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Williamson

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Constraining electroweakinos in the minimal Dirac gaugino model

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Abstract

Supersymmetric models with Dirac instead of Majorana gaugino masses have distinct phenomenological consequences. In this paper, we investigate the electroweakino sector of the Minimal Dirac Gaugino Supersymmetric Standard Model (MDGSSM) with regards to dark matter (DM) and collider constraints. We delineate the parameter space where the lightest neutralino of the MDGSSM is a viable DM candidate, that makes for at least part of the observed relic abundance while evading constraints from DM direct detection, LEP and low-energy data, and LHC Higgs measurements. The collider phenomenology of the thus emerging scenarios is characterised by the richer electroweakino spectrum as compared to the Minimal Supersymmetric Standard Model (MSSM) – 6 neutralinos and 3 charginos instead of 4 and 2 in the MSSM, naturally small mass splittings, and the frequent presence of long-lived particles, both charginos and/or neutralinos. Reinterpreting ATLAS and CMS analyses with the help of SModelS and MadAnalysis 5, we discuss the sensitivity of existing LHC searches for new physics to these scenarios and show which cases can be constrained and which escape detection. Finally, we propose a set of benchmark points which can be useful for further studies, designing dedicated experimental analyses and/or investigating the potential of future experiments.



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28 1 Introduction

29 The lightest neutralino [1–3] in supersymmetric models with conserved R-parity has been the
30 prototype for particle dark matter (DM) for decades, motivating a multitude of phenomeno-
31 logical studies regarding both astrophysical properties and collider signatures. The ever tight-
32 ening experimental constraints, in particular from the null results in direct DM detection ex-
33 periments, are however severely challenging many of the most popular realisations. This is in
34 particular true for the so-called well-tempered neutralino [4] of the Minimal Supersymmetric
35 Standard Model (MSSM), which has been pushed into blind spots [5] of direct DM detection.
36 One sub-TeV scenario that survives in the MSSM is bino-wino DM [6–9], whose discovery is,
37 however, very difficult experimentally [10–12].

38 It is thus interesting to investigate neutralino DM beyond the MSSM. While a large litera-
39 ture exists on this topic, most of it concentrates on models where the neutralinos – or gauginos
40 in general – have Majorana soft masses. Models with Dirac gauginos (DG) have received much
41 less attention, despite excellent theoretical and phenomenological motivations [13–59]. The
42 phenomenology of neutralinos and charginos (“electroweakinos” or “EW-inos”) in DG models
43 is indeed quite different from that of the MSSM. The aim of this work is therefore to provide
44 up-to-date constraints on this sector for a specific realisation of DGs, within the context of the
45 Minimal Dirac Gaugino Supersymmetric Standard Model (MDGSSM).

46 The colourful states in DG models can be easily looked for at the LHC, even if they are
47 “supersafe” compared to the MSSM – see e.g. [47, 58, 60–71]. The properties of the Higgs sector
48 have been well studied, and also point to the colourful states being heavy [38, 56, 59, 72–74].

49 However, currently there is no reason that the electroweak fermions must be heavy, and so far
50 the only real constraints on them have been through DM studies. Therefore we shall begin by
51 revisiting neutralino DM, previously examined in detail in [75] (see also [76, 77]), which we
52 update in this work. We will focus on the EW-ino sector, considering the lightest neutralino
53 $\tilde{\chi}_1^0$ as the Lightest Supersymmetric Particle (LSP), and look for scenarios where the $\tilde{\chi}_1^0$ is a
54 good DM candidate in agreement with relic density and direct detection constraints. In this,
55 we assume that all other new particles apart from the EW-inos are heavy and play no role in
56 the phenomenological considerations.

57 While the measurement of the DM abundance and limits on its interactions with nuclei
58 have been improved since previous analyses of the model, our major new contribution shall
59 be the examination of up-to-date LHC constraints, in view of DM-collider complementarity.
60 For example, certain collider searches are optimal for scenarios that can only over-populate
61 the relic density of dark matter in the universe, so by considering both together we obtain a
62 more complete picture.

63 Owing to the additional singlet, triplet and octet chiral superfields necessary for intro-
64 ducing DG masses, the EW-ino sector of the MDGSSM comprises six neutralinos and three
65 charginos, as compared to four and two, respectively, in the MSSM. More concretely, one
66 obtains pairs of bino-like, wino-like and higgsino-like neutralinos, with small mass splittings
67 *within* the bino (wino) pairs induced by the couplings λ_S (λ_T) between the singlet (triplet)
68 fermions with the Higgs and higgsino fields. As we recently pointed out in [69], this can po-
69 tentially lead to a long-lived $\tilde{\chi}_2^0$ due to a small splitting between the bino-like states. Moreover,
70 as we will see, one may also have long-lived $\tilde{\chi}_1^\pm$. As a further important aspect of this work,
71 we will therefore discuss the potential of probing DG DM scenarios with Long-Lived Particle
72 (LLP) searches at the LHC.

73 LHC signatures of long-lived Dirac charginos were also discussed in [78], albeit in a gauge-
74 mediated R-symmetric model. The phenomenology of Dirac neutralinos and charginos at e^+e^-
75 colliders was discussed in [79].

76 The paper is organised as follows. In section 2 we discuss the EW-ino sector of DG models in
77 general and within the MDGSSM, the focus of this work, in particular. This is supplemented by
78 a comparative review of the Minimal R-Symmetric Standard Model (MRSSM) in appendix A.1.
79 In section 3 we explain our numerical analysis: concretely, the setup of the parameter scan, the
80 tools used and constraints imposed, and how chargino and neutralino decays are computed for
81 very small mass differences. In particular, when the phase-space for decays is small enough,
82 hadronic decays are best described by (multi) pion states (rather than quarks), and we describe
83 the implementation of the numerical code to deal with this. Furthermore, loop-induced decays
84 of EW-inos into lighter ones with the emission of a photon can be important, and we describe
85 updates to public codes to handle them correctly.

86 The results of our study are presented in section 4. We first delineate the viable parameter
87 space where the lightest neutralino of the MDGSSM is at least part of the DM of the universe,
88 and then discuss consequences for collider phenomenology. Re-interpreting ATLAS and CMS
89 searches for new physics, we characterise the scenarios that are excluded and those that escape
90 detection at the LHC. In addition, we give a comparison of the applicability of a simplified
91 models approach to the limits obtained with a full recasting. We also briefly comment on the
92 prospects of the MATHUSLA experiment. In section 5 we then propose a set of benchmark
93 points for further studies. A summary and conclusions are given in section 6.

94 The appendices contain additional details on the implementation of the parameter scan
95 of the EW-ino sector (appendix A.2), and on the identification of parameter space wherein lie
96 experimentally acceptable values of the Higgs mass (appendix A.3). Finally, in appendix A.4,
97 we provide some details on the reinterpretation of a 139 fb^{-1} EW-ino search from ATLAS,
98 which we developed for this study.

2 Electroweakino sectors of Dirac gaugino models

2.1 Classes of models

Models with Dirac gaugino masses differ in the choice of fields that are added to extend those of the MSSM, and also in the treatment of the R-symmetry. Both of these have significant consequences for the scalar (“Higgs”) and EW-ino sectors. In this work, we shall focus on constraints on the EW-ino sector in the MDGSSM. Therefore, to understand the potential generality of our results, we shall here summarise the different choices that can be made in other models, before giving the details for ours.

To introduce Dirac masses for the gauginos, we need to add a Weyl fermion in the adjoint representation of each gauge group; these are embedded in chiral superfields \mathbf{S} , \mathbf{T} , \mathbf{O} which are respectively a singlet, triplet and octet, and carry zero R-charge. Some model variants neglect a field for one or more gauge groups, see e.g. [28, 80]; limits for those cases will therefore be very different.

The Dirac mass terms are written by the *supersoft* [16] operators

$$\mathcal{L}_{\text{supersoft}} = \int d^2\theta \left[\sqrt{2} m_{DY} \theta^\alpha \mathbf{W}_{1\alpha} \mathbf{S} + 2\sqrt{2} m_{D2} \theta^\alpha \text{tr}(\mathbf{W}_{2\alpha} \mathbf{T}) + 2\sqrt{2} m_{D3} \theta^\alpha \text{tr}(\mathbf{W}_{3\alpha} \mathbf{O}) \right] + \text{h.c.}, \quad (1)$$

where $\mathbf{W}_{i\alpha}$ are the supersymmetric gauge field strengths. It is possible to add Dirac gaugino masses through other operators, but this leads to a hard breaking of supersymmetry unless the singlet field is omitted – see e.g. [55]. On the other hand, whether we add supersoft operators or not, the difference appears in the scalar sector (the above operators lead to scalar trilinear terms proportional to the Dirac mass), so would not make a large difference to our results.

There are then two classes of Dirac gaugino models: ones for which the R-symmetry is conserved, and those for which it is violated. If it is conserved, with the canonical example being the MRSSM, then since the gauginos all carry R-charge, the EW-inos must be exactly Dirac fermions. For a concise review of the EW sector of the MRSSM see [50] section 2.3; in appendix A.1 we review the EW sector of that model to contrast with the MDGSSM, with some additional comments about R-symmetry breaking and its relevance to the phenomenology that we discuss later. However, in that class of models the phenomenology is different to that described here.

The second major class of models is those for which the R-symmetry is violated. This includes the minimal choices in terms of numbers of additional fields – the SOHDM [28], “MSSM without μ term” [81] and MDGSSM, as well as extensions with more fields, e.g. to allow unification of the gauge couplings, such as the CMDGSSM [72, 77]. The constraints on the EW-ino sectors of these models should be broadly similar. Crucially in these models – in contrast to those where the EW-inos are exactly Dirac – the neutralinos are pseudo-Dirac Majorana fermions. This means that they come in pairs with a small mass splitting, in particular between the neutral partner of a bino or wino LSP and the LSP itself. This has significant consequences for dark matter in the model, as has already been explored in e.g. [75, 77]: coannihilation occurs naturally. However, we shall also see here that it has significant consequences for the collider constraints: the decays from $\tilde{\chi}_2^0$ to $\tilde{\chi}_1^0$ are generally soft and hard to observe, and lead to a long-lived particle in some of the parameter space.

2.2 Electroweakinos in the MDGSSM

Here we shall summarise the important features of the EW-ino sector of the MDGSSM. Our notation and definitions are essentially identical to [75], to which we refer the reader for a

Table 1: Field content in Dirac gaugino models, apart from quark and lepton superfields, and possible R-symmetry charges prior to the addition of the *explicit* R-symmetry breaking term B_μ ; note that R_H is arbitrary. Top panel: chiral and gauge multiplet fields as in the MSSM; bottom panel: chiral and gauge multiplet fields added to those of the MSSM to allow Dirac masses for the gauginos.

Chiral and gauge multiplet fields of the MSSM

Superfield	Scalars	Fermions	Vectors	$(SU(3), SU(2), U(1)_Y)$	R
\mathbf{H}_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$		$(\mathbf{1}, \mathbf{2}, 1/2)$	R_H
\mathbf{H}_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$		$(\mathbf{1}, \mathbf{2}, -1/2)$	$2 - R_H$
$\mathbf{W}_{3,\alpha}$		λ_3	G_μ	$(\mathbf{8}, \mathbf{1}, 0)$	1
$\mathbf{W}_{2,\alpha}$		$\tilde{W}^0, \tilde{W}^\pm$	W_μ^\pm, W_μ^0	$(\mathbf{1}, \mathbf{3}, 0)$	1
$\mathbf{W}_{Y,\alpha}$		\tilde{B}	B_μ	$(\mathbf{1}, \mathbf{1}, 0)$	1

Additional chiral and gauge multiplet fields in the case of Dirac gauginos

Superfield	Scalars, $R = 0$	Fermions, $R = -1$	$(SU(3), SU(2), U(1)_Y)$
\mathbf{O}	$O^a = \frac{1}{\sqrt{2}}(O_1^a + iO_2^a)$	χ_O^a	$(\mathbf{8}, \mathbf{1}, 0)$
\mathbf{T}	$T^0 = \frac{1}{\sqrt{2}}(T_P^0 + iT_M^0), T^\pm$	$\tilde{W}'^0, \tilde{W}'^\pm$	$(\mathbf{1}, \mathbf{3}, 0)$
\mathbf{S}	$S = \frac{1}{\sqrt{2}}(S_R + iS_I)$	\tilde{B}'^0	$(\mathbf{1}, \mathbf{1}, 0)$

141 more complete treatment.

142 The MDGSSM can be defined as the minimal extension of the MSSM allowing for Dirac
 143 gaugino masses. We add one adjoint chiral superfield for each gauge group, and nothing
 144 else: the field content is summarised in Table 1. We also assume that there is an under-
 145 lying R-symmetry that prevents R-symmetry-violating couplings in the superpotential and
 146 supersymmetry-breaking sector, *except* for an explicit breaking in the Higgs sector through
 147 a (small) B_μ term. This was suggested in the ‘‘MSSM without μ -term’’ [81] as such a term nat-
 148 urally has a special origin through gravity mediation; it is also stable under renormalisation
 149 group evolution, as the B_μ term does not induce other R-symmetry violating terms.

150 The singlet and triplet fields can have new superpotential couplings with the Higgs,

$$W = W_{\text{MSSM}} + \lambda_S \mathbf{S} \mathbf{H}_u \cdot \mathbf{H}_d + 2\lambda_T \mathbf{H}_d \cdot \mathbf{T} \mathbf{H}_u. \quad (2)$$

151 These new couplings may or may not have an underlying motivation from $N = 2$ supersym-
 152 metry, which has been explored in detail [59]. After electroweak symmetry breaking (EWSB),
 153 we obtain 6 neutralino and 3 chargino mass eigenstates (as compared to 4 and 2, respectively,
 154 in the MSSM). The neutralino mass matrix \mathcal{M}_N in the basis $(\tilde{B}', \tilde{B}, \tilde{W}'^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$ is given
 155 by

$$\mathcal{M}_N = \begin{pmatrix} 0 & m_{DY} & 0 & 0 & -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta \\ m_{DY} & 0 & 0 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & 0 & m_{D2} & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta \\ 0 & 0 & m_{D2} & 0 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W s_\beta & -m_Z s_W c_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W s_\beta & m_Z c_W c_\beta & 0 & -\mu \\ -\frac{\sqrt{2}\lambda_S}{g_Y} m_Z s_W c_\beta & m_Z s_W s_\beta & -\frac{\sqrt{2}\lambda_T}{g_2} m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}, \quad (3)$$

156

157 where $s_W = \sin \theta_W$, $s_\beta = \sin \beta$ and $c_\beta = \cos \beta$; $\tan \beta = v_u/v_d$ is the ratio of the Higgs vevs;
 158 m_{DY} and m_{D2} are the ‘bino’ and ‘wino’ Dirac mass parameters; μ is the higgsino mass term,
 159 and λ_S and λ_T are the couplings between the singlet and triplet fermions with the Higgs and

160 higgsino fields. By diagonalising eq. (3), one obtains pairs of bino-like, wino-like and higgsino-
 161 like neutralinos,¹ with small mass splittings *within* the bino or wino pairs induced by λ_S or
 162 λ_T , respectively. For instance, if m_{DY} is sufficiently smaller than m_{D2} and μ , we find mostly
 163 bino/U(1) adjoint $\tilde{\chi}_{1,2}^0$ as the lightest states with a mass splitting given by

$$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq \left| 2 \frac{M_Z^2 s_W^2 (2\lambda_S^2 - g_Y^2)}{\mu g_Y^2} c_\beta s_\beta \right|. \quad (4)$$

164 Alternative approximate formulae for the mass-splitting in other cases were also given in [75].

165 Turning to the charged EW-inos, the chargino mass matrix in the basis $v^+ = (\tilde{W}'^+, \tilde{W}^+, \tilde{H}_u^+)$,
 166 $v^- = (\tilde{W}'^-, \tilde{W}^-, \tilde{H}_d^-)$ is given by:

$$\mathcal{M}_C = \begin{pmatrix} 0 & m_{D2} & \frac{2\lambda_T}{g_2} m_W c_\beta \\ m_{D2} & 0 & \sqrt{2} m_W s_\beta \\ -\frac{2\lambda_T}{g_2} m_W s_\beta & \sqrt{2} m_W c_\beta & \mu \end{pmatrix}. \quad (5)$$

167 This can give a higgsino-like $\tilde{\chi}^\pm$ as in the MSSM, but we now have *two* wino-like $\tilde{\chi}^\pm$ – the
 168 latter ones again with a small splitting driven by λ_T . A wino LSP therefore consists of a set of
 169 *two* neutral Majorana fermions and *two* Dirac charginos, all with similar masses.

170 Note that in both eqs. (3) and (5), Majorana mass terms are absent, since we assume
 171 that the only source of R-symmetry breaking in the model is the B_μ term. If we were to add
 172 Majorana masses for the gauginos, or supersymmetric masses for the singlet/triplet fields, then
 173 they would appear as diagonal terms in the above matrices (see e.g. [75] for the neutralino
 174 and chargino mass matrices with such terms included), and would generically lead to larger
 175 splitting of the pseudo-Dirac states.

176 3 Setup of the numerical analysis

177 3.1 Parameter scan

178 We now turn to the numerical analysis. Focusing solely on the EW-ino sector, the parameter
 179 space we consider is:

$$0 < m_{DY}, m_{D2}, \mu < 2 \text{ TeV}; \quad 1.7 < \tan \beta < 60; \quad -3 < \lambda_S, \lambda_T < 3. \quad (6)$$

180 The rest of the sparticle content of the MDGSSM is assumed to be heavy, with slepton masses
 181 fixed at 2 TeV, soft masses of the 1st/2nd and 3rd generation squarks set to 3 TeV and 3.5 TeV,
 182 respectively, and gluino masses set to 4 TeV. The rest of parameters are set to the same values
 183 as in [69]; in particular trilinear A -terms are set to zero.

184 The mass spectrum and branching ratios are computed with SPheno v4.0.3 [82,83], using
 185 the DiracGauginos model [84] exported from SARAH [85–88]. This is interfaced to mi-
 186 crOMEGAs v5.2 [89–91]² for the computation of the relic density, direct detection limits and
 187 other constraints explained below. To efficiently scan over the EW-ino parameters, eq. (6), we
 188 implemented a Markov Chain Monte Carlo (MCMC) Metropolis-Hastings algorithm that walks
 189 towards the minimum of the negative log-likelihood function, $-\log(L)$, defined as

$$-\log(L) = \chi_{\Omega h^2}^2 - \log(p_{\text{XIT}}) + \log(m_{\text{LSP}}). \quad (7)$$

190 Here,

¹For simplicity, we refer to the mostly bino/U(1) adjoint states collectively as binos, and to the mostly wino/SU(2) adjoint ones as winos.

