section is dominated by the Higgs diagrams. The relic density constraint gives a relation between $\mu$ and $M_1$, depending on $\tan \beta$ and on the sign of $\mu$ (figures 8). In particular for $\mu < 0$ the two states are close enough and also coannihilation effects become relevant. At low LSP masses in the negative branch, the mixing is not maximal and it is given by

$$N_{11} \simeq 1 - \frac{N_{13}^2}{2} - \frac{N_{14}^2}{2},$$

$$N_{13} \simeq -\frac{\sin \theta_w M_Z}{M_1^2 - \mu^2} (\mu \sin \beta + M_1 \cos \beta),$$

$$N_{14} \simeq \frac{\sin \theta_w M_Z}{M_1^2 - \mu^2} (\mu \cos \beta + M_1 \sin \beta),$$

while the cross section is proportional to $|M_Z(M_1 + \mu \sin 2\beta)/(\mu^2 - M_1^2)|^2$. As the LSP mass increases, the relic density constraint needs more mixing and more coannihilation, the two states become more degenerate and the cross section increases. Also for $\mu > 0$ at small LSP mass there is small mixing between the Bino and the higgsino. In this region coannihilation is not present. The relation between the masses of the two states keep constant the annihilation cross section into Higgs and gauge bosons (such that the constraint on the relic density is fulfilled) and the nucleon-neutralino scattering cross section.

The $\bar{t}t$ threshold is visible only for $\mu < 0$ because for positive $\mu$ there is no coannihilation and the dominant annihilation channel is into gauge bosons. For $m_{LSP} > m_t$ (also the annihilation in $\bar{t}t$ is present), in order to get the correct relic density the two states have to
become less degenerate such that the new annihilation channel is balanced by the weaker coannihilation effect.

Once the region of maximal mixing is reached, the $m_{\text{LSP}} \approx 500 \ (900)$ GeV for positive (negative) $\mu$ respectively, we have $(N_{11}, N_{12}, N_{13}, N_{14}) \approx (1/\sqrt{2}, 0, 1/2, \mp 1/2)$, where the $\mp$ sign refers to the cases $\mu \approx \pm M_1$. Thus the cross section is proportional to $|\cos \beta + \text{sign}(\mu) \sin \beta|^2$ and it is constant for both sign of $\mu$. The suppression in the negative $\mu$ branch is again due to the sign of $\mu$ and the value of $\tan \beta$.

LUX bounds already exclude the regions $\mu < 1$ TeV for small $\tan \beta$ and $|\mu| < 500$ GeV for large $\tan \beta$. When the higgsino becomes the LSP and $m_{\tilde{B}}$ become heavier and heavier, the Higgs exchange become suppressed and the twist-2 and gluon diagrams will eventually dominate. However their contribution is suppressed by a factor 10 due to a cancellation between the gluon and twist-2 diagrams. When the scale of the LSP is such that coannihilation does not help anymore to maintain the correct relic density, the mixing is

$$N_{11} \approx \frac{(\sin \beta \pm \cos \beta) \sin \theta_w M_Z}{\mp M_1 \sqrt{2}}, \quad N_{13} \approx \pm \frac{1}{\sqrt{2}}, \quad N_{14} \approx \frac{1}{\sqrt{2}},$$

the Higgs diagrams are suppressed by $M_1$ and the cross section decreases. The figure shows also the indirect bound from gluino searches: a 16 TeV gluino corresponds to $M_1 \approx 2.4$ TeV. This is the reach for a 100 TeV collider in the $(m_{\text{LSP}}, \sigma_{SI})$ plane. However direct detection is stronger for $\mu > 0$: indeed LZ can reach $M_1 \approx 7$ TeV corresponding to gluinos around 42 TeV. On the other hand the curve for negative $\mu$ is not bounded by LUX and LZ will explore pure higgsino states with $M_1 < 1.7$ TeV. The gluino reach for a 100 TeV collider is stronger in this scenario. Continuing along the yellow curve, there is a value of $M_1$ such that the Higgs contribution is of the same order of the gluon and twist-2 diagrams and the cross section vanishes. Due to the cancellation uncertainty become $\mathcal{O}(1)$ and we cannot tell where exactly the cancellation happens. While the Bino completely decouples ($m_{\tilde{B}} = \mathcal{O}(100 \text{ TeV})$), the Higgs amplitude vanishes and the cross section reaches the value of the pure higgsino case given by the gluon+twist-2 diagrams:

$$\sigma_{SI}^N \lesssim 10^{-48} \text{ cm}^2.$$  

When the LSP does not contribute to the whole DM abundance, the interplay between collider and direct dark matter searches is better shown in figure 8. The dark blue area describes the region where the relic abundance exceeds the experimental value. The dark magenta is the bound by LUX, the light magenta region shows the reach of LZ and the light blue is the neutrino background. In red is the bound on charginos from LEP [71]. In the plot are shown also future reach from mono-jet searches ($m_{\tilde{\chi}_1^0} \approx 870$ GeV, [31]) and the indirect reach coming from gluinos at a 100 TeV collider ($m_{\tilde{g}} \approx 16$ TeV). According to the left panel of figure 8, for $\mu < 0$ thermal Bino-higgsino DM is not constrained by Direct Detection searches. Future experiments can however explore scenarios where $\mu \approx -1.1$ TeV and $M_1 < 1.7$ TeV. Nonetheless the strongest reach in this kind of models would come from a 100 TeV collider: gluino pair searches have the potential to explore a large area of the parameter space, while mono-jet searches will not have enough sensitivity to explore pure
GM with universal gaugino masses

![Graph showing contours of SI neutralino-nucleon cross section for higgsino dark matter (red curves). The black arrows show the uncertainty on the cross section. The parameter $\mu$ is fixed such that the lightest neutralino has the correct relic density. The colour shading for actual bounds, future reach and background for direct detection are the same as in the previous figure. The green shaded area shows the expected reach at a 100 TeV collider for gluino searches.](image)

**Figure 9.** Contours of SI neutralino-nucleon cross section in [$\text{cm}^2$] for higgsino dark matter (red curves). The black arrows show the uncertainty on the cross section. The parameter $\mu$ is fixed such that the lightest neutralino has the correct relic density. The colour shading for actual bounds, future reach and background for direct detection are the same as in the previous figure. The green shaded area shows the expected reach at a 100 TeV collider for gluino searches.

thermal higgsinos. The right panel shows how the Direct Detection reach is stronger for $\mu > 0$.

The pure higgsino region is shown in figure 9 and it is interesting because it does not require the coincidence $|\mu - M_1| \ll |\mu|$ in order to explain the WIMP miracle. Figure 9 shows the dependence of $\tan \beta$ as a function of the gluino mass (and thus $M_1 = \alpha_1/\alpha_3 M_3$), for a dark matter particle with the correct relic density for $M_3 < 0$ and $M_3 > 0$ in the left and right panel respectively (now we fixed $\mu$ to be positive and the sign of $M_3$ can vary). The value of the parameter $\mu$ has been fixed by requiring the correct relic density and it is approximately 1.1 TeV across the whole plot. The colour labelling is the same as in the previous figures except for the green region that denotes the reach for gluinos at a 100 TeV collider. The red curves represent the SI cross section, while the black arrows show the uncertainties on the cross section. We notice that, as already stated before, the collider reach is weaker than the direct detection experiments for $M_3 > 0$, while in the other case it can be competitive.

### 3.2 Anomaly Mediation

In split SUSY with Anomaly Mediation [6, 72, 73] the physical gaugino masses are predicted in terms of the gravitino mass. The leading contributions to Bino and Wino masses come from one-loop anomaly mediation and threshold effects

$$M_{1,2} = \frac{\beta_{1,2} g_{1,2}}{g_{1,2}} m_{3/2} + \frac{\alpha_{1,2}}{2\pi} \frac{\mu \tan \beta}{\tan^2 \beta + 1} \left( 1 + \ln \left( \frac{1 + \tan^{-2} \beta}{\tan^2 \beta + 1} \right) \right) \left( 1 + \frac{\mu^2}{\mu^2} \right),$$

(3.6)
where $g_i$ is the corresponding gauge coupling, $\beta_i$ its beta function, $m_{3/2}$ is the gravitino mass and $\tilde{m}$ is the scalar mass-scale. The gluino mass receives contributions only from anomaly mediation. In this scenario the scalars (except the SM-like Higgs) are heavy and close to the gravitino mass, while the gauginos are light. Higgsinos are not constrained.

Figure 10 shows the spectrum of split Susy with anomaly mediation. Depending on the contribution of the higgsinos the nature of the LSP changes. Light higgsinos lead to a spectrum in which the higgsino is the LSP and the ratio between gauginos is $M_1 : M_2 : M_3 \simeq 3 : 1 : 9$. Scenarios in which the Wino is the LSP are allowed if the higgsino is heavier than the Wino. For very heavy higgsinos the threshold corrections in (3.6) dominate and the Bino become the LSP.

The model is entirely described in terms of four parameters: $m_{3/2}$, $\mu$, $\tan\beta$ and $\tilde{m}$. However the value of the Higgs mass gives a relation between $\tan\beta$ and $\tilde{m}$. In order to have heavy scalars compatible with the Higgs mass we choose $\tan\beta = 2$. We also discuss how the results change in the large $\tan\beta$ scenario.