²More precisely, we used a private pre-release version of micrOMEGAs v5.2, which does however give the same results as the official release.

- 191 • $\chi_{\Omega h^2}^2$ is the χ^2 -test of the computed neutralino relic density compared to the observed
 192 relic density, $\Omega h^2_{\text{Planck}} = 0.12$ [92]. In a first scan, this is implemented as an upper
 193 bound only, that is

$$\chi_{\Omega h^2}^2 = \frac{(\Omega h^2 - \Omega h^2_{\text{Planck}})^2}{\Delta_{\Omega}^2} \quad (8)$$

194 if $\Omega h^2 > \Omega h^2_{\text{Planck}}$, and zero otherwise. In a second scan, eq. (8) is applied as a two-sided
 195 bound for all Ωh^2 . Allowing for a 10% theoretical uncertainty (as a rough estimate, to
 196 account e.g. for the fact that the relic density calculation is done at the tree level only),
 197 we take $\Delta_{\Omega}^2 = 0.1 \Omega h^2_{\text{Planck}}$.

- 198 • p_{X1T} is the p -value for the parameter point being excluded by XENON1T results [93]. The
 199 confidence level (CL) being given by $1 - p_{\text{X1T}}$, a value of $p_{\text{X1T}} = 0.1$ (0.05) corresponds
 200 to 90% (95%) CL exclusion. To compute p_{X1T} , the LSP-nucleon scattering cross sections
 201 are rescaled by a factor $\Omega h^2 / \Omega h^2_{\text{Planck}}$.

- 202 • m_{LSP} is the mass of the neutralino LSP, added to avoid the potential curse of dimension-
 203 ality.³

204 In order to explore the whole parameter space, a small jump probability is introduced
 205 which prevents the scan from getting stuck in local minima of $-\log(L)$. We ran several Markov
 206 Chains from different, randomly drawn starting points; the algorithm is outlined step-by-step
 207 in appendix A.2.

208 The light Higgs mass, m_h , also depends on the input parameters, and it is thus important
 209 to find the subset of the parameter space where it agrees with the experimentally measured
 210 value. Instead of including m_h in the likelihood function, eq. (7), that guides the MCMC scan,
 211 we implemented a Random Forest Classifier that predicts whether a given input point has m_h
 212 within a specific target range. As the desired range we take $120 < m_h < 130$ GeV, assuming
 213 $m_h \simeq 125$ GeV can then always be achieved by tuning parameters in the stop sector. Points
 214 outside $120 < m_h < 130$ GeV are discarded. This significantly speeds up the scan. Details on
 215 the Higgs mass classifier are given in appendix A.3.

216 In the various MCMC runs we kept for further analysis all points scanned over, which

- 217 1. have a neutralino LSP (charged LSPs are discarded);
 218 2. have a light Higgs boson in the range $120 < m_h < 130$ GeV (see above);
 219 3. avoid mass limits from supersymmetry searches at LEP as well as constraints from the Z
 220 boson invisible decay width as implemented in micrOMEGAs [90];
 221 4. have $\Omega h^2 < 1.1 \Omega h^2_{\text{Planck}}$ (or $\Omega h^2 = \Omega h^2_{\text{Planck}} \pm 10\%$) and
 222 5. have $p_{\text{X1T}} > 0.1$.

223 With the procedure outlined above, many points with very light LSP, in the mass range be-
 224 low $m_h/2$ and even below $m_Z/2$, are retained. We therefore added two more constraints *a*
 225 *posteriori*. Namely, we require for valid points that

- 226 6. $\Delta\rho$ lies within 3σ of the measured value $\Delta\rho_{\text{exp}} = (3.9 \pm 1.9) \times 10^{-4}$ [94], the 3σ range
 227 being chosen in order to include the Standard Model (SM) value of $\Delta\rho = 0$;

³Due to the exponential increase in the volume of the parameter space, one risks having too many points with an m_{LSP} at the TeV scale. Current LHC searches are not sensitive to such heavy EW-inos.

228 7. signal-strength constraints from the SM-like Higgs boson as computed with Lilith-2 [95]
 229 give a p -value of $p_{\text{Lilith}} > 0.05$; this eliminates in particular points in which $m_{\text{LSP}} < m_h/2$,
 230 where the branching ratio of the SM-like Higgs boson into neutralinos or charginos is
 231 too large.

232 Points which do not fulfil these conditions are discarded. We thus collect in total 52550 scan
 233 points (out of $\mathcal{O}(10^6)$ tested points), which fulfil all constraints, as the basis for our phe-
 234 nomenological analysis.

235 3.2 Treatment of electroweakino decays

236 As argued above and will become apparent in the next section, many of the interesting scenar-
 237 ios in the MDGSSM feature the second neutralino and/or the lightest chargino very close in
 238 mass to the LSP. With mass splittings of $\mathcal{O}(1)$ GeV, $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$ decays into $\tilde{\chi}_1^0$ + pion(s) and $\tilde{\chi}_2^{0,\pm}$
 239 decays into $\tilde{\chi}_1^{0,\pm} + \gamma$ become important. These decays were in the first case not implemented,
 240 and in the second not treated correctly in the standard SPheno/SARAH. We therefore de-
 241 scribe below how these decays are computed in our analysis; the corresponding modified code
 242 is available online [96].⁴

243 Note that the precise calculation of the chargino and neutralino decays is important not
 244 only for the collider signatures (influencing branching ratios and decay lengths), but can also
 245 impact the DM relic abundance and/or direct detection cross sections.

246 3.2.1 Chargino decays into pions

247 When the mass splitting between chargino and lightest neutralino becomes sufficiently small,
 248 three-body decays via an off-shell W -boson, $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + (W_\mu^\pm)^*$ start to dominate. How-
 249 ever, as pointed out in e.g. Appendix A of [98] (see also [100] and references therein), when
 250 $\Delta m \lesssim 1.5$ GeV it is not accurate to describe the W^* decays in terms of quarks, but instead we
 251 should treat the final states as one, two or three pions (with Kaon final states being Cabibbo-
 252 suppressed)⁵; and for $\Delta m < m_\pi$ the hadronic channel is closed. Surprisingly, these decays
 253 have not previously been fully implemented in spectrum generators; SPheno contains only
 254 decays to single pions from neutralinos or charginos in the MSSM via an off-shell W or Z bo-
 255 son, and SARAH does not currently include even these. A full generic calculation of decays
 256 with mesons as final states for both charged and neutral EW-inos (and its implementation in
 257 SARAH) should be presented elsewhere; for this work we have adapted the results of [97–99]
 258 which include only the decay via an off-shell W :

$$\Gamma(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \pi^-) = \frac{f_\pi^2 G_F^2 |\vec{k}_\pi|}{2\pi g_2^2 \tilde{m}_-^2} \left\{ (|c_L|^2 + |c_R|^2) [(\tilde{m}_-^2 - \tilde{m}_0^2)^2 - m_\pi^2 (\tilde{m}_-^2 + \tilde{m}_0^2)] \right. \\ \left. + 4\tilde{m}_0 \tilde{m}_- m_\pi^2 \text{Re}(c_L c_R^*) \right\} \quad (9)$$

259

$$\Gamma(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \pi^- \pi^0) = \frac{G_F^2}{192\pi^3 g_2^2 \tilde{m}_-^3} \int_{4m_\pi^2}^{(\Delta m_{\tilde{\chi}_1})^2} dq^2 |F(q^2)|^2 \left(1 - \frac{4m_\pi^2}{q^2}\right)^{3/2} \lambda^{1/2}(\tilde{m}_-^2, \tilde{m}_0^2, q^2) \\ \left\{ [|c_L|^2 + |c_R|^2] [q^2 (\tilde{m}_-^2 + \tilde{m}_0^2 - 2q^2) + (\tilde{m}_-^2 - \tilde{m}_0^2)^2] - 12\text{Re}(c_L c_R^*) q^2 \tilde{m}_- \tilde{m}_0 \right\}; \quad (10)$$

⁴We leave the decays of $\tilde{\chi}_i^0$ to $\tilde{\chi}_j^\pm$ + pion(s) to future work.

⁵As the mass difference is raised above $\Delta m = 1.5$ GeV it is found numerically that, with many hadronic decay modes being kinematically open, there is a smooth transition to a description in terms of quarks.

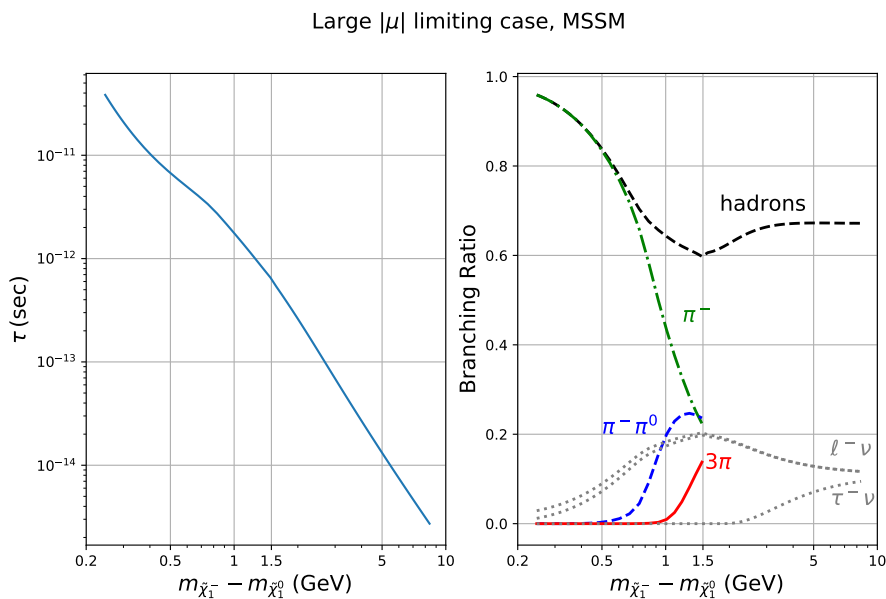


Figure 1: Chargino decays in the MSSM limit of our model; see text for details.

260

$$\Gamma(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 3\pi) = \frac{G_F^2}{6912\pi^5 g_2^2 \tilde{m}_-^3 f_\pi^2} \int_{9m_\pi^2}^{(\Delta m_{\tilde{\chi}_1})^2} dq^2 \lambda^{1/2}(\tilde{m}_-, \tilde{m}_0^2, q^2) |BW_a(q^2)|^2 g(q^2) \left\{ [|c_L|^2 + |c_R|^2] \left[\tilde{m}_-^2 + \tilde{m}_0^2 - 2q^2 + \frac{(\tilde{m}_-^2 - \tilde{m}_0^2)^2}{q^2} \right] - 12\text{Re}(c_L c_R^*) \tilde{m}_- \tilde{m}_0 \right\}. \quad (11)$$

261 Here \tilde{m}_-, \tilde{m}_0 are the masses of the $\tilde{\chi}_1^-, \tilde{\chi}_1^0$ respectively, $\vec{k}_\pi = \lambda^{1/2}(\tilde{m}_-, \tilde{m}_0^2, m_\pi^2)/(2\tilde{m}_-)$ is the
 262 pion’s 3-momentum in the chargino rest frame, and $f_\pi \simeq 93$ MeV is the pion decay constant.
 263 The couplings c_L, c_R are the left and right couplings of the chargino and neutralino to the W-
 264 boson, which can be defined as $\mathcal{L} \supset -\tilde{\chi}_1^- \gamma^\mu (c_L P_L + c_R P_R) \chi_0^- W_\mu^-$. The couplings of the W-boson
 265 to the light quarks and the W mass are encoded in G_F ; in SARAH we make the substitution
 266 $G_F^2 \rightarrow g_2^2 |c_L^{u\bar{d}W}|^2 / (16M_W^4)$, where $c_L^{u\bar{d}W}$ is the coupling of the up and down quarks to the W-
 267 boson.

268 While the single pion decay can be simply understood in terms of the overlap of the axial
 269 current with the pion, the two- and three-pion decays proceed via exchange of virtual mesons
 270 which then decay to pions. The form factors for these processes are then determined by QCD,
 271 and so working at leading order in the electroweak couplings we can use experimental data for
 272 processes involving the same final states; in this case we can use τ lepton decays. The two-pion
 273 decays are dominated by ρ and ρ' meson exchange, and the form factor $F(q^2)$ was defined in
 274 eqs. (A3) and (A4) of [98]. The expressions for the Breit–Wigner propagator BW_a of the a_1
 275 meson (and *not* the a_2 meson as stated in [97–99]), which dominates 3π production, as well
 276 as for the three-pion phase space factor $g(q^2)$ can be found in eqs. (3.16)–(3.18) of [100]. As
 277 in [97–99] we use the propagator without “dispersive correction,” and so include a factor of
 278 1.35 to compensate for the underestimate of $\tau^- \rightarrow 3\pi \nu_\tau$ decays by 35%. Note finally that the
 279 three-pion decay includes both $\pi^- \pi^0 \pi^0$ and $\pi^- \pi^- \pi^+$ modes, which are assumed to be equal.

280 For comparison with [97–99], in Figure 1 we reproduce Fig. 6 from [98] (same as Fig. 1
 281 in [99]) with our code by taking the MSSM-limit of our model; we add Majorana gaug-
 282 ino masses for the wino fixed at $M_2 = 200$ GeV and scan over values for the bino mass of

Large $|\mu|$ limiting case, MDGSSM

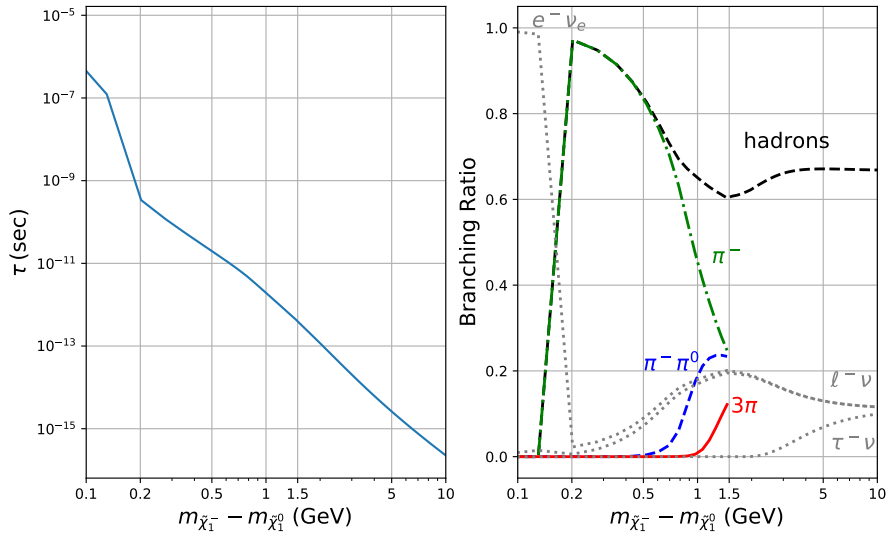


Figure 2: Chargino decays in the MDGSSM.

283 $M_1 \in [210, 220]$ GeV while taking $\mu = 2000$ GeV and adding supersymmetric masses for the
 284 **S** and **T** fields of $M_S = M_T = 1$ TeV. Keeping $\tan\beta = 34.664$ and $B_\mu = (1 \text{ TeV})^2$ we have a
 285 spectrum with effectively only Majorana charginos and neutralinos, which can be easily tuned
 286 in mass relative to each other by changing the bino mass.

287 In Figure 2 we show the equivalent expressions in the case of interest for this paper,
 288 where there are no Majorana masses for the gauginos. We take $\tan\beta = 34.664$, $\mu = 2$ TeV,
 289 $\nu_T = -0.568$ GeV, $\nu_S = 0.92$ GeV, $\lambda_S = -0.2$, $\sqrt{2}\lambda_T = 0.2687$, $m_{D2} = 200$ GeV, and vary m_{DY}
 290 between 210 and 221 GeV. We find identical behaviour for both models, except the overall
 291 decay rate is slightly different; and note that in this scenario we have $\tilde{\chi}_2^0$ almost degenerate
 292 with $\tilde{\chi}_1^0$, so we include decays of $\tilde{\chi}_1^\pm$ to *both* states of the pseudo-Dirac LSP

293 Finally, we implemented the decays of neutralinos to single pions via the expression

$$\Gamma(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \pi^0) = \frac{f_\pi^2 G_F^2 c_W^2 |\vec{k}_\pi|}{2\pi g^2 \tilde{m}_2^2} \left\{ (|c_L|^2 + |c_R|^2) [(\tilde{m}_2^2 - \tilde{m}_1^2)^2 - m_\pi^2 (\tilde{m}_2^2 + \tilde{m}_1^2)] \right. \\ \left. + 4\tilde{m}_1 \tilde{m}_2 m_\pi^2 \text{Re}(c_L c_R^*) \right\}, \quad (12)$$

294 where now $\tilde{m}_{1,2}$ are the masses of $\tilde{\chi}_{1,2}^0$ and c_L, c_R are the couplings for the neutralinos to the
 295 Z -boson analogously defined as above; since the neutralino is Majorana in nature we must
 296 have $c_R = -c_L^*$.

297 3.2.2 Neutralino decays into photons

298 In the MDGSSM, the mass splitting between the two lightest neutralinos is naturally small.⁶
 299 Therefore in a significant part of the parameter space the dominant $\tilde{\chi}_2^0$ decay mode is the
 300 loop-induced process $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma$. This is controlled by an effective operator

$$\mathcal{L} = \bar{\Psi}_1 \gamma^\mu \gamma^\nu (C_{12} P_L + C_{12}^* P_R) \Psi_2 F_{\mu\nu}, \quad (13)$$

⁶This could be even more so in the case of the MRSSM with a small R-symmetry violation.

301 where $\Psi_i \equiv \begin{pmatrix} \chi_i^0 \\ \bar{\chi}_i \end{pmatrix}$ is a Majorana spinor, and yields

$$\Gamma(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma) = \frac{|C_{12}|^2 (m_{\tilde{\chi}_2}^2 - m_{\tilde{\chi}_1}^2)^3}{2\pi m_{\tilde{\chi}_2}^3}. \quad (14)$$

302 Our expectation (and indeed as we find for most of our points) is that $|C_{12}| \sim 10^{-5} - 10^{-6} \text{ GeV}^{-1}$.

303 This loop decay process is calculated in SPheno/SARAH using the routines described in
 304 [101]. However, we found that the handling of fermionic two-body decays involving photons
 305 or gluons was not correctly handled in the spin structure summation. Suppose we have S-
 306 matrix elements \mathcal{M} for a decay $F(p_1) \rightarrow F(p_2) + V(p_3)$ with a vector having wavefunction ε_μ ,
 307 then we can decompose the amplitudes according to their Lorentz structures (putting v_i for
 308 the antifermion wavefunctions) as

$$\mathcal{M} = \varepsilon_\mu \mathcal{M}^\mu = \varepsilon_\mu(p_3) \left[x_1 \bar{v}_1 P_L \gamma^\mu v_2 + x_2 \bar{v}_1 P_R \gamma^\mu v_2 + p_1^\mu x_3 \bar{v}_1 P_L v_2 + p_1^\mu x_4 \bar{v}_1 P_R v_2 \right]. \quad (15)$$

309 This is the decomposition made in SARAH which computes the values of the amplitudes
 310 $\{x_i\}$. Now, if V is massless, and since \mathcal{M} is an S-matrix element, the Ward identity requires
 311 $(p_3)_\mu \mathcal{M}^\mu = 0$ (note that this requires that we include self-energy diagrams in the case of
 312 charged fermions), and this leads to two equations relating the $\{x_i\}$:

$$x_3 = \frac{m_1 x_2 - m_2 x_1}{p_1 \cdot p_3}, \quad x_4 = \frac{m_1 x_1 - m_2 x_2}{p_1 \cdot p_3}, \quad \text{where } p_1 \cdot p_3 = \frac{1}{2}(m_1^2 - m_2^2). \quad (16)$$

313 Here, m_1 and m_2 are the masses of the first and second fermion, respectively. Performing the
 314 spin and polarisation sums naively, we have the matrix

$$\sum_{\text{spins, polarisations}} \mathcal{M} \mathcal{M}^* \equiv x_i \mathcal{M}_{ij} x_j^*, \quad (17)$$

$$\mathcal{M}_{ij} = \begin{pmatrix} 2(m_1^2 + m_2^2) & -8m_1 m_2 & 2m_1^2 m_2 & m_1(m_1^2 + m_2^2) \\ -8m_1 m_2 & 2(m_1^2 + m_2^2) & m_1(m_1^2 + m_2^2) & 2m_1^2 m_2 \\ 2m_1^2 m_2 & m_1(m_1^2 + m_2^2) & -m_1^2(m_1^2 + m_2^2) & -2m_1^3 m_2 \\ m_1(m_1^2 + m_2^2) & 2m_1^2 m_2 & -2m_1^3 m_2 & -m_1^2(m_1^2 + m_2^2) \end{pmatrix}.$$

315 When we substitute in the Ward identities and re-express as just x_1, x_2 we have

$$\sum_{\text{spins, polarisations}} \mathcal{M} \mathcal{M}^* = (x_1, x_2) \begin{pmatrix} 2(m_1^2 + m_2^2) & -4m_1 m_2 \\ -4m_1 m_2 & 2(m_1^2 + m_2^2) \end{pmatrix} \begin{pmatrix} x_1^* \\ x_2^* \end{pmatrix}. \quad (18)$$

316 This matrix will yield real, positive-definite widths for any value of the matrix elements x_1, x_2 ,
 317 whereas this is not manifestly true for eq. (17). For earlier versions of SARAH, instead of one
 318 of these expressions above, an incorrect formula was used. As of SARAH version 4.14.3 we
 319 implemented the spin summation for loop decay matrix elements given in eq. (18), i.e. in such
 320 decays we compute the Lorentz structures corresponding to x_1, x_2 and ignore x_3, x_4 .

321 This applies to all $\tilde{\chi}_{i \neq 1}^0 \rightarrow \tilde{\chi}_1^0 \gamma$ and $\tilde{\chi}_{j \neq 1}^\pm \rightarrow \tilde{\chi}_1^\pm \gamma$ transitions.

322 4 Results

323 4.1 Properties of viable scan points

324 We are now in the position to discuss the results from the MCMC scans. We begin by con-
 325 sidering the properties of the $\tilde{\chi}_1^0$ as a DM candidate. Figure 3(a) shows the bino, wino and

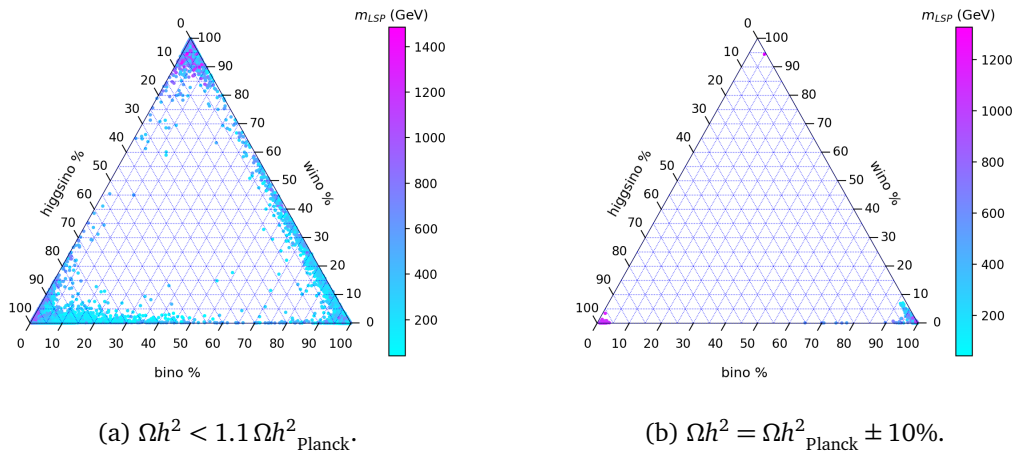


Figure 3: Bino, wino and higgsino admixtures of the LSP in the region where it makes up for (a) at least a part or (b) all of the DM abundance; limits from XENON1T and all other constraints listed in section 3.1 are also satisfied. The colour denotes the mass of the LSP.

326 higgsino composition of the $\tilde{\chi}_1^0$ when only an upper bound on Ωh^2 is imposed; all points in
 327 the plot also satisfy XENON1T ($p_{\text{X1T}} > 0.1$) and all other constraints listed in section 3.1. We
 328 see that cases where the $\tilde{\chi}_1^0$ is a mixture of all states (bino, wino and higgsino) are excluded,
 329 while cases where it is a mixture of only two states, with one component being dominant,
 330 can satisfy all constraints. Also noteworthy is that there are plenty of points in the low-mass
 331 region, $m_{\text{LSP}} < 400$ GeV.

332 Figure 3(b) shows the points where the $\tilde{\chi}_1^0$ makes for all the DM abundance. This, of
 333 course, imposes much stronger constraints. In general, scenarios with strong admixtures of
 334 two or more EW-ino states are excluded and the valid points are confined to the corners of
 335 (almost) pure bino, wino or higgsino. Similar to the MSSM, the higgsino and especially the
 336 wino DM cases are heavy, with masses $\gtrsim 1$ TeV, and only about a 5% admixture of another
 337 interaction eigenstate; in the wino case, the MCMC scan gave only one surviving point within
 338 the parameter ranges scanned over. Light masses are found only for bino-like DM; in this case
 339 there can also be slightly larger admixtures of another state: concretely we find up to about
 340 10% wino or up to 35% higgsino components.

341 As mentioned, we assume that all other sparticles besides the EW-inos are heavy. Hence, co-
 342 annihilations of EW-inos which are close in mass to the LSP must be the dominating processes
 343 to achieve Ωh^2 of the order of 0.1 or below. The relation between mass, bino/wino/higgsino
 344 nature of the LSP, relic density and mass difference to the next-to-lightest sparticle (NLSP) is
 345 illustrated in Figure 4. The three panels of this figure show m_{LSP} vs. Ωh^2 for the points from
 346 Figure 3(a), where the LSP is $> 50\%$ bino, wino, or higgsino, respectively. The NLSP–LSP mass
 347 difference is shown in colour, while different symbols denote neutral and charged NLSPs. Two
 348 things are apparent besides the dependence of Ωh^2 on $m_{\tilde{\chi}_1^0}$ for the different scenarios:

349 1. All three cases feature small NLSP–LSP mass differences. For a wino-like LSP, this mass
 350 difference is at most 3 GeV. For bino-like and higgsino-like LSPs it can go up to nearly
 351 25 GeV, though for most points it is just few GeV.

352 2. The NLSP can be neutral or charged, that is in all three cases we can have mass orderings
 353 $\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0$ as well as $\tilde{\chi}_1^0 < \tilde{\chi}_2^0 < \tilde{\chi}_1^\pm$.

354 For bino-like LSP points outside the Z and Higgs-funnel regions, a small mass difference be-
 355 tween the LSP and NLSP is however not sufficient—co-annihilations with other nearby states

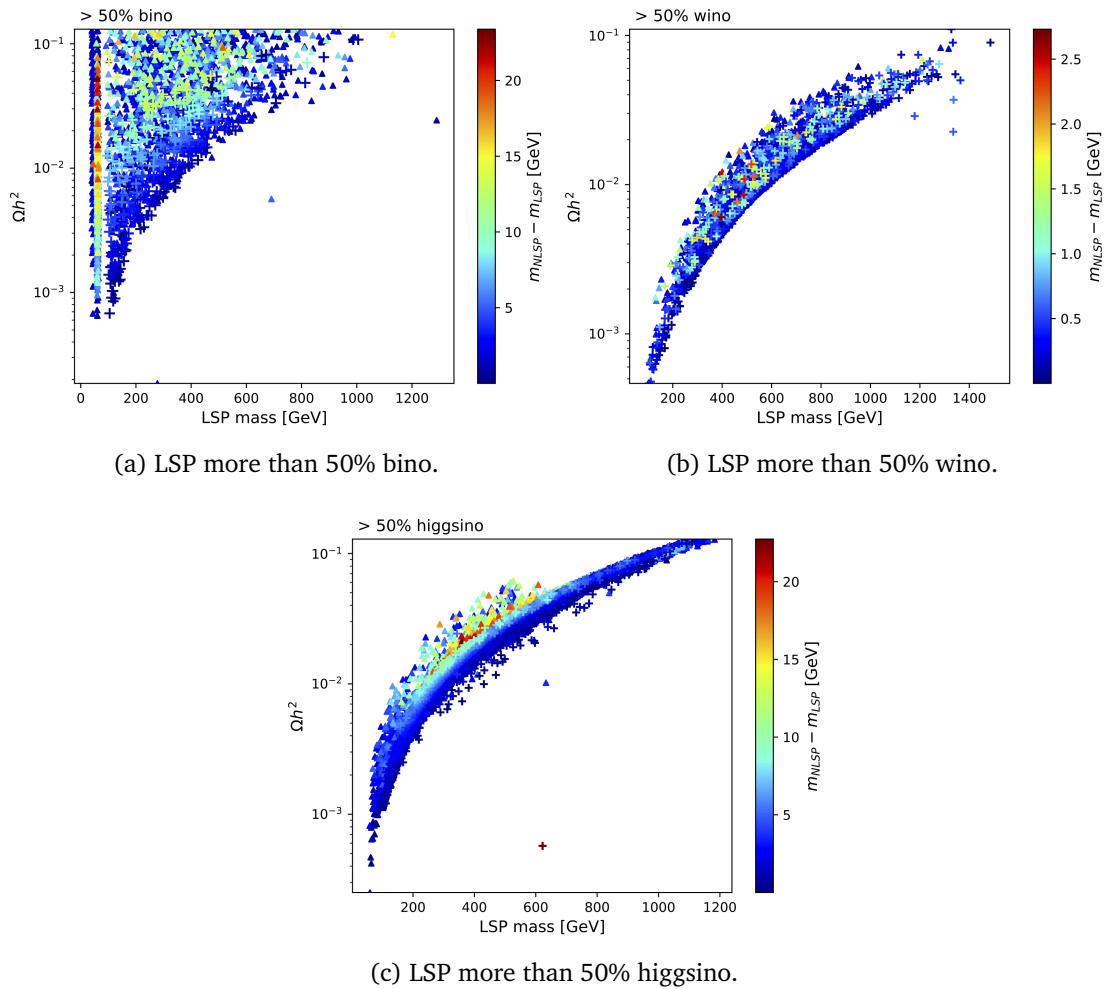


Figure 4: m_{LSP} vs. Ωh^2 for points from Figure 3(a), where (a) LSP > 50% bino, (b) LSP > 50% wino, and (c) LSP > 50% higgsino. In color, the NLSP-LSP mass difference. Triangles represent neutral NLSPs while crosses represent charged NLSPs.

356 are required to achieve $\Omega h^2 \leq 0.132$. Indeed, as shown in Figure 5, we have $m_{D2} \approx m_{DY}$,
 357 with typically $m_{D2}/m_{DY} \approx 0.9\text{--}1.4$, over much of the bino-LSP parameter space outside the
 358 funnel regions. This leads to bino-wino co-annihilation scenarios like also found in the MSSM.
 359 The scattered points with large ratios m_{D2}/m_{DY} have $\mu \approx m_{DY}$, i.e. a triplet of higgsinos
 360 close to the bins. Outside the funnel regions, the bino-like LSP points therefore feature
 361 $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \lesssim 30$ GeV and $m_{\tilde{\chi}_{3,4}^0} - m_{\tilde{\chi}_1^0} \lesssim 60$ GeV in addition to $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim 20$ GeV.

362 For completeness we also give the maximal mass differences found within triplets (quadru-
 363 plets) of higgsino (wino) states in the higgsino (wino) LSP scenarios. Concretely we have
 364 $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \lesssim 15$ GeV and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \lesssim 50\text{--}10$ GeV (decreasing with increasing $m_{\tilde{\chi}_1^0}$) in the
 365 higgsino LSP case. In the wino LSP case, $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \lesssim 4$ GeV, while $m_{\tilde{\chi}_{2,\tilde{\chi}_2^\pm}^0} - m_{\tilde{\chi}_1^0} \lesssim 20$ GeV
 366 (though mostly below 10 GeV). However, as noted before, either mass ordering, $m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_1^\pm}$
 367 or $m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^0}$ is possible.

368 An important point to note is that the mass differences are often so small that the NLSP
 369 (and sometimes even the NNLSP) becomes long-lived on collider scales, i.e. it has a potentially
 370 visible decay length of $c\tau > 1$ mm. This is illustrated in Figure 6, which shows in the left
 371 panel the mean decay length of the LLPs as function of their mass difference to the LSP. Long-
 372 lived charginos will lead to charged tracks in the detector, while long-lived neutralinos could

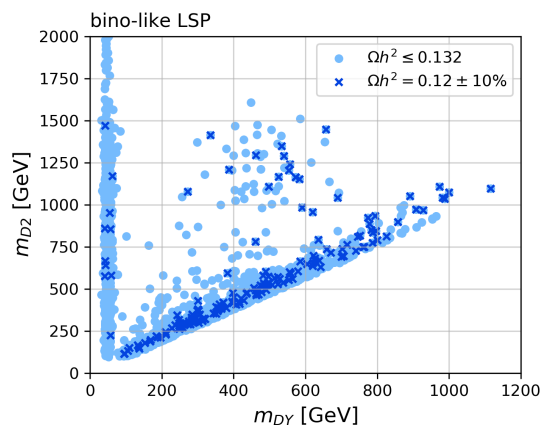


Figure 5: m_{DY} vs. m_{D2} for scan points with a bino-like LSP, cf. Figure 4(a).

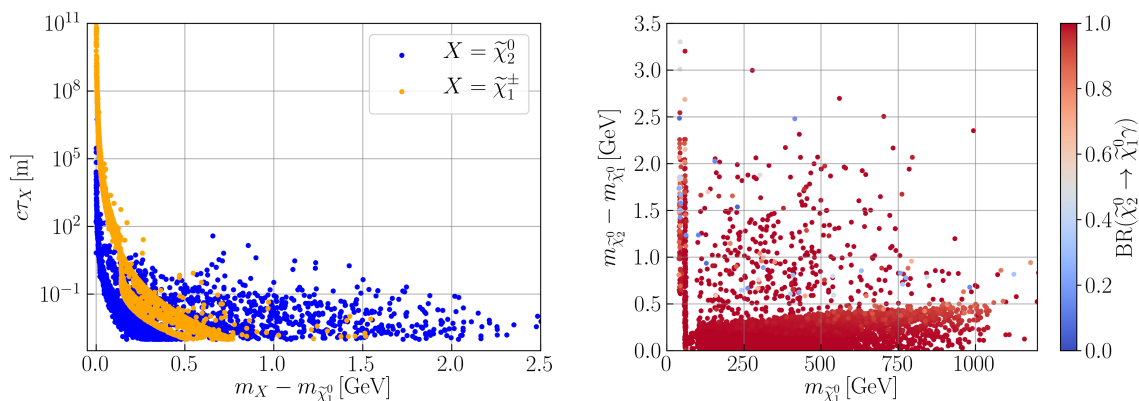


Figure 6: Left: Mean decay length $c\tau$ as a function of the mass difference with the LSP, for all points with long-lived particles ($c\tau > 1$ mm); blue points have a neutralino and orange points a chargino LLP. Right: $m_{\tilde{\chi}_2^0}$ vs. $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ for points with long-lived neutralinos; the branching ratio of the loop decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ is indicated in colour.

373 potentially lead to displaced vertices. However, given the small mass differences involved, the
 374 decay products of the latter will be very soft. The right panel in Figure 6 shows the importance
 375 of the radiative decay of long-lived $\tilde{\chi}_2^0$ s in the plane of $\tilde{\chi}_1^0$ mass vs. $\tilde{\chi}_2^0 - \tilde{\chi}_1^0$ mass difference. As
 376 can be seen, decays into (soft) photons are clearly dominant.

377 Let us now turn to the region where the $\tilde{\chi}_1^0$ would account for all the DM. Figure 7 (left)
 378 shows the points with $\Omega h^2 = \Omega h^2_{\text{Planck}} \pm 10\%$ in the plane of $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. Points with
 379 bino-like, higgsino-like and wino-like $\tilde{\chi}_1^0$ are distinguished by different colours and symbols.
 380 As expected from the discussion above, there are three distinct regions of bino-like, higgsino-
 381 like and wino-like DM, indicated in blue, green and orange, respectively.