In figure 11 we show the spin independent cross section that satisfies the relic density constraint. We start with the case $\mu < M_2$ and discuss the behaviour of the cross section and the bounds as the higgsino mass is increased. The yellow curve describes a mostly higgsino LSP state. At $m_{\text{LSP}} \simeq 1.1$ TeV the cross section behaviour is the same explained for the Universal Gaugino masses scenario. The neutrino background make difficult for future direct detection experiments to probe this region of the parameter space, while LZ will probe only anomaly mediated spectra with higgsino LSP and $M_2 \lesssim 10$ TeV. As $M_2$ approaches $\mu$ the coupling increases and so does the cross section. A 100 TeV collider may explore a very small region where $1.2 \lesssim |\mu| \lesssim 1.7$ TeV. When $\mu \sim M_2$ the mixing is maximal, the tree level Higgs exchange dominate and the LUX bounds apply. In this region the cross section is constant and the Higgs coupling is proportional to

$$ (\cos\beta + \text{sign}(\mu) \sin\beta). $$

The lower curve represents the cross section for $\mu < 0$ which is suppressed by the sign of $\mu$. At large $\tan\beta$ the sign of $\mu$ become irrelevant. Analogously to what happens for the pure higgsino case, the cross section decreases when $\mu \gg M_2$ and the LSP approaches the pure
Wino state. Indeed now the mixing is given by $N_{12} \sim 1$,

$$N_{13} \simeq \frac{\cos \theta_w M_Z}{|\mu|^2} (M_2 \cos \beta + \mu \sin \beta) \quad N_{14} \simeq \frac{\cos \theta_w M_Z}{|\mu|^2} (M_2 \sin \beta + \mu \cos \beta), \quad (3.8)$$

and the Higgs coupling becomes

$$- \frac{\cos \theta_w M_Z}{|\mu|^2} (M_2 \sin 2\beta). \quad (3.9)$$

The cross section therefore decreases as the higgsino decouples from the Wino. In this regime the gluon and the twist-2 diagrams are also important. However as for the higgsino case the gluon and the twist-2 amplitudes accidentally cancel suppressing their contribution by a factor 5. Going down along the blue curve there is a value of $\mu$ for which the cross section vanish because the Higgs diagrams cancel the gluon+twist-2 contributions. Due to $\mathcal{O}(1)$ uncertainties it is not possible to define exactly for which value of $\mu$ this cancellation happens. When the higgsino and the Bino are both decoupled, the cross section is estimated to be

$$\sigma_{SI}^N \lesssim 10^{-47} \text{cm}^2. \quad (3.10)$$

If one keeps increasing the value of $\mu$, with $M_2$ fixed in order to reproduce the correct relic density, the Bino decreases (see (3.6)). While the splitting between Wino and Bino decreases, the cross section increases because the Higgs diagrams become negligible with respect to the other contributions ($N_{11}$ is negligible with respect to $N_{12}$ and $N_{13}$ and $N_{14}$ are given by equation (3.8)). This is the flat part of the blue curve. In this region the neutralino is a pure Wino, with $M_1$ closer and closer and $\mu$ decoupled. The mixing between

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**Figure 11.** Spin independent nucleon-neutralino cross section in a split SUSY with anomaly mediation model (red is Bino-like, yellow is higgsino-like and blue is Wino-like). The magenta area is the actual bound by LUX, the dashed magenta line is the projected reach of LZ. The neutrino background is shaded in light blue. The numbers are explained in the legend on the right panel.
Bino and Wino is always negligible for mass splitting larger than a GeV. Once $M_1 < M_2$ the Higgs diagrams, the only contributions to the cross section, become suppressed by the large value of $\mu$. In this region the neutralino is almost a pure Bino with the mixing given by (3.3). In this case in order to have the correct relic, the Bino must coannihilate with the Wino and therefore the splitting must be $\lesssim 30$ GeV. In order to decrease the gaugino mass scale and maintain such splitting, $\mu$ has to decrease and thus the cross section increases, being the Higgs coupling given by

$$M_W \tan \theta_w \frac{M_1 + \mu \sin 2\beta}{|\mu|^2}. \quad (3.11)$$

There is no top threshold in this case because the annihilation into $t\bar{t}$ is not the dominant contribution. A 100 TeV collider could be able to explore the whole region where the LSP is a mixed Bino/higgsino and Bino/Wino state from the LEP bound to $M_{LSP} \sim 3.1$ TeV. Given the large value of $\mu$, at large $\tan \beta$ the cross section is further suppressed.