382 From the collider point of view, the bino-like DM region is perhaps the most interesting
 383 one, as it has masses below a TeV. We find that, in this case, the NLSP is always the $\tilde{\chi}_2^0$ with mass
 384 differences $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ ranging from about 0.2 GeV to 16 GeV. As already pointed in [75, 76],
 385 this small mass splitting helps achieve the correct relic density through $\tilde{\chi}_{1,2}^0$ co-annihilation.
 386 In the region of $m_{\tilde{\chi}_1^0} = 100 - 1000$ GeV, it is induced by $-\lambda_s \simeq 0.05 - 1.26$.⁷ For lower masses,
 387 $m_{\tilde{\chi}_1^0} \simeq 40$ GeV or $m_{\tilde{\chi}_1^0} \simeq 60$ GeV, where the DM annihilation proceeds via the Z or h pole, and

⁷Our conventions differ (as usual) from the SARAHDiracGauginos implementation: $\lambda_s \equiv -\text{lam}$ and

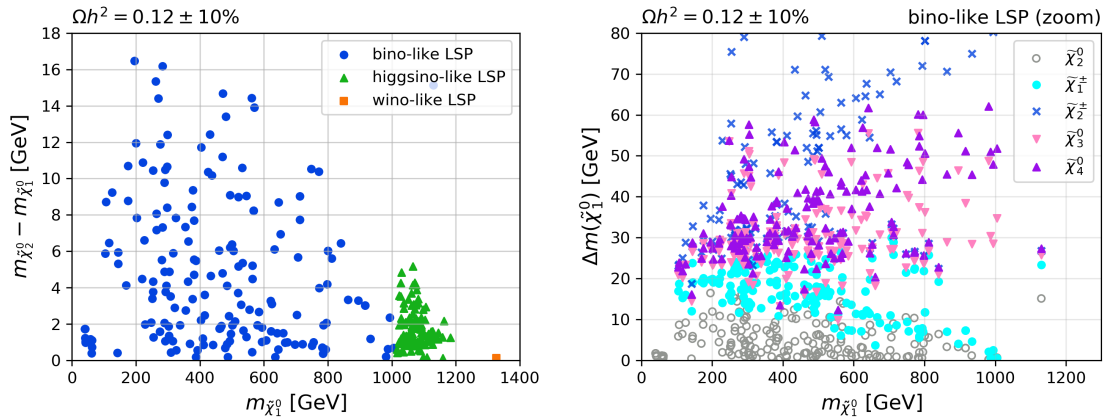


Figure 7: Left: m_{LSP} vs. NLSP–LSP mass difference for points from Figure 3(b); points with bino-, higgsino-, and wino-like LSP are shown in blue, green and orange, respectively. Right: mass differences Δm of $\tilde{\chi}_{2,3,4}^0$ and $\tilde{\chi}_{1,2}^\pm$ to the $\tilde{\chi}_1^0$ as function of the $\tilde{\chi}_1^0$ mass, for the bino DM points of the right panel.

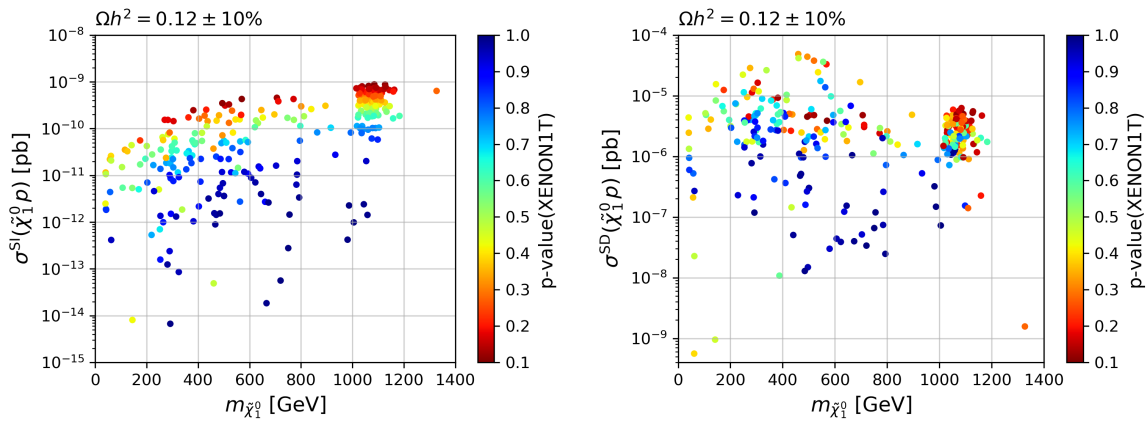


Figure 8: Spin-independent (left) and spin-dependent (right) $\tilde{\chi}_1^0$ scattering cross sections on protons as function of the $\tilde{\chi}_1^0$ mass, for the points with $\Omega h^2 = 0.12 \pm 10\%$. The colour code indicates the p -value for XENON1T.

388 we have $\Delta m \simeq 0.4\text{--}1.7$ GeV and $|\lambda_S| \simeq 6 \times 10^{-4}\text{--}0.26$ (with $\lambda_S \simeq -0.26$ to 0.02). With
 389 the exception of the funnel region, all the bino-like points in the left panel of Figure 7
 390 have a $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{3,4}^0$ close in mass to the $\tilde{\chi}_1^0$. This is shown explicitly in the right panel of the
 391 same figure. Concretely, we have $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \lesssim 30$ GeV and $m_{\tilde{\chi}_{3,4}^0} - m_{\tilde{\chi}_1^0} \approx 10\text{--}60$ GeV. Often,
 392 that is when the LSP has a small wino admixture, the $\tilde{\chi}_2^\pm$ is also close in mass. In most cases
 393 $m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_3^0}$ although the opposite case also occurs. All in all this creates peculiar compressed
 394 EW-ino spectra; they are similar to the bino-wino DM scenario in the MSSM, but there are
 395 more states involved and the possible mass splittings are somewhat larger. In any case, the
 396 dominant signatures are 3-body and/or radiative decays of heavier into lighter EW-inos; only
 397 the heavier $\tilde{\chi}_{2,3}^\pm$ and $\tilde{\chi}_{5,6}^0$ can decay via an on-shell W , Z or h^0 .

398 Finally we show in Figure 8 the spin-independent (σ^{SI}) and spin-dependent (σ^{SD}) $\tilde{\chi}_1^0$
 399 scattering cross sections on protons, with the p -value from XENON1T indicated in colour.

$\lambda_T \equiv \text{LT}/\sqrt{2}$ in SARAH convention.

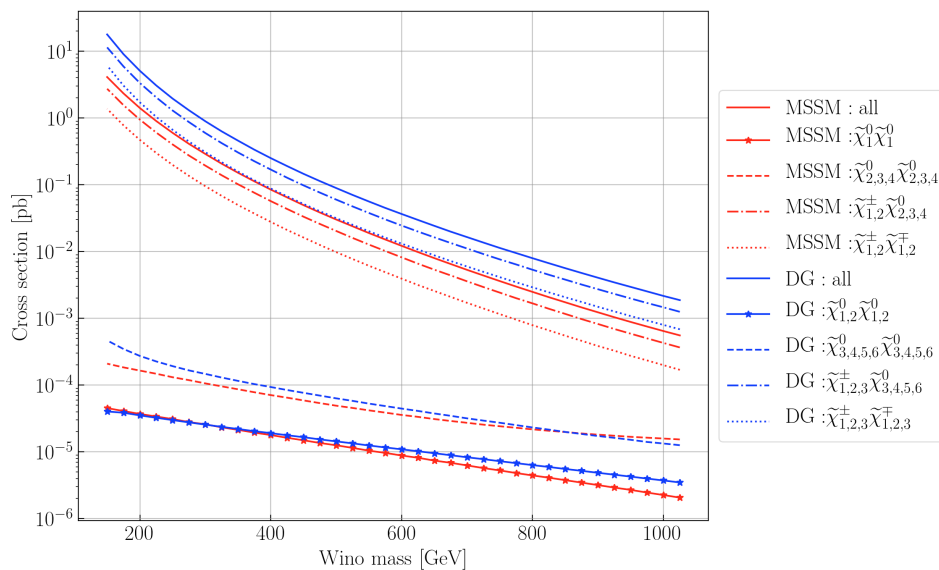


Figure 9: EW-ino production cross sections at the 13 TeV LHC as a function of the wino mass parameter, in blue for the MDGSSM and in red for the MSSM; the ratio of the bino and wino mass parameters is fixed as $m_{D2} = 1.2 m_{DY}$ (MDGSSM) and $M_2 = 1.2 M_1$ (MSSM), while $\mu \simeq 1400$ GeV, $\tan \beta \simeq 10$, $\lambda_S \simeq -0.29$ and $\sqrt{2}\lambda_T \simeq -1.40$.

400 While the bulk of the points has cross sections that should be testable in future DM direct
 401 detection experiments, there are also a few points with cross sections below the neutrino floor.
 402 We note in passing that the scattering cross section on neutrons (not shown) is not exactly the
 403 same in this model but can differ from that on protons by few percent.

404 4.2 LHC constraints

405 Let us now turn to the question of how the DG EW-ino scenarios from the previous subsection
 406 can be constrained at the LHC. Before reinterpreting various ATLAS and CMS SUSY searches,
 407 it is important to point out that the cross sections for EW-ino production are larger in the
 408 MDGSSM than in the MSSM. For illustration, Figure 9 compares the production cross sections
 409 for pp collisions at 13 TeV in the two models. The cross sections are shown as a function of
 410 the wino mass parameter, with $m_{D2} = 1.2 m_{DY}$ ($M_2 = 1.2 M_1$) for the MDGSSM (MSSM); the
 411 other parameters are $\mu \simeq 1400$ GeV, $\tan \beta \simeq 10$, $\lambda_S \simeq -0.29$ and $\sqrt{2}\lambda_T \simeq -1.40$. While
 412 LSP-LSP production is almost the same in the two models, chargino-neutralino and chargino-
 413 chargino production is about a factor 3–5 larger in the MDGSSM, due to the larger number of
 414 degrees of freedom.

415 4.2.1 Constraints from prompt searches

416 SModels

417 We start by checking the constraints from searches for promptly decaying new particles with
 418 SModelS [102–105]. The working principle of SModelS is to decompose all signatures occur-
 419 ring in a given model or scenario into simplified model topologies, also referred to as simpli-
 420 fied model spectra (SMS). Each SMS is defined by the masses of the BSM states, the vertex
 421 structure, and the SM and BSM final states. After this decomposition, the signal weights,
 422 determined in terms of cross-sections times branching ratios, $\sigma \times \text{BR}$, are matched against a

423 database of LHC results. SModelS reports its results in the form of r -values, defined as the
 424 ratio of the theory prediction over the observed upper limit, for each experimental constraint
 425 that is matched in the database. All points for which at least one r -value equals or exceeds
 426 unity ($r_{\max} \geq 1$) are considered as excluded.

427 Concretely we are using SModelS v1.2.3 [105]. For our purpose, the most relevant “prompt”
 428 search results from Run 2 included in the v1.2.3 database are those from

- 429 • the ATLAS EW-ino searches with 139 fb^{-1} , constraining $WZ^{(*)} + E_T^{\text{miss}}$ (ATLAS-SUSY-
 430 2018-06 [106]), $WH + E_T^{\text{miss}}$ (ATLAS-SUSY-2019-08 [107]) and $WW^{(*)} + E_T^{\text{miss}}$ (ATLAS-
 431 SUSY-2018-32 [108]) signatures arising from chargino-neutralino or chargino-chargino
 432 production, as well as
- 433 • the CMS EW-ino combination for 35.9 fb^{-1} , CMS-SUS-17-004 [109], constraining
 434 $WZ^{(*)} + E_T^{\text{miss}}$ and $WH + E_T^{\text{miss}}$ signatures from chargino-neutralino production.

435 One modification we made to the SModelS v1.2.3 database is that we included the combined
 436 $WZ^{(*)} + E_T^{\text{miss}}$ constraints from Fig. 8a of [109]; the original v1.2.3 release has only those
 437 from Fig. 7a, which are weaker. It is interesting to note that the CMS combination [109] for
 438 35.9 fb^{-1} sometimes still gives stronger limits than the individual ATLAS analyses [106–108]
 439 for full Run 2 luminosity.

440 The SLHA files produced with SPheno in our MCMC scan contain the mass spectrum and
 441 decay tables. For evaluating the simplified model constraints with SModelS, also the LHC cross
 442 sections at $\sqrt{s} = 8$ and 13 TeV are needed. They are conveniently added to the SLHA files by
 443 means of the SModelS–micrOMEGAs interface [90], which moreover automatically produces
 444 the correct `particles.py` file to declare the even and odd particle content for SModelS.
 445 Once the cross sections are computed, the evaluation of LHC constraints in SModelS takes a
 446 few seconds per point, which makes it possible to check the full dataset of 52.5k scan points.

447 The results are shown in Figures 10 and 11. The left panels in Figure 10 show the points
 448 excluded by SModelS ($r_{\max} \geq 1$), in the plane of $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{\chi}_{3,4}^0}$ (top left) and $m_{\tilde{\chi}_j^\pm}$ vs. $m_{\tilde{\chi}_{3,4}^0}$
 449 (bottom left), the difference between $\tilde{\chi}_{3,4}^0$ not being discernible on the plots. Points with bino-
 450 like or higgsino-like LSPs are distinguished by different colours and symbols: light blue dots
 451 for bino-like LSP points and magenta/pink triangles for higgsino-like LSP points. There are no
 452 excluded points with wino-like LSPs.

453 As can be seen, apart from two exceptions, all bino LSP points excluded by SModelS lie in
 454 the Z or h funnel region and have almost mass-degenerate $\tilde{\chi}_{3,4}^0$ and $\tilde{\chi}_1^\pm$ — actually most of the
 455 time they have mass-degenerate $\tilde{\chi}_{3,4}^0$ and $\tilde{\chi}_{1,2}^\pm$ corresponding to a quadruplet of wino states,
 456 as winos have much higher production cross sections than higgsinos. The reach is up to about
 457 750 GeV for wino-like $\tilde{\chi}_{3,4}^0$, $\tilde{\chi}_{1,2}^\pm$. When the next-to-lightest states are higgsinos and winos are
 458 heavy, the exclusion reaches only $m_{\tilde{\chi}_{3,4}^0}, m_{\tilde{\chi}_1^\pm} \lesssim 400 \text{ GeV}$.

459 The higgsino LSP points excluded by SModelS have $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$ masses up to about
 460 200 GeV and always feature light winos ($\tilde{\chi}_{3,4}^0, \tilde{\chi}_{2,3}^\pm$) below about 500 GeV . In terms of soft
 461 terms, the excluded bino LSP points have $m_{D2} < 750 \text{ GeV}$ or $\mu < 400 \text{ GeV}$, while the excluded
 462 higgsino LSP points have $\mu < 200 \text{ GeV}$ and $m_{D2} < 500 \text{ GeV}$ (see Figure 11).

463 The right panels of Figures 10 and 11 show the same mass and parameter planes as the
 464 left panels but distinguish the signatures, which are responsible for the exclusion, by different
 465 colours/symbols. We see that $WH + E_T^{\text{miss}}$ simplified model results exclude only bino-LSP
 466 points in the h -funnel region, but can reach up to $m_{\tilde{\chi}_{3,4}^0} \lesssim 750 \text{ GeV}$; all these points have
 467 $m_{DY} \approx 60 \text{ GeV}$, $m_{D2} \lesssim 750 \text{ GeV}$ and $\mu \gtrsim m_{D2}$, cf. Figure 11 (right). The $WZ^{(*)} + E_T^{\text{miss}}$
 468 ($WW^{(*)} + E_T^{\text{miss}}$) simplified model results exclude bino-LSP points in the Z - and h -funnel regions
 469 for winos up to roughly 600 (400) GeV , and higgsino-LSP points with masses up to roughly 200

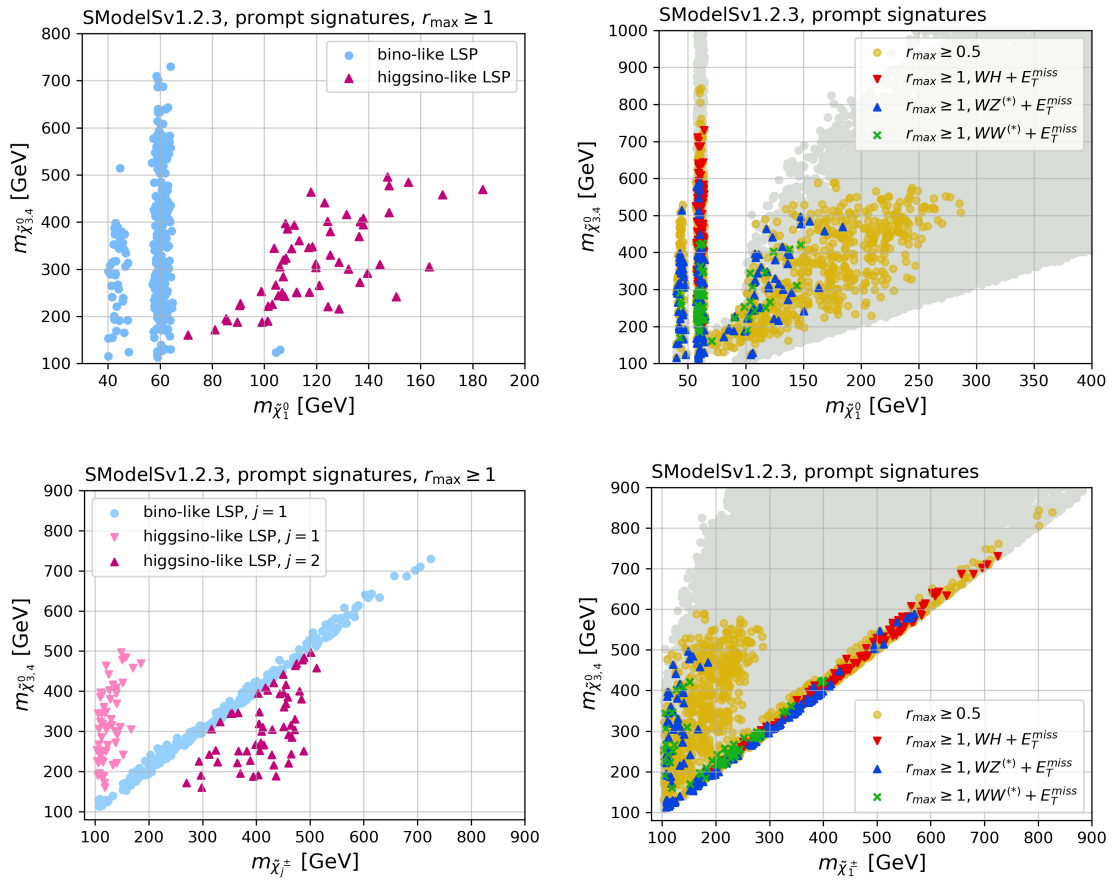


Figure 10: LHC constraints from prompt searches evaluated with SModelS. The left panels show the excluded points, $r_{\max} \geq 1$, in the $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{\chi}_{3,4}^0}$ (top) and $m_{\tilde{\chi}_j^\pm}$ vs. $m_{\tilde{\chi}_{3,4}^0}$ (bottom) planes, with bino-like or higgsino-like LSP points distinguished by different colours and symbols as indicated in the plot labels. The right panels show the same mass planes but distinguish the signatures, which are responsible for the exclusion, by different colours/symbols (again, see plot labels); moreover the region with $r_{\max} \geq 0.5$ is shown in yellow, and that covered by all scan points in grey.

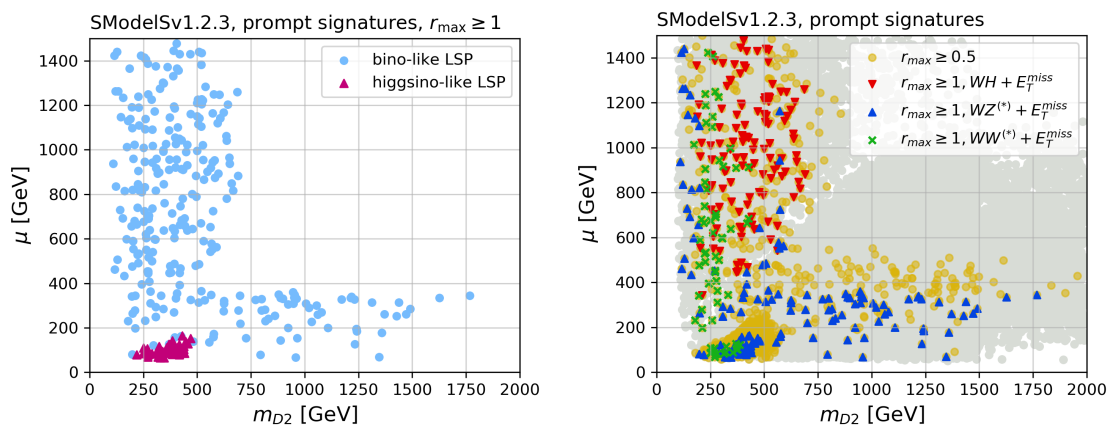


Figure 11: As Figure 10 but in the m_{D2} vs. μ plane.

470 (150) GeV when the wino-like states are below 500 (400) GeV. Correspondingly, in Figure 11
 471 (right) the green crosses lie in the range $m_{D2} \lesssim 500$ GeV, while blue triangles lie in the region
 472 of $m_{D2} \lesssim 600$ GeV or $\mu \lesssim 400$ GeV.

473 For completeness, the right panels of Figures 10 and 11 also show the region with
 474 $r_{\max} \geq 0.5$. This is primarily to indicate how the reach might improve with, e.g., more statis-
 475 tics. It also serves to illustrate the effect of a possible underestimation of the visible signal in
 476 the SMS approach, although in the comparison with MadAnalysis 5 below we will see that the
 477 limits from simplified models and full recasting actually agree quite well.

478 We note that we have run SModelS with the default configuration of $\text{sigmacut}=0.01$ fb,
 479 $\text{minmassgap}=5$ GeV and $\text{maxcond}=0.2$. Long-lived $\tilde{\chi}_2^0$ are always treated as E_T^{miss} irrespective
 480 of the actual decay length, as the $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + X$ decays (X mostly being a photon) are too
 481 soft to be picked up/vetoed by the signal selections of the analyses under consideration.⁸ The
 482 excluded regions depend only slightly on these choices. Overall the constraints are very weak:
 483 of the almost 53k scan points, only 340 are excluded by the prompt search results in SModelS;
 484 548 (1126) points have $r_{\max} > 0.8$ (0.5).

485 MadAnalysis 5

486 One disadvantage of the simplified model constraints is that they assume that charginos and
 487 neutralinos leading to $WZ^{(*)} + E_T^{\text{miss}}$ or $WH + E_T^{\text{miss}}$ signatures are mass degenerate. SMod-
 488 elS allows a small deviation from this assumption, but $\tilde{\chi}_i^\pm \tilde{\chi}_j^0$ production with sizeable differ-
 489 ences between $m_{\tilde{\chi}_i^\pm}$ and $m_{\tilde{\chi}_j^0}$ will not be constrained. Moreover, the simplified model results
 490 from [106–109] are cross section upper limits only, which means that different contributions
 491 to the same signal region cannot be combined (to that end efficiency maps would be neces-
 492 sary [103]). It is therefore interesting to check whether full recasting based on Monte Carlo
 493 event simulation can extend the limits derived with SModelS.

494 Here we use the recast codes [110–112] for Run 2 EW-ino searches available in MadAnal-
 495 ysis 5 [113–116].⁹ These are

- 496 • two CMS searches in leptons + E_T^{miss} final states for 35.9 fb^{-1} of Run 2 data, namely
 497 the multi-lepton analysis CMS-SUS-16-039 [117], for which the combination of signal
 498 regions via the simplified likelihood approach has recently been implemented in Mad-
 499 Analysis 5 (see contribution no. 15 in [118]), and the soft lepton analysis CMS-SUS-16-
 500 048 [119], which targets compressed EW-inos; as well as
- 501 • the ATLAS search in the $1l + H(\rightarrow b\bar{b}) + E_T^{\text{miss}}$ final state based on 139 fb^{-1} of data,
 502 ATLAS-SUSY-2019-08 [107], which targets the $WH + E_T^{\text{miss}}$ channel and which we newly
 503 implemented for this study (details are given in appendix A.4).

504 For these analyses we again treat the two lightest neutralino states as LSPs, assuming the
 505 transition $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0$ is too soft as to be visible in the detector. For the CMS 35.9 fb^{-1} anal-
 506 yses, we simulate all possible combinations of $\tilde{\chi}_{1,2}^0$ with the heavy neutralinos, charginos,
 507 and pair production of charginos; while to recast the analysis of [107] we must simulate
 508 $pp \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_{j>2}^0 + n\text{jets}$, where n is between zero and two. The hard process is simulated in
 509 MadGraph5_aMC@NLO [120] v2.6 and passed to Pythia 8.2 [121] for showering. Mad-
 510 Analysis 5 handles the detector simulation with Delphes 3 [122] with different cards for each
 511 analysis, and then computes exclusion confidence levels $(1 - \text{CL}_s)$, including the combination
 512 of signal regions for the multi-lepton analysis. For the two 35.9 fb^{-1} analyses we simulate 50k
 513 events, and the whole simulation takes more than an hour per point on an 8-core desktop PC.

⁸To this end, we added `if abs(pid) == 1000023: width = 0.0*GeV` in the `getPromptDecays()` function of `slhaDecomposer.py`; this avoids setting the $\tilde{\chi}_2^0$ decay widths to zero in the input SLHA files.

⁹See <http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase>.

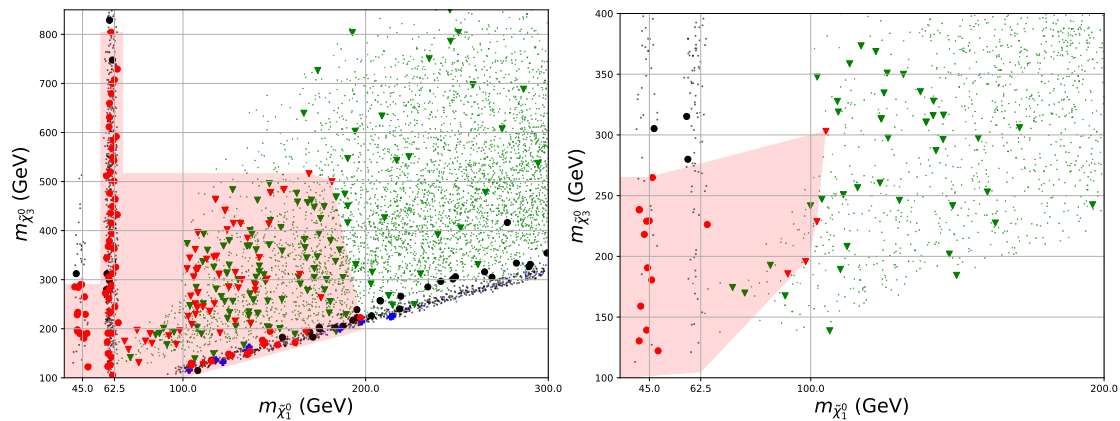


Figure 12: DM-compatible points found in our scan ($\Omega h^2 \leq 0.132$) in the plane of lightest neutralino vs. third lightest neutralino mass. The left plot shows points for which $m_{D2} < 900$ GeV, the right plot has $m_{D2} > 700$ GeV. Higgsino-like LSP points are shown in green, winos in blue and binos in black. The red transparent region surrounds all points that were found to be excluded using MadAnalysis 5; the location of the recast points are shown as large circles (binos), crosses (winos) and triangles (higgsinos). Excluded points are coloured red.

514 For the ATLAS 139 fb⁻¹ analysis, we simulate 100k events (because of the loss of efficiency
 515 in merging jets, and targeting only *b*-jets from the Higgs and in particular the leptonic decay
 516 channel of the *W*) and each point requires 3 hours.

517 The reach of collider searches depends greatly on the wino fraction of the EW-inos. Winos
 518 have a much higher production cross section than higgsinos or binos, and thus we can divide
 519 the scan points into those where m_{D2} is “light” and “heavy.” The results are shown in Figure 12.
 520 They show the distribution of points in our scan in the $m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_3^0}$ plane. In our model, there
 521 is always a pseudo-Dirac LSP, so the lightest neutralinos are nearly degenerate; for a higgsino-
 522 or wino-like LSP the lightest chargino is nearly degenerate with the LSP. However, $m_{\tilde{\chi}_3^0}$ gives
 523 the location of the next lightest states, irrespective of the LSP type. In this plane we show the
 524 points that we tested using MadAnalysis 5, and delineate the region encompassing all excluded
 525 points.

526 For “light” $m_{D2} < 900$ GeV, nearly all tested points in the Higgs funnel are excluded by
 527 [107] up to $m_{\tilde{\chi}_3} = 800$ GeV; the Z-funnel is excluded for $m_{\tilde{\chi}_3} \lesssim 300$ GeV. Otherwise we can
 528 find excluded points in the region $m_{\tilde{\chi}_1^0} \lesssim 200$ GeV, $m_{\tilde{\chi}_3^0} \lesssim 520$ GeV. While for small $m_{\tilde{\chi}_3^0} - m_{\tilde{\chi}_1^0}$
 529 the ATLAS-SUSY-2019-08 search [107] is not effective, at large values of $m_{\tilde{\chi}_3^0}$ some points are
 530 excluded by this analysis, and others still by CMS-SUS-16-039 [117] and/or CMS-SUS-16-
 531 048 [119]. We note here that the availability of the covariance matrix for signal regions A
 532 of [117] is quite crucial for achieving a good sensitivity. It would be highly beneficial to have
 533 more such (full or simplified) likelihood data that allows for the combination of signal regions!

534 For “heavy” $m_{D2} > 700$ GeV,¹⁰ we barely constrain the model at all: clearly Z-funnel points
 535 are excluded up to about $m_{\tilde{\chi}_3^0} = 260$ GeV; but we only find excluded points for $m_{\tilde{\chi}_1^0} \lesssim 100$ GeV,
 536 $m_{\tilde{\chi}_3} \lesssim 300$ GeV. Hence one of the main conclusions of this work is that higgsino/bino mixtures
 537 in this model, where $m_{D2} > 700$ GeV, are essentially unconstrained for $m_{\tilde{\chi}_1^0} \gtrsim 120$ GeV.

538 In general, as in [69], one may expect a full recast in MadAnalysis 5 to be much more pow-
 539 erful than a simplified models approach. However, comparing the results from MadAnalysis 5

¹⁰The regions are only not disjoint so that we can include the entire constrained reach of the Higgs funnel in the “light” plot; away from the Higgs funnel there would be no difference in the “light” m_{D2} plot if we took $m_{D2} < 700$ GeV.

540 to those from SModelS, a surprisingly good agreement is found between the r -values from like
 541 searches (such as the $WH + E_T^{\text{miss}}$ channel in the same analysis).¹¹ Indeed, from comparing
 542 Figures 12 with the upper two panels in Figure 10, we see that the excluded region is very
 543 similar, with perhaps a small advantage to the full MadAnalysis5 recasting at the top of the
 544 Higgs funnel and at larger values of $m_{\tilde{\chi}_3^0}$ for higgsino LSPs, while SModelS (partly thanks to
 545 more 139 fb^{-1} analyses) is more powerful in the Z -funnel region. A detailed comparison leads
 546 to the following observations:

- 547 • The $WZ + E_T^{\text{miss}}$ upper limits in SModelS can be more powerful than the recasting of
 548 the individual analyses implemented in MadAnalysis5. As an example, consider the
 549 two neighbouring points with $(m_{D_Y}, m_{D_2}, \mu, \tan \beta, -\lambda_S, \sqrt{2}\lambda_T) = (742.6, 435.7, 164.1,$
 550 $5.83, 0.751, 0.491)$ and $(746.6, 459.9, 154.2, 12.77, 0.846, 0.466)$, with mass param-
 551 eters in GeV units. They respectively have $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_5^0}) = (189, 474, 753)$ GeV and
 552 $(182, 500, 761)$ GeV, i.e. well spread spectra with higgsino LSPs. For the first point
 553 SModelS gives $r_{\text{max}} = 0.99$ and for the second $r_{\text{max}} = 0.84$ from the CMS EW-ino com-
 554 bination [109]. The $1 - \text{CL}_s$ values from MadAnalysis5 are 0.79 and 0.84, respectively,
 555 from the combination of signal regions A of the CMS multi-lepton search [117]; in terms
 556 of the ratio r_{MA5} of predicted over excluded (visible) cross sections, this corresponds to
 557 $r_{\text{MA5}} = 0.67$ and 0.71, so somewhat lower than the values from SModelS.
- 558 • The $WH + E_T^{\text{miss}}$ signal for the two example points above splits up into several compo-
 559 nents (corresponding to different mass vectors) in SModelS, which each give r -values
 560 of roughly 0.3 but cannot be combined. The recast of ATLAS-SUSY-2019-08 [107] with
 561 MadAnalysis5, on the other hand, takes the complete signal into account and gives
 562 $1 - \text{CL}_s = 0.77$ for the first and 0.96 for the second point.
- 563 • The points excluded with MadAnalysis5 but not with SModelS typically contain complex
 564 spectra with all EW-inos below about 800 GeV, which all contribute to the signal.
- 565 • Most tested points away from the Higgs funnel region, which are excluded with Mad-
 566 Analysis5 but not with SModelS, have $r_{\text{max}} > 0.8$.
- 567 • There also exist points which are excluded by SModelS but not by the recasting with
 568 MadAnalysis5. In these cases the exclusion typically comes from the CMS EW-ino com-
 569 bination [109]; detailed likelihood information would be needed to emulate this com-
 570 bination in recasting codes.

571 It would be interesting to revisit these conclusions once more EW-ino analyses are im-
 572 plemented in full recasting tools, but it is clear that, since adding more luminosity does not
 573 dramatically alter the constraints, the SModelS approach can be used as a reliable (and much
 574 faster) way of constraining the EW-ino sector; and that the constraints on EW-inos in Dirac
 575 gaugino models are still rather weak, particularly for higgsino LSPs where the wino is heavy.

576 4.2.2 Constraints from searches for long-lived particles

577 As mentioned in section 4.1, a relevant fraction (about 20%) of the points in our dataset con-
 578 tain LLPs. Long-lived charginos, which occur in about 14% of all points, can be constrained
 579 by Heavy Stable Charged Particles (HSCP) and Disappearing Tracks (DT) searches. Displaced
 580 vertex (DV) searches could potentially be sensitive to long-lived neutralinos; in our case how-
 581 ever, the decay products of long-lived neutralinos are typically soft photons, and there is no
 582 ATLAS or CMS analysis which would be sensitive to these.

¹¹We shall see this explicitly for some benchmark scenarios in section 5.

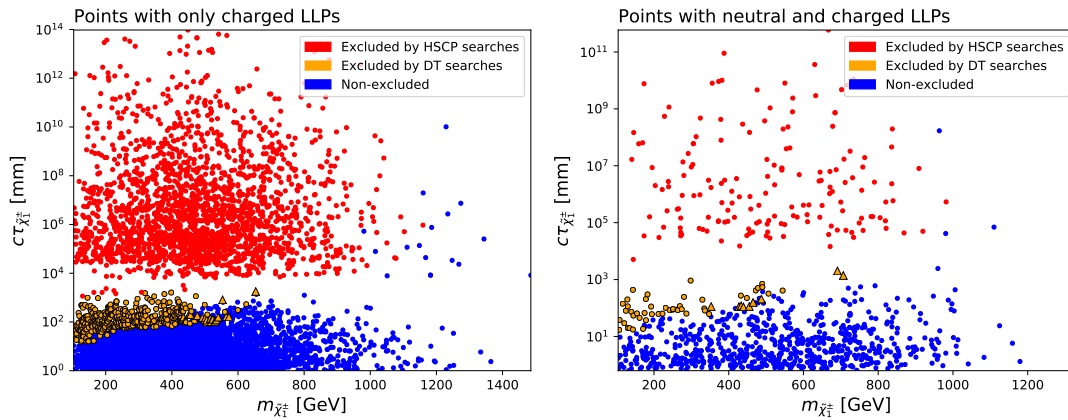


Figure 13: Exclusion plots for points with only charged LLPs (left) and points with neutral and charged LLPs (right), obtained in the simplified model approach. Red points are excluded by the HSCP searches implemented in SModelS, orange points are excluded by DT searches; the latter are plotted as circles if excluded at 36 fb^{-1} and as triangles if excluded at 140 fb^{-1} . Non-excluded points are shown in blue.

583 We therefore concentrate on constraints from HSCP and DT searches. They can conve-
 584 niently be treated in the context of simplified models. For HSCP constraints we again use
 585 SModelS, which has upper limit and efficiency maps from the full 8 TeV [123] and early
 586 13 TeV (13 fb^{-1}) [124] CMS analyses implemented. (The treatment of LLPs in SModelS is
 587 described in detail in Refs. [104, 125].) A new 13 TeV analysis for 36 fb^{-1} is available from
 588 ATLAS [126], but not yet included in SModelS; we will come back to this below.

589 For the DT case, the ATLAS [127] and CMS [128] analyses for 36 fb^{-1} provide 95% CL
 590 upper limits on $\sigma \times \text{BR}$ in terms of chargino mass and lifetime on HEPData [129, 130].
 591 Here, $\sigma \times \text{BR}$ stands for the cross section of direct production of charginos, which includes
 592 $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production, times $\text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm)$, for each produced chargino. Using the
 593 `interpolate.griddata` function from `scipy`, we estimated the corresponding 95% CL up-
 594 per limits for our scan points within the reach of each analysis¹² from a linear interpolation
 595 of the HEPData tables. This was then used to compute r -values as the ratio of the predicted
 596 signal over the observed upper limit, similar to what is done in SModelS. The points with only
 597 charged ($\tilde{\chi}_1^\pm$) LLPs and those with both charged and neutral ($\tilde{\chi}_2^0$) LLPs are treated on equal
 598 footing. However, for the points which have both a neutral and a charged LLP, if $m_{\tilde{\chi}_1^\pm} > m_{\tilde{\chi}_2^0}$,
 599 the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ direct production cross section and the branching fraction of $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_2^0 \pi^\pm$ were also
 600 included.