The $(\mu, M_2)$ and the $(M_1, M_2)$ planes are shown in figure 12. The upper panels show the $(\mu, M_2)$ planes for $\mu < 0$ (left) and $\mu > 0$ (right). The blue region is excluded by the requirement on the relic density. The dark and light green areas describe the constraints from long lived Winos at LHC8 and the future reach for a 100 TeV collider. The grey lines shows the bounds and reach on gluino pair searches. It is interesting to note that the direct detection reach is limited in the left panel, due to the suppression of the cross section for $\mu < 0$. On the right panel the two different searches are complementary. The bottom panel shows the plane $(M_1, M_2)$, for both positive and negative $\mu$. The colour coding is the same as in the upper plots. The yellow line that cuts the panel in two represent the area in which the higgsino is the LSP and it cuts the plane in a region with $\mu > 0$ (left) and $\mu < 0$ (right). The yellow region is strongly connected with the upper plots. The blue stripe overlapping the yellow line is a region in which $M_1$ is decoupled and it shows the crossing between the Wino LSP parameter space and the higgsino one. A large region of the parameter space could be probed at a 100 TeV collider, leaving unexplored just the narrow region corresponding to the pure Wino and higgsino cases.

4 Conclusions

In this paper, we have presented the mass reach of several electroweakino searches for future hadron colliders, their implications for DM and the complementarity with direct detection experiments.

In particular we have studied scenarios where Wino NLSPs decay into leptons (or $b$-jets and leptons) and Bino LSP, with long-lived charged Winos in models of anomaly mediation and with Wino or higgsino LSP in GMSB models. Concerning direct detection experiments we analysed split SUSY with universal gaugino masses and models of anomaly mediation. We analysed both the cases in which the lightest neutralino contributes entirely or partially to the dark matter abundance.

The LHC excludes electroweakinos up to few hundred GeV, well below the interesting cases of pure Wino or higgsino dark matter. In addition, current bounds from LUX are
stronger in models with universal gaugino masses and positive $\mu$ but are non-existent or very weak in the other scenarios studied.

Electroweakino collider searches are relevant, for example, in low scale gauge mediation models with universal gaugino masses and large $\tan\beta$ or in models of anomaly mediation. Indeed in the first scenario the gluino is expected to be at the same scale or below the squarks (the Higgs mass fixes this scale to be around $10 \text{ TeV}$) that means a Wino around $3 \text{ TeV}$. Such Winos could be explored at a $100 \text{ TeV}$ collider with less than $100 \text{ fb}^{-1}$ of

Figure 12. The parameter space region allowed by the requirement that the neutralino relic abundance does not exceed the relic density in the plane ($\mu$, $M_2$) for $\mu < 0$ ($\mu > 0$) in the left (right) panel. The bottom panel shows the plane ($M_1$, $M_2$). Direct Detection and collider constraints and future reach are also shown.
luminosity. In anomaly mediation the ratio between the gluino and the Wino mass is large, making the Wino searches more powerful: a 100 TeV collider with few ab$^{-1}$ of luminosity could explore 3 TeV Winos ($m_{\text{gluino}} \gtrsim 20$ TeV).

In split SUSY models with universal gaugino masses the strongest mass reach comes from direct detection in the positive $\mu$ scenario. The combination of direct detection experiments, and monojet and gluino searches at a 100 TeV collider will leave unexplored a narrow region with $\mu \gtrsim 870$ GeV and $M_1 \gtrsim 5$ TeV. On the other hand in the negative $\mu$ case direct detection experiments are weaker, due to the suppression of the cross section. However gluino and monojet searches may explore also the region where the neutrino background limits direct detection experiments.

In anomaly mediation models direct detection experiments and collider searches are complementary. Indeed searches on long-lived Winos set strong mass reach in regions where direct detection is weak. The interplay between gluino searches, long-lived Winos and direct detection may cover large area of the parameter space where the neutralino does not contribute to the whole dark matter. Only in the case with positive $\mu$, LZ may probe pure thermal Winos or higgsinos.

In conclusion we showed what are the prospects for neutralino dark matter in future direct detection experiments and collider searches. We also showed that direct bounds from electroweakino searches are not always stronger than the bounds from gluino pair production. Moreover we showed the interplay and complementarity between the two kind of searches, indicating that both have great potential for discovering dark matter. As a final remark it is interesting to note that at the LHC13 at least 10 fb$^{-1}$ of luminosity (expected by the end of 2015) are needed in order to match the current limits from the LHC8 on the electroweakino searches discussed. Moreover in the low mass region an increase of the luminosity of a factor ten might have the same effect of increasing the centre of mass energy of a factor two or more.

We are still far from exploring all the parameter space for Wino and higgsino dark matter but a 100 TeV collider seems to be a necessary tool in order to achieve this goal.

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Note added: after the completion of this work Ref. [74] appeared with partial overlap with our results.

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