601 There is also a new CMS DT analysis [131], which presents full Run 2 results for 140 fb^{-1} .
 602 At the time of our study, this analysis did not yet provide any auxiliary (numerical) material
 603 for reinterpretation. We therefore digitised the limits curves from Figures 1a–1d of that paper,
 604 and used them to construct linearly interpolated limit maps which are employed in the same
 605 way as described in the previous paragraph. Since the interpolation is based on only four
 606 values of chargino lifetimes, $\tau_{\tilde{\chi}_1^\pm} = 0.33, 3.34, 33.4$ and 333 ns , this is however less precise
 607 than the interpolated limits for 36 fb^{-1} .

608 The results are shown in Figure 13 in the plane of chargino mass vs. mean decay length; on
 609 the left for points with long-lived charginos, on the right for point with long-lived charginos and
 610 neutralinos. Red points are excluded by the HSCP searches implemented in SModelS: orange

¹²This is $95 < m_{\tilde{\chi}_1^\pm} < 600 \text{ GeV}$ and $0.05 < \tau_{\tilde{\chi}_1^\pm} < 4 \text{ ns}$ ($15 < c\tau_{\tilde{\chi}_1^\pm} < 1200 \text{ mm}$) for the ATLAS analysis [127], and $100 < m_{\tilde{\chi}_1^\pm} < 900 \text{ GeV}$ and $0.067 < \tau_{\tilde{\chi}_1^\pm} < 333.56 \text{ ns}$ ($20 < c\tau_{\tilde{\chi}_1^\pm} < 100068 \text{ mm}$) for the CMS analysis [128].

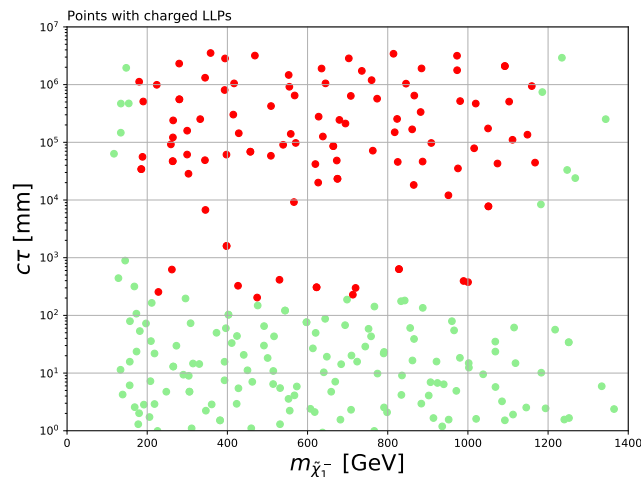


Figure 14: Exclusion for charged LLPs using A. Lessa’s recast code for the ATLAS HSCP search [126] from <https://github.com/llprecasting/recastingCodes>; red points are excluded, green points are not excluded by this analysis.

611 points are excluded by DT searches. The HSCP limits from [123, 124] eliminate basically all
 612 long-lived chargino scenarios with $c\tau_{\tilde{\chi}^\pm} \gtrsim 1$ m up to about 1 TeV chargino mass. The exclusion
 613 by the DT searches [127, 128] covers $10 \text{ mm} \lesssim c\tau_{\tilde{\chi}_1^\pm} \lesssim 1$ m and $m_{\tilde{\chi}_1^\pm}$ up to about 600 GeV;
 614 this is only slightly extended to higher masses by our reinterpretation of the limits of [131].
 615 The white band in-between $c\tau \approx 10^3$ – 10^4 mm corresponds to $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \approx m_{\pi^\pm}$: the chargino
 616 lifetime changes significantly when decays into pions become kinematically forbidden.

617 To verify the HSCP results from SModelS and extend them to 36 fb^{-1} , we adapted the
 618 code for recasting the ATLAS analysis [126] written by A. Lessa and hosted at <https://github.com/llprecasting/recastingCodes>. This requires simulating hard processes of single/double
 619 chargino LLP production with *two* additional hard jets, which was performed at leading order
 620 with MadGraph5_aMC@NLO. The above code then calls Pythia 8.2 to shower and decay
 621 the events, and process the cuts. It uses experiment-provided efficiency tables for truth-level
 622 events rather than detector simulation, and therefore does not simulate the presence of a
 623 magnetic field. However, the code was validated by the original author for the MSSM chargino
 624 case and found to give excellent agreement.
 625

626 We wrote a parallelised version of the recast code to speed up the workflow (which is avail-
 627 able upon request); the bottleneck in this case is actually the simulation of the hard process
 628 (unlike for the prompt recasting case in the previous section), and our sample was simulated
 629 on one desktop. We show the result in Figure 14. For decay lengths $c\tau_{\tilde{\chi}_1^\pm} > 1$ m, the exclusion
 630 is very similar to that from SModelS, only slightly extending it in the $m_{\tilde{\chi}_1^\pm} \approx 1$ –1.2 TeV range.
 631 For decay lengths of about 0.2–1 m, the recasting with event simulation allows the exclusion
 632 of points in the 0.2–1 TeV mass range; this region is not covered by SModelS. As with the
 633 SModelS results, we see that LLP searches are extremely powerful, and where a parameter
 634 point contains an LLP with a mass and lifetime in the correct range for a search, there is no
 635 possibility to evade exclusion.

636 4.3 Future experiments: MATHUSLA

637 We also investigated the possibility of seeing events in the MATHUSLA detector [132], which
 638 would be built $\mathcal{O}(100)$ m from the collision point at the LHC, and so would be able to detect
 639 neutral particles that decay after such a long distance. Prima facie this would seem ideal to
 640 search for the decays of long-lived neutralino NLSPs; pseudo-Dirac states should be excel-

641 lent candidates for this (indeed, the possibility of looking for similar particles if they were of
 642 $\mathcal{O}(\text{GeV})$ in mass at the SHiP detector was investigated in [133]). However, in our case the only
 643 states that have sufficient lifetime to reach the detector have mass splittings of $\mathcal{O}(10)$ MeV (or
 644 less), and decays $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma$ vastly dominate, with a tiny fraction of decays to electrons.

645 In the detectors in the roof of MATHUSLA the photons must have more than 200 MeV (or 1
 646 GeV for electrons) to be registered. Moreover, it is anticipated to reconstruct the decay vertex
 647 in the decay region, requiring more than one track; in our case only one track would appear,
 648 and much too soft to trigger a response. Hence, unless new search strategies are employed,
 649 our long-lived $\tilde{\chi}_2^0$ will escape detection.

650 5 Benchmark points

651 In this section we present a few sample points which may serve as benchmarks for further
 652 studies, designing dedicated experimental analyses and/or investigating the potential of future
 653 experiments. Parameters, masses, and other relevant quantities are listed in Tables 2 and 3.

654 **Point 1** (SPhenoDiracGauginos_667) lies in the h -funnel region. It features almost pure
 655 bino $\tilde{\chi}_{1,2}^0$ with masses of 62–63 GeV, higgsino-like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{3,4}^0$ with masses around 560–
 656 580 GeV, and heavy wino-like $\tilde{\chi}_{5,6}^0$ and $\tilde{\chi}_{2,3}^\pm$ around 1.2 TeV. A relic abundance in accordance
 657 with the cosmologically observed value is achieved through $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ co-annihilation into $b\bar{b}$
 658 (63%), gg (17%) and $\tau^+ \tau^-$ (13%) via s -channel h exchange.¹³ Kinematically just allowed,
 659 invisible decays of the Higgs boson have a tiny branching ratio, $\text{BR}(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0) = 5.2 \times 10^{-4}$,
 660 and thus do not affect current Higgs measurements or coupling fits. The main decay modes of
 661 the EW-inos are:

662

mass	decays
1254 GeV	$\tilde{\chi}_3^\pm \rightarrow \tilde{\chi}_1^\pm Z$ (57%), $\tilde{\chi}_1^\pm h$ (42%)
1235 GeV	$\tilde{\chi}_6^0 \rightarrow \tilde{\chi}_3^0 Z$ (32%), $\tilde{\chi}_4^0 h$ (29%), $\tilde{\chi}_1^\pm W^\pm$ (36%)
1233 GeV	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_4^0 Z$ (33%), $\tilde{\chi}_3^0 h$ (30%), $\tilde{\chi}_1^\pm W^\pm$ (36%)
1212 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_3^0 W^\pm$ (49%), $\tilde{\chi}_4^0 W^\pm$ (49%)
663 584 GeV	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 h$ (33%), $\tilde{\chi}_2^0 h$ (25%), $\tilde{\chi}_2^0 Z$ (21%), $\tilde{\chi}_1^0 Z$ (20%)
582 GeV	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 Z$ (30%), $\tilde{\chi}_2^0 Z$ (26%), $\tilde{\chi}_2^0 h$ (24%), $\tilde{\chi}_1^0 h$ (20%)
564 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm$ (51%), $\tilde{\chi}_2^0 W^\pm$ (48%)
63 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (86%); $\Gamma_{\text{tot}} = 6.6 \times 10^{-17}$ GeV ($c\tau \approx 3$ m)
664 62 GeV	$\tilde{\chi}_1^0$, stable

665 Regarding LHC signals, $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_{3,4}^0$ production has a cross section of about 9 fb at $\sqrt{s} = 13$ TeV
 666 and leads to almost equal rates of $WZ + E_T^{\text{miss}}$ and $WH + E_T^{\text{miss}}$ ($H \equiv h$) signatures, accompa-
 667 nied by soft displaced photons in 3/4 of the cases. With $\tilde{\chi}_{3,4}^0$ masses only 1.7 GeV apart,
 668 SModelS adds up signal contributions from $\tilde{\chi}_1^\pm \tilde{\chi}_3^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_4^0$ production. This gives r -values
 669 of about 0.4 for the $WH + E_T^{\text{miss}}$ topology (ATLAS-SUSY-2019-08 [107]) and about 0.3 for
 670 the $WZ + E_T^{\text{miss}}$ topology (CMS-SUS-17-004 [109] and ATLAS-SUSY-2017-03 [134])¹⁴ in good
 671 agreement with the exclusion CL, $1 - \text{CL}_s = 0.645$, obtained with MadAnalysis 5 from recast-

¹³This is one example where the precise calculation of the NLSP decays influences the value of the relic density. Without the $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ loop calculation, $\Gamma_{\text{tot}}(\tilde{\chi}_2^0) = 9 \times 10^{-18}$ GeV and $\Omega h^2 = 0.111$. Including the loop decay, we get $\Gamma_{\text{tot}}(\tilde{\chi}_2^0) = 6.6 \times 10^{-17}$ GeV and $\Omega h^2 = 0.127$. Note also that one has to set `useSLHAwidth=1` in micrOMEGAS to reproduce these values with SLHA file input.

¹⁴This drops to $r \lesssim 0.1$ if displaced $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ decays are not explicitly ignored in SModelS.

Table 2: Overview of benchmark points 1–5. Masses and mass parameters are in GeV, $\tilde{\chi}_{1p}^0$ scattering cross sections in pb, and LHC cross sections in fb units. $f_{\tilde{b}}$, $f_{\tilde{w}}$ and $f_{\tilde{h}}$ are the bino, wino and higgsino fractions of the $\tilde{\chi}_1^0$, respectively. r_{\max} is the highest r -value from SModelS (when relevant), while $1 - \text{CL}_s$ is the exclusion CL from MadAnalysis5. σ_{LHC13} and σ_{LHC14} are the total EW-ino production cross sections (sum over all channels) at 13 and 14 TeV computed with MadGraph5_aMC@NLO; the statistical uncertainties on these cross sections are 3% for Point 2, and about 5–7% otherwise.

Point	1	2	3	4	5
m_{DY}	62.58	184.24	553.94	555.47	382.20
m_{D2}	1170.19	221.81	553.59	602.61	594.06
μ	605.67	1454.11	1481.55	1115.58	480.55
$\tan\beta$	15.63	10.44	7.92	12.28	28.05
$-\lambda_S$	0.016	1.13	0.97	0.60	0.27
$\sqrt{2}\lambda_T$	-1.26	-0.86	0.07	-1.2	-0.93
$m_{\tilde{\chi}_1^0}$	62.34	195.23	561.69	563.82	387.74
$m_{\tilde{\chi}_2^0}$	63.45	211.70	576.12	568.31	387.92
$m_{\tilde{\chi}_3^0}$	581.86	222.47	589.85	600.39	432.96
$m_{\tilde{\chi}_4^0}$	583.62	224.13	592.91	606.63	433.87
$m_{\tilde{\chi}_5^0}$	1233.07	1523.80	1532.71	1162.02	669.12
$m_{\tilde{\chi}_6^0}$	1234.85	1528.71	1536.34	1166.42	669.53
$m_{\tilde{\chi}_1^\pm}$	563.75	215.00	588.28	580.86	398.60
$m_{\tilde{\chi}_2^\pm}$	1212.35	229.86	592.69	626.84	619.96
$m_{\tilde{\chi}_3^\pm}$	1254.34	1521.61	1527.55	1184.63	703.47
$f_{\tilde{b}}$	0.997	0.95	0.97	0.96	0.997
$f_{\tilde{w}}$	$O(10^{-5})$	0.04	0.02	0.03	$O(10^{-5})$
$f_{\tilde{h}}$	$O(10^{-3})$	0.01	0.01	0.01	$O(10^{-3})$
Ωh^2	0.127	0.116	0.127	0.127	0.113
$\sigma^{\text{SI}}(\tilde{\chi}_1^0 p)$	9.4×10^{-13}	2.2×10^{-11}	1.6×10^{-10}	1.2×10^{-10}	1.8×10^{-10}
$\sigma^{\text{SD}}(\tilde{\chi}_1^0 p)$	2.7×10^{-7}	4×10^{-6}	1.9×10^{-6}	2.7×10^{-6}	1.1×10^{-8}
p_{X1T}	0.93	0.62	0.42	0.50	0.29
r_{\max}	0.39	–	–	–	–
$1 - \text{CL}_s$	0.65	0.51	0.02	0.03	0.07
σ_{LHC13}	14.9	2581	41.2	35.9	87.8
σ_{LHC14}	18.0	2910	49.6	43.8	103.1

672 ing ATLAS-SUSY-2019-08 [107], and $1 - \text{CL}_s = 0.26$ from the combination of signal regions A
 673 from CMS-SUS-16-039 [117].

674 **Point 2** (SPHenoDiracGauginos_50075) has a $\tilde{\chi}_1^0$ mass of 195 GeV and a large $\tilde{\chi}_1^0 - \tilde{\chi}_2^0$
 675 mass difference of 16 GeV due to $\lambda_S = -1.13$. The LSP is 95% bino and 4% wino. The next-
 676 lightest states are the wino-like $\tilde{\chi}_{1,2}^\pm$ and $\tilde{\chi}_{3,4}^0$ with masses of 215–230 GeV ($m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_{3,4}^0} < m_{\tilde{\chi}_2^\pm}$).
 677 The higgsino-like $\tilde{\chi}_3^\pm$ and $\tilde{\chi}_{5,6}^0$ are heavy with masses around 1.5 TeV. A relic density of the
 678 right order, $\Omega h^2 = 0.116$, is achieved primarily through co-annihilations, in particular $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$
 679 (29%) and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ (20%) co-annihilation into a large variety of final states; the main LSP pair-
 680 annihilation channel is $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+ W^-$ and contributes 15%. The main decay modes relevant
 681 for collider signatures are:

Table 3: Overview of benchmark points 6–10. Notation and units as in Table 2. The statistical uncertainties on the LHC cross sections are about 10% for Points 6–8, 6–7% for Point 9 and 3–4% for Point 10.

Point	6	7	8	9	10
m_{DY}	1452.39	1919.27	1304.08	1365.50	809.67
m_{D2}	1459.01	1229.16	1269.15	848.28	446.83
μ	1033.56	1105.53	1957.19	572.96	224.68
$\tan \beta$	7.67	17.17	33.24	9.57	6.05
$-\lambda_S$	0.81	1.10	1.39	0.90	0.81
$\sqrt{2}\lambda_T$	0.42	0.29	0.05	0.31	0.37
$m_{\tilde{\chi}_1^0}$	1075.01	1158.96	1327.19	605.27	246.93
$m_{\tilde{\chi}_2^0}$	1079.15	1159.09	1327.31	605.71	247.19
$m_{\tilde{\chi}_3^0}$	1470.39	1295.59	1346.21	900.98	484.79
$m_{\tilde{\chi}_4^0}$	1473.61	1296.08	1356.92	901.04	485.79
$m_{\tilde{\chi}_5^0}$	1527.23	1951.32	2076.15	1380.78	821.83
$m_{\tilde{\chi}_6^0}$	1528.27	1957.08	2078.22	1383.37	821.86
$m_{\tilde{\chi}_1^\pm}$	1081.00	1159.38	1327.28	605.50	247.28
$m_{\tilde{\chi}_2^\pm}$	1526.26	1291.71	1331.70	898.31	480.35
$m_{\tilde{\chi}_3^\pm}$	1528.71	1299.64	2059.14	903.81	490.70
f_b	0.02	0.01	0.05	0.01	0.02
$f_{\tilde{W}}$	$O(10^{-4})$	0.03	0.94	$O(10^{-3})$	0.01
f_h	0.98	0.96	0.01	0.99	0.97
Ωh^2	0.112	0.124	0.11	0.04	0.006
$\sigma^{\text{SI}}(\tilde{\chi}_1^0 p)$	4.1×10^{-10}	6.2×10^{-10}	6.4×10^{-10}	5.6×10^{-11}	1.2×10^{-9}
$\sigma^{\text{SD}}(\tilde{\chi}_1^0 p)$	4.2×10^{-6}	2.3×10^{-7}	1.6×10^{-9}	1.3×10^{-6}	2.1×10^{-5}
p_{X1T}	0.35	0.20	0.28	0.92	0.46
r_{max}	–	–	0.28	–	0.39
$1 - \text{CL}_s$	–	–	–	–	0.73
σ_{LHC13}	0.48	0.65	0.32	13.2	490.5
σ_{LHC14}	0.64	0.90	0.45	16.3	557.3

682

mass	decays
230 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^0 W^*$ (82%), $\tilde{\chi}_1^\pm \gamma$ (11%)
220 GeV	$\tilde{\chi}_{3,4}^0 \rightarrow \tilde{\chi}_1^\pm W^*$ (98–99%), $\tilde{\chi}_1^0 \gamma$ (2–1%)
215 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^*$ (100%)
212 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (87%), $\tilde{\chi}_1^0 Z^*$ (13%); $\Gamma_{\text{tot}} = 8.2 \times 10^{-10}$ GeV (prompt)
195 GeV	$\tilde{\chi}_1^0$, stable

683

684

685 Despite the large cross section for $\tilde{\chi}_{1,2}^\pm \tilde{\chi}_{3,4}^0$ ($\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^-$) production of 1.6 (0.9) pb at $\sqrt{s} = 13$ TeV,
686 the point remains unchallenged by current LHC results. Recasting with MadAnalysis 5 gives
687 $1 - \text{CL}_s \approx 0.51$ from both the CMS soft leptons [119] and multi-leptons [117] + E_T^{miss} searches
688 (CMS-SUS-16-048 and CMS-SUS-16-039), but no constraints can be obtained from simplified
689 model results due to the complexity of the arising signatures. In fact, 86% of the total signal
690 cross section is classified as “missing topologies” in SModelS, i.e. topologies for which no
691 simplified model results are available. The main reason for this is that the $\tilde{\chi}_{3,4}^0$ decay via $\tilde{\chi}_1^\pm$,
692 and thus $\tilde{\chi}_{1,2}^\pm \tilde{\chi}_{3,4}^0$ production gives events with softish jets and/or leptons from 3 off-shell W s.

693 It would be interesting to see whether the photons from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ decays would be observable
 694 at, e.g., an e^+e^- collider.

695 **Point 3** (SPhenoDiracGauginos_12711) is similar to Point 2 but has a heavier bino-wino
 696 mass scale of 560–590 GeV. The $\tilde{\chi}_1^0$ – $\tilde{\chi}_2^0$ mass difference is 14 GeV ($\lambda_S = -0.97$) and the LSP
 697 is 97% bino and 2% wino. The wino-like states are all compressed within 5 GeV around
 698 $m \simeq 590$ GeV. $\Omega h^2 = 0.127$ hence comes dominantly from co-annihilations among the wino-
 699 like states, with minor contributions from $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+W^-$ (3%) and $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm \rightarrow WZ$ or Wh (2%
 700 each). The collider signatures are, however, quite different from Point 2, given the predomi-
 701 nance of photonic decays:

702

mass	decays
593 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^\pm \gamma$ (77%), $\tilde{\chi}_1^0 W^*$ (23%)
	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (61%), $\tilde{\chi}_1^\pm W^*$ (27%), $\tilde{\chi}_2^0 \gamma$ (7%)
590 GeV	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (83%), $\tilde{\chi}_2^0 \gamma$ (13%)
588 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_2^0 W^*$ (55%), $\tilde{\chi}_1^0 W^*$ (45%)
576 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (92%), $\tilde{\chi}_1^0 Z^*$ (8%); $\Gamma_{\text{tot}} = 3.3 \times 10^{-10}$ GeV (prompt)
562 GeV	$\tilde{\chi}_1^0$, stable

704

705 Moreover, the total relevant EW-ino production cross section is only 41 fb at $\sqrt{s} = 13$ TeV,
 706 compared to ≈ 2.6 pb for Point 2. Therefore, again, no relevant constraints are obtained from
 707 the current LHC searches. In particular, SModelS does not give any constraints from EW-ino
 708 searches but reports 34 fb as missing topology cross section, 64% of which go on account of
 709 $W^*(\rightarrow 2 \text{ jets or } l\nu) + \gamma + E_T^{\text{miss}}$ signatures.

710

711 **Point 4** (SPhenoDiracGauginos_2231) has bino and wino masses of the order of 600 GeV
 712 similar to Point 3, but features a smaller $\tilde{\chi}_1^0$ – $\tilde{\chi}_2^0$ mass difference of 4.5 GeV ($\lambda_S = -0.6$) and
 713 a larger spread, of about 46 GeV, in the masses of the wino-like states ($\sqrt{2}\lambda_T = 1.2$). The
 714 higgsinos are again heavy. $\Omega h^2 = 0.127$ comes to 46% from $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ annihilation; the rest is
 715 mostly $\tilde{\chi}_1^\pm$ co-annihilation with $\tilde{\chi}_{1,2,3}^0$. The $pp \rightarrow \tilde{\chi}_{1,2}^\pm \tilde{\chi}_{3,4}^0$ ($\tilde{\chi}_{1,2}^+ \tilde{\chi}_{1,2}^-$) production cross section
 716 is 24 (12) fb at 13 TeV. Signal events are characterised by multiple soft jets and/or leptons
 717 $+E_T^{\text{miss}}$ arising from 3-body decays via off-shell W- or Z- bosons as follows:

718

mass	decays
627 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^0 W^*$ (62%), $\tilde{\chi}_2^0 W^*$ (9%), $\tilde{\chi}_3^0 W^*$ (20%), $\tilde{\chi}_4^0 W^*$ (7%)
607 GeV	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^\pm W^*$ (99.9%)
600 GeV	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^\pm W^*$ (99.9%)
581 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^*$ (97%), $\tilde{\chi}_2^0 W^*$ (3%)
568 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (98%), $\tilde{\chi}_1^0 Z^*$ (2%); $\Gamma_{\text{tot}} = 3.8 \times 10^{-12}$ GeV (prompt)
564 GeV	$\tilde{\chi}_1^0$, stable

720

721 **Point 5** (SPhenoDiracGauginos_16420) has the complete EW-ino spectrum below ≈ 700 GeV.
 722 With $m_{D_Y} < \mu < m_{D_2}$ in steps of roughly 100 GeV, the mass ordering is binos < higgsinos <
 723 winos. Small $\lambda_S = -0.27$ and large $\sqrt{2}\lambda_T = -0.93$ create small mass splittings within the
 724 binos and larger mass splitting within the winos. Concretely, the $\tilde{\chi}_{1,2}^0$ are 99.7% bino-like
 725 with masses of 388 GeV and a mass splitting between them of only 200 MeV. The higgsino-
 726 like states have masses of about 400–430 GeV and the wino-like ones of about 620–700 GeV.
 727 $\Omega h^2 = 0.113$ is dominated by $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ annihilation, which makes up 60% of the total annihila-

tion cross section; the largest individual channel is $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow Zh$ contributing 14%. Nonetheless $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ (13%) and $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ (12%) co-annihilations are also important. $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ co-annihilation contributes about 4%. The decay modes determining the collider signatures are as follows:

731

mass	decays
703 GeV	$\tilde{\chi}_3^\pm \rightarrow \tilde{\chi}_1^\pm Z$ (78%), $\tilde{\chi}_1^\pm h$ (16%), $\tilde{\chi}_{3,4}^0 W^\pm$ (6%)
670 GeV	$\tilde{\chi}_6^0 \rightarrow \tilde{\chi}_4^0 Z$ (45%), $\tilde{\chi}_1^\pm W^\pm$ (36%), $\tilde{\chi}_3^0 h$ (18%)
669 GeV	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_3^0 Z$ (46%), $\tilde{\chi}_1^\pm W^\pm$ (35%), $\tilde{\chi}_4^0 h$ (18%)
620 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_3^0 W^\pm$ (50%), $\tilde{\chi}_4^0 W^\pm$ (50%)
434 GeV	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^\pm W^*$ (99%)
433 GeV	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^\pm W^*$ (99%)
399 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_2^0 W^*$ (58%), $\tilde{\chi}_1^0 W^*$ (42%)
388 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (100%); $\Gamma_{\text{tot}} = 4.1 \times 10^{-16}$ GeV ($c\tau \approx 0.5$ m)
388 GeV	$\tilde{\chi}_1^0$, stable

733

The $\tilde{\chi}_i^+ \tilde{\chi}_j^-$ and $\tilde{\chi}_i^\pm \tilde{\chi}_k^0$ ($i, j = 1, 2, 3; k = 3 \dots 6$) production cross sections are 27 fb and 55 fb at the 13 TeV LHC, respectively, but again no relevant constraints can be obtained from re-interpretation of the current SUSY searches.

For the design of dedicated analyses it is relevant to note that $\tilde{\chi}_{2,3}^\pm \tilde{\chi}_{5,6}^0$ production would give signatures like $2W2Z + E_T^{\text{miss}}$ or $3W1Z + E_T^{\text{miss}}$, etc., accompanied by additional jets and/or leptons from intermediate $\tilde{\chi}_{3,4}^0 \rightarrow \tilde{\chi}_1^\pm W^*$ decays appearing in the cascade.

We also note that the $\tilde{\chi}_2^0$ is long-lived with a mean decay length of about 0.5 m. However, given the tiny mass difference to the $\tilde{\chi}_1^0$ of 180 MeV, the displaced photon from the $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ transition will be extremely soft and thus hard, if not impossible, to detect.

Point 6 (SPhenoDiracGauginos_11321) is a higgsino DM point with $m_{\tilde{\chi}_1^0} \simeq 1.1$ TeV and a rather large mass splitting between the higgsino-like states, $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq 4$ GeV and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \simeq 6$ GeV. Here, $\Omega h^2 = 0.112$ results mainly from $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and $\tilde{\chi}_{1,2}^0 \tilde{\chi}_1^\pm$ co-annihilations. The main decay modes of the heavy EW-ino spectrum are:

747

mass	decays
1529 GeV	$\tilde{\chi}_3^\pm \rightarrow \tilde{\chi}_1^\pm Z$ (90%), $\tilde{\chi}_1^\pm h$ (8%)
1528 GeV	$\tilde{\chi}_6^0 \rightarrow \tilde{\chi}_1^0 Z$ (83%), $\tilde{\chi}_2^0 h$ (6%), $\tilde{\chi}_1^\pm W^\mp$ (7%), $\tilde{\chi}_2^0 Z$ (4%)
1527 GeV	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_1^0 Z$ (62%), $\tilde{\chi}_2^0 Z$ (22%), $\tilde{\chi}_1^\pm W^\mp$ (8%), $\tilde{\chi}_2^0 h$ (6%)
1526 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^\pm Z^\pm$ (60%), $\tilde{\chi}_1^0 W^\pm$ (17%), $\tilde{\chi}_2^0 W^\pm$ (17%), $\tilde{\chi}_1^\pm h$ (6%)
1474 GeV	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 Z$ (69%), $\tilde{\chi}_2^0 Z$ (15%), $\tilde{\chi}_1^\pm W^\mp$ (8%), $\tilde{\chi}_2^0 h$ (7%)
1470 GeV	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_2^0 Z$ (79%), $\tilde{\chi}_1^\pm W^\mp$ (9%), $\tilde{\chi}_1^0 h$ (8%), $\tilde{\chi}_1^0 Z$ (5%)
1081 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^*$ (100%)
1079 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ (89%), $\tilde{\chi}_1^0 \gamma$ (11%); $\Gamma_{\text{tot}} = 9.9 \times 10^{-10}$ GeV (prompt)
1075 GeV	$\tilde{\chi}_1^0$, stable

749

The LHC production cross sections are however very low for such heavy EW-inos, below 1 fb at 13–14 TeV. This is clearly a case for the high luminosity (HL) LHC, or a higher-energy machine.

Point 7 (SPhenoDiracGauginos_37) is another higgsino DM point with $m_{\tilde{\chi}_1^0} \simeq 1.1$ TeV but small, sub-GeV mass splittings between the higgsino-like states, $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq 120$ MeV and $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \simeq 400$ MeV. Co-annihilations between $\tilde{\chi}_1^0, \tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ result in $\Omega h^2 = 0.124$. The main decay modes are:

756

mass	decays
1957 GeV	$\tilde{\chi}_6^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (33%), $\tilde{\chi}_{1,2}^0 Z$ (33%), $\tilde{\chi}_{1,2}^0 h$ (31%)
1951 GeV	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (33%), $\tilde{\chi}_{1,2}^0 Z$ (32%), $\tilde{\chi}_{1,2}^0 h$ (32%)
1300 GeV	$\tilde{\chi}_3^\pm \rightarrow \tilde{\chi}_1^\pm h$ (55%), $\tilde{\chi}_1^\pm h$ (40%), $\tilde{\chi}_{1,2}^0 W^\pm$ (5%)
1296 GeV	$\tilde{\chi}_{3,4}^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (44%), $\tilde{\chi}_{1,2}^0 Z$ (31%), $\tilde{\chi}_{1,2}^0 h$ (25%)
1292 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^0 W^\pm$ (49%), $\tilde{\chi}_2^0 W^\pm$ (50%)
1159 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ (69%), $\tilde{\chi}_2^0 \pi^\pm$ (21%); $\Gamma_{\text{tot}} = 3.4 \times 10^{-14}$ GeV ($c\tau \approx 6$ mm)
	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (100%); $\Gamma_{\text{tot}} = 2.1 \times 10^{-15}$ GeV ($c\tau \approx 92$ mm)
1159 GeV	$\tilde{\chi}_1^0$, stable

758

759 The high degree of compression of the higgsino states causes both the $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^\pm$ to be
 760 long-lived with mean decay lengths of 92 mm and 6 mm, respectively. While the $\tilde{\chi}_2^0$ likely
 761 appears as invisible co-LSP, production of $\tilde{\chi}_1^\pm$ (either directly or through decays of heavier EW-
 762 inos) can lead to short tracks in the detector. Overall this gives a mix of prompt and displaced
 763 signatures as discussed in more detail for Points 9 and 10. Again, cross sections are below 1 fb
 764 in pp collisions at 13–14 TeV.

765 **Point 8** (SPHenoDiracGauginos_100) is the one wino LSP point that our MCMC found
 766 (within the parameter space of $m_{D\tilde{Y}}, m_{D2}, \mu < 2$ TeV), where the $\tilde{\chi}_1^0$ accounts for all the DM.
 767 Three of the wino-like states, $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$, are quasi-degenerate at a mass of 1327 GeV, with
 768 the fourth one, $\tilde{\chi}_2^\pm$, being 5 GeV heavier. The relic density is $\Omega h^2 = 0.11$ as a result of co-
 769 annihilations between all four winos. What is special regarding collider signatures is that
 770 the $\tilde{\chi}_2^\pm$ decays into $\tilde{\chi}_1^\pm + \gamma$, while the $\tilde{\chi}_1^\pm$ is quasi-stable on collider scales. Chargino-pair and
 771 chargino-neutralino production is thus characterised by 1–2 HSCP tracks, in part accompanied
 772 by prompt photons. In more detail, the spectrum of decays is:

773

mass	decays
2078 GeV	$\tilde{\chi}_6^0 \rightarrow \tilde{\chi}_4^0 Z$ (28%), $\tilde{\chi}_3^0 h$ (21%), $\tilde{\chi}_2^0 h$ (18%), $\tilde{\chi}_1^0 Z$ (14%), $\tilde{\chi}_2^\pm W^\mp$ (10%)
2076 GeV	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_4^0 h$ (24%), $\tilde{\chi}_3^0 Z$ (24%), $\tilde{\chi}_2^0 Z$ (21%), $\tilde{\chi}_1^0 h$ (12%), $\tilde{\chi}_2^\pm W^\mp$ (11%)
2059 GeV	$\tilde{\chi}_3^\pm \rightarrow \tilde{\chi}_3^0 W^\pm$ (41%), $\tilde{\chi}_4^0 W^\pm$ (37%) $\tilde{\chi}_1^\pm Z$ (9%), $\tilde{\chi}_1^\pm h$ (9%)
1356	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^\pm W^*$ (81%), $\tilde{\chi}_2^\pm W^*$ (19%)
1346	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^\pm W^*$ (65%), $\tilde{\chi}_2^\pm W^*$ (35%)
1332 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^\pm \gamma$ (100%)
1327 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 e^\pm \nu$ (100%); $\Gamma_{\text{tot}} = 2.3 \times 10^{-18}$ GeV ($c\tau \approx 84$ m)
	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (100%); $\Gamma_{\text{tot}} = 1.6 \times 10^{-16}$ GeV ($c\tau \approx 1.2$ m)
1327 GeV	$\tilde{\chi}_1^0$, stable

775

776 Like for Points 6 and 7, the LHC cross sections are very low for such a heavy spectrum. Nonethe-
 777 less SModelS gives $r_{\text{max}} = 0.28$ from HSCP searches; from the Pythia-based recasting we
 778 compute $1 - \text{CL}_s = 0.38$. We hence expect that this point will be testable at Run 3 of the LHC.

779 **Point 9** (SPHenoDiracGauginos_625) is an example for higgsino-like LSPs at lower mass,
 780 around 600 GeV, where the $\tilde{\chi}_1^0$ is underabundant, constituting about 30% of the DM in the stan-
 781 dard freeze-out picture. The higgsino-like states are highly compressed, $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \simeq 230$ MeV
 782 and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq 435$ MeV, which renders the $\tilde{\chi}_1^\pm$ long-lived with a mean decay length of
 783 55 mm. Direct $\tilde{\chi}_1^\pm$ production has a cross section of about 10 fb at the 13 TeV LHC; more
 784 concretely $\sigma(pp \rightarrow \chi_1^\pm \chi_{1,2}^0) \simeq 8$ fb and $\sigma(pp \rightarrow \chi_1^+ \chi_2^-) \simeq 2$ fb. The $\tilde{\chi}_1^\pm$ can also be produced

785 in decays of heavier EW-inos, in particular of the wino-like $\tilde{\chi}_{3,4}^0$ and $\tilde{\chi}_{2,3}^\pm$, which have masses
 786 around 900 GeV. This gives rise to WZ , WH and WW events (with or without E_T^{miss}) accom-
 787 panied by short disappearing tracks with a cross section of about 2 fb at 13 TeV. The classic,
 788 prompt WZ , WH , $WW + E_T^{\text{miss}}$ signatures also have a cross section of the same order (about
 789 2 fb). While all this is below Run 2 sensitivity, it shows an interesting potential for searches at
 790 high luminosity. The detailed spectrum of decays is:

791

mass	decays
1383 GeV	$\tilde{\chi}_6^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (35%), $\tilde{\chi}_{1,2}^0 Z$ (33%), $\tilde{\chi}_{1,2}^0 h$ (31%)
1381 GeV	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (34%), $\tilde{\chi}_{1,2}^0 Z$ (33%), $\tilde{\chi}_{1,2}^0 h$ (32%)
904 GeV	$\tilde{\chi}_3^\pm \rightarrow \tilde{\chi}_1^\pm Z$ (49%), $\tilde{\chi}_1^\pm h$ (44%), $\tilde{\chi}_{1,2}^0 W^\pm$ (7%)
901 GeV	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_{1,2}^0 Z$ (37%), $\tilde{\chi}_{1,2}^0 h$ (31%), $\tilde{\chi}_1^\pm W^\mp$ (33%)
898 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (34%), $\tilde{\chi}_{1,2}^0 Z$ (33%), $\tilde{\chi}_{1,2}^0 h$ (32%)
898 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_{1,2}^0 W^\pm$ (94%), $\tilde{\chi}_1^\pm h$ (3%), $\tilde{\chi}_1^\pm Z$ (3%)
606 GeV	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (87%), $\tilde{\chi}_1^0 \pi^0$ (11%); $\Gamma_{\text{tot}} = 2.5 \times 10^{-13}$ GeV ($c\tau \lesssim 1$ mm)
	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ (96%), $\tilde{\chi}_1^0 l^\pm \nu$ (4%); $\Gamma_{\text{tot}} = 3.6 \times 10^{-15}$ GeV ($c\tau \approx 55$ mm)
605 GeV	$\tilde{\chi}_1^0$, stable

793

794 **Point 10** (SPhenoDiracGauginos_236) is another example of a low-mass higgsino LSP
 795 point with long-lived charginos. The peculiarity of this point is that the whole EW-ino spec-
 796 trum lies below 1 TeV: the higgsino-, wino- and bino-like states have masses around 250, 500
 797 and 800 GeV, respectively. The $\tilde{\chi}_1^0$ is highly underabundant in this case, providing only 5%
 798 of the DM relic density. Nonetheless the point is interesting from the collider perspective, as
 799 it has light masses that escape current limits. Moreover, with a mean decay length of the $\tilde{\chi}_1^\pm$
 800 of about 13 mm, it gives rise to both prompt and DT signatures. Indeed, SModelS reports
 801 $r_{\text{max}} = 0.39$ for the prompt part of the signal, concretely for $WZ + E_T^{\text{miss}}$ from ATLAS-SUSY-
 802 2017-03 ($\sigma = 17.51$ fb compared to the 95% CL limit of $\sigma_{95} = 44.97$ fb). The cross section
 803 for one or two DTs is estimated as 0.4 pb by SModelS, however the short tracks caused by
 804 $\tilde{\chi}_1^\pm$ decays are outside the range of the DT search results considered in section 4.2.2. Last
 805 but not least, DTs with additional gauge or Higgs bosons have a cross section of about 50 fb.¹⁵
 806 Recasting with MadAnalysis 5 gives $1 - \text{CL}_s = 0.73$ (corresponding to $r = 0.6$) from the ATLAS-
 807 SUSY-2019-08 [107] analysis. The decay patterns of Point 10 are as follows:

808

mass	decays
822 GeV	$\tilde{\chi}_6^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (35%), $\tilde{\chi}_{1,2}^0 Z$ (34%), $\tilde{\chi}_{1,2}^0 h$ (29%)
	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ (35%), $\tilde{\chi}_{1,2}^0 Z$ (33%), $\tilde{\chi}_{1,2}^0 h$ (30%)
491 GeV	$\tilde{\chi}_3^\pm \rightarrow \tilde{\chi}_1^\pm Z$ (50%), $\tilde{\chi}_1^\pm h$ (34%), $\tilde{\chi}_{1,2}^0 W^\pm$ (15%)
486 GeV	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_{1,2}^0 Z$ (37%), $\tilde{\chi}_1^\pm W^\mp$ (35%), $\tilde{\chi}_{1,2}^0 h$ (28%)
485 GeV	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_{1,2}^0 Z$ (44%), $\tilde{\chi}_1^\pm W^\mp$ (33%), $\tilde{\chi}_{1,2}^0 h$ (22%)
480 GeV	$\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_{1,2}^0 W^\pm$ (90%), $\tilde{\chi}_1^\pm h$ (5%), $\tilde{\chi}_1^\pm Z$ (5%)
247 GeV	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ (92%), $\tilde{\chi}_1^0 l^\pm \nu$ (8%); $\Gamma_{\text{tot}} = 1.5 \times 10^{-14}$ GeV ($c\tau \approx 13$ mm)
	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ (95%), $\tilde{\chi}_1^0 \pi^0$ (5%); $\Gamma_{\text{tot}} = 1.2 \times 10^{-13}$ GeV ($c\tau \approx 2$ mm)
247 GeV	$\tilde{\chi}_1^0$, stable

810

811 **The SLHA files for these 10 points**, which can be used as input for MadGraph, micrOMEGAS
 812 or SModelS are available via Zenodo [135]. The main difference between the SLHA files

¹⁵See [104, 125] for details on the computation of the prompt and displaced signal fractions in SModelS.

813 for MadGraph5_aMC@NLO or micrOMEGAs is that the MadGraph5_aMC@NLO ones have
814 complex mixing matrices, while the micrOMEGAs ones have real mixing matrices and thus
815 neutralino masses can have negative sign. The SModelS input files consist of masses, decay ta-
816 bles and cross sections in SLHA format but don't include mixing matrices. The CalcHEP model
817 files for micrOMEGAs are also provided at [135]. The UFO model for MadGraph5_aMC@NLO
818 is available at [84], and the SPheno code at [96].

819 6 Conclusions

820 Supersymmetric models with Dirac instead of Majorana gaugino masses have distinct phe-
821 nomenological features. In this paper, we investigated the electroweakino sector of the Min-
822 imal Dirac Gaugino Supersymmetric Standard Model. The MDGSSM can be defined as the
823 minimal Dirac gaugino extension of the MSSM: to introduce DG masses, one adjoint chiral
824 superfield is added for each gauge group, but nothing else. The model has an underlying
825 R-symmetry that is explicitly broken in the Higgs sector through a (small) B_μ term, and new
826 superpotential couplings λ_S and λ_T of the singlet and triplet fields with the Higgs. The re-
827 sulting EW-ino sector thus comprises two bino, four wino and three higgsino states, which
828 mix to form six neutralino and three chargino mass eigenstates (as compared to four and two,
829 respectively, in the MSSM) with naturally small mass splittings induced by λ_S and λ_T .

830 All this has interesting consequences for dark matter and collider phenomenology. We
831 explored the parameter space where the $\tilde{\chi}_1^0$ is a good DM candidate in agreement with relic
832 density and direct detection constraints, updating previous such studies. The collider phe-
833 nomenology of the emerging DM-motivated scenarios is characterised by the richer EW-ino
834 spectrum as compared to the MSSM, naturally small mass splittings as mentioned above, and
835 the frequent presence of long-lived charginos and/or neutralinos.

836 We worked out the current LHC constraints on these scenarios by re-interpreting SUSY and
837 LLP searches from ATLAS and CMS, in both a simplified model approach and full recasting
838 using Monte Carlo event simulation. While HSCP and disappearing track searches give quite
839 powerful limits on scenarios with charged LLPs, scenarios with mostly E_T^{miss} signatures remain
840 poorly constrained. Indeed, the prompt SUSY searches only allow the exclusion of (certain)
841 points with an LSP below 200 GeV, which drops to about 100 GeV when the winos are heavy.
842 This is a stark contrast to the picture for constraints on colourful sparticles, and indicates that
843 this sector of the theory is likely most promising for future work. We provided a set of 10
844 benchmark points to this end.

845 We also demonstrated the usefulness of a simplified models approach for EW-inos, in com-
846 paring it to a full recasting. While cross section upper limits have the in-built shortcoming of
847 not being able to properly account for complex spectra (where several signals overlap), the
848 results are close enough to give a good estimate of the excluded region. This is particularly
849 true since it is a *much* faster method of obtaining constraints, and the implementation of new
850 results is much more straightforward (and hence more complete and up-to-date). Moreover,
851 the constraining power could easily be improved if more efficiency maps and likelihood infor-
852 mation were available and implemented. This holds for both prompt and LLP searches.

853 We note in this context that, while this study was finalised, ATLAS made pyhf likelihood
854 files for the $1l+H(\rightarrow b\bar{b})+E_T^{\text{miss}}$ EW-ino search [107] available on HEPData [136] in addition
855 to digitised acceptance and efficiency maps. We appreciate this very much and are looking
856 forward to using this data in future studies. To go a step further, it would be very interesting
857 if the assumption $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ could be lifted in the simplified model interpretations.

858 Furthermore, the implementation in other recasting tools of more analyses with the full
859 $\approx 140 \text{ fb}^{-1}$ integrated luminosity from Run 2 would be of high utility in constraining the

EW-ino sector. Here, the recasting of LLP searches is also a high priority, as theories with such particles are very easily constrained, with the limits reaching much higher masses than for searches for promptly decaying particles. A review of available tools for reinterpretation and detailed recommendations for the presentation of results from new physics searches are available in [137].

Last but not least, we note that the automation of the calculation of particle decays when there is little phase space will also be a fruitful avenue for future work.

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A Appendices

A.1 Electroweakinos in the MRSSM

In this appendix we provide a review of the EW-ino sector of the MRSSM in our notation, to contrast with the phenomenology of the MDGSSM.

The MRSSM [19] is characterised by preserving a $U(1)$ R-symmetry even after EWSB. To allow the Higgs fields to obtain vacuum expectation values, they must have vanishing R-charges, and we therefore need to add additional partner fields $R_{u,d}$ so that the higgsinos can obtain a mass (analogous to the μ -term in the MSSM).

The relevant field content is summarised in Table 4. The superpotential of the MRSSM is

$$W^{\text{MRSSM}} = \mu_u \mathbf{R}_u \cdot \mathbf{H}_u + \mu_d \mathbf{R}_d \cdot \mathbf{H}_d + \lambda_{S_u} \mathbf{S} \mathbf{R}_u \cdot \mathbf{H}_u + \lambda_{S_d} \mathbf{S} \mathbf{R}_d \cdot \mathbf{H}_d + 2\lambda_{T_u} \mathbf{R}_u \cdot \mathbf{T} \mathbf{H}_u + 2\lambda_{T_d} \mathbf{R}_d \cdot \mathbf{T} \mathbf{H}_d. \quad (19)$$

Here we define the triplet as

$$\mathbf{T} \equiv \frac{1}{2} \mathbf{T}^a \sigma^a = \frac{1}{2} \begin{pmatrix} \mathbf{T}_0 & \sqrt{2} \mathbf{T}_+ \\ \sqrt{2} \mathbf{T}_- & -\mathbf{T}_0 \end{pmatrix}. \quad (20)$$

Notably the model has an $N = 2$ supersymmetry if

$$\lambda_{S_u} = g_Y / \sqrt{2}, \quad \lambda_{S_d} = -g_Y / \sqrt{2}, \quad \lambda_{T_u} = g_2 / \sqrt{2}, \quad \lambda_{T_d} = g_2 / \sqrt{2}. \quad (21)$$

Table 4: Chiral and gauge supermultiplets in the MRSSM, in addition to the quarks and leptons.

Names		Spin 0, $R = 0$	Spin 1/2, $R = -1$		$SU(3), SU(2), U(1)_Y$
Higgs	\mathbf{H}_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$		$(\mathbf{1}, \mathbf{2}, 1/2)$
	\mathbf{H}_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$		$(\mathbf{1}, \mathbf{2}, -1/2)$
DG-octet	\mathbf{O}	O	χ_o		$(\mathbf{8}, \mathbf{1}, 0)$
DG-triplet	\mathbf{T}	$\{T^0, T^\pm\}$	$\{\chi_T^\pm, \chi_T^0\}$		$(\mathbf{1}, \mathbf{3}, 0)$
DG-singlet	\mathbf{S}	S	χ_s		$(\mathbf{1}, \mathbf{1}, 0)$
Names		Spin 0, $R = 2$	Spin 1/2, $R = 1$	Spin 1, $R = 0$	$SU(3), SU(2), U(1)_Y$
Gluons	\mathbf{W}_{3a}		\tilde{g}_α	g	$(\mathbf{8}, \mathbf{1}, 0)$
W	\mathbf{W}_{2a}		$\tilde{W}^\pm, \tilde{W}^0$	W^\pm, W^0	$(\mathbf{1}, \mathbf{3}, 0)$
B	\mathbf{W}_{1a}		\tilde{B}	B	$(\mathbf{1}, \mathbf{1}, 0)$
R-Higgs	\mathbf{R}_d	(R_d^+, R_d^0)	$(\tilde{R}_d^+, \tilde{R}_d^0)$		$(\mathbf{1}, \mathbf{2}, 1/2)$
	\mathbf{R}_u	(R_u^0, R_u^-)	$(\tilde{R}_u^0, \tilde{R}_u^-)$		$(\mathbf{1}, \mathbf{2}, -1/2)$

895 The above definitions are common to e.g. [38, 59, 75] and can be translated to the notation
 896 of [50] via

$$\lambda_{S_u} \equiv \lambda_u, \quad \lambda_{S_d} \equiv \lambda_d, \quad \lambda_{T_u} \equiv \frac{1}{\sqrt{2}}\Lambda_u, \quad \lambda_{T_d} \equiv \frac{1}{\sqrt{2}}\Lambda_d. \quad (22)$$

897 The Higgs fields as well as the triplet and singlet scalars have R-charges 0, so their fermionic
 898 partners all have R-charge -1 . The $R_{u,d}$ fields have R-charges 2, so the R-higgsinos have R-
 899 charge 1. Together with the “conventional” bino and wino fields, which also have R-charge 1,
 900 this gives $2 \times$ four Dirac spinors with opposite R-charges. After EWSB, the EW gauginos and
 901 (R-)higgsinos thus form four Dirac neutralinos with mass-matrix

$$\mathcal{L}_{\text{MRSSM}} \supset -(\tilde{B}, \tilde{W}^0, \tilde{R}_d^0, \tilde{R}_u^0) \begin{pmatrix} m_{DY} & 0 & -\frac{1}{2}g_Y v_d & \frac{1}{2}g_Y v_u \\ 0 & m_{D2} & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{2}\lambda_{S_d} v_d & -\frac{1}{2}\lambda_{T_d} v_d & -\mu_d^{\text{eff},+} & 0 \\ \frac{1}{2}\lambda_{S_u} v_u & -\frac{1}{2}\lambda_{T_u} v_u & 0 & \mu_u^{\text{eff},-} \end{pmatrix} \begin{pmatrix} \chi_S^0 \\ \chi_T^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}, \quad (23)$$

902 where

$$\mu_{u,d}^{\text{eff},\pm} \equiv \mu_{u,d} + \frac{1}{\sqrt{2}}\lambda_{S_{u,d}} v_S \pm \frac{1}{\sqrt{2}}\lambda_{T_{u,d}} v_T. \quad (24)$$

903 The above mass matrix looks very similar to that of the MSSM in the case of $N = 2$ supersym-
 904 metry!

905 On the other hand, for the charginos, although there are eight Weyl spinors, these organise
 906 into four Dirac spinors, and again into two pairs with opposite R-charges. So we have

$$\mathcal{L}_{\text{MRSSM}} \supset -(\chi_T^-, \tilde{H}_d^-) \begin{pmatrix} g_2 v_T + m_{D2} & \lambda_{T_d} v_d \\ \frac{1}{\sqrt{2}}g_2 v_d & \mu_d^{\text{eff},-} \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{R}_d^+ \end{pmatrix} \\ -(\tilde{W}^-, \tilde{R}_u^-) \begin{pmatrix} -g_2 v_T + m_{D2} & \frac{1}{\sqrt{2}}g_2 v_u \\ -\lambda_{T_u} v_u & -\mu_u^{\text{eff},+} \end{pmatrix} \begin{pmatrix} \chi_T^+ \\ \tilde{H}_u^+ \end{pmatrix} + \text{h.c.} \quad (25)$$

907 The MRSSM therefore does not entail naturally small splittings between EW-ino states.
 908 However, if the R-symmetry is broken by a small parameter, then this situation is reversed:
 909 small mass splittings would appear between each of the Dirac states.

910 A.2 MCMC scan: steps of the implementation

911 The algorithm starts from a random uniformly drawn point, computes $-\log(L)$ denoted as
 912 $-\log(L)_{\text{old}}$, then a new point is drawn from a Gaussian distribution around the previous point,
 913 from which $-\log(L)$, denoted as $-\log(L)_{\text{new}}$, is computed. If $pp \times \log(L)_{\text{new}} \leq \log(L)_{\text{old}}$,
 914 where pp is a random number between 0 and 1, the old point is replaced by the new one and
 915 $-\log(L)_{\text{old}} = -\log(L)_{\text{new}}$. The next points will be drawn from a Gaussian distribution around
 916 the point that corresponds to $-\log(L)_{\text{old}}$. The steps of the implementation are the following:

- 917 1. Draw a starting point from a random uniform distribution.
- 918 2. If point lies within allowed scan range, eq. (6), compute spectrum with SPheno. If the
 919 computation fails, go back to step 1 (or 9).
- 920 3. Check if $120 < m_h < 130$ GeV. If not, go back to step 1 (or 9).
- 921 4. Call micrOMEGAs, check if the point is excluded by LEP mass limits or invisible Z decays,
 922 or if the LSP is charged. If yes to any, go back to step 1 (or 9).
- 923 5. Compute the relic density and p_{X1T} with micrOMEGAs.
- 924 6. If relic density below $\Omega h^2_{\text{Planck}} + 10\% = 0.132$, save point.
- 925 7. Compute $\chi^2_{\Omega h^2}$ for relic density.
- 926 8. Compute $-\log(L)_{\text{old}} = \chi^2_{\Omega h^2} - \log(p_{X1T}) + \log(m_{\text{LSP}})$.
- 927 9. Draw a new point from a Gaussian distribution around the old one.
- 928 10. Repeat steps 2 to 7.
- 929 11. Compute $-\log(L)_{\text{new}}$.
- 930 12. Run the Metropolis–Hastings algorithm:
 931 $pp = \text{random.uniform}(0,1)$
 932 **If** $pp \times \log(L)_{\text{new}} \leq \log(L)_{\text{old}}$:
 933 $\log(L)_{\text{old}} = \log(L)_{\text{new}}$
- 934 13. Iteration++. While iteration $< n_{\text{iterations}}$: repeat steps 9 to 13.

935 This algorithm was run several times, starting from a different random point each time, to
 936 explore the whole parameter space defined by eq. (6).

937 A.3 Higgs mass classifier

938 A common drawback for the efficiency of phenomenological parameter scans, is finding the
 939 subset of the parameter space where the Higgs mass m_h is around the experimentally measured
 940 value. Our case is not the exception, as m_h depends on all the input variables considered in our
 941 study. This is clear for μ , the mass term in the scalar potential, and $\tan\beta$, the ratio between
 942 the vevs. For the soft terms, the dependence becomes apparent when one realises that in DG
 943 models, the Higgs quartic coupling receives corrections of the form

$$\delta\lambda \sim \mathcal{O}\left(\frac{g_Y m_{DY}}{m_{SR}}\right)^2 + \mathcal{O}\left(\frac{\sqrt{2}\lambda_S m_{DY}}{m_{SR}}\right)^2 + \mathcal{O}\left(\frac{g_2 m_{D2}}{m_{TP}}\right)^2 + \mathcal{O}\left(\frac{\sqrt{2}\lambda_T m_{D2}}{m_{TP}}\right)^2, \quad (26)$$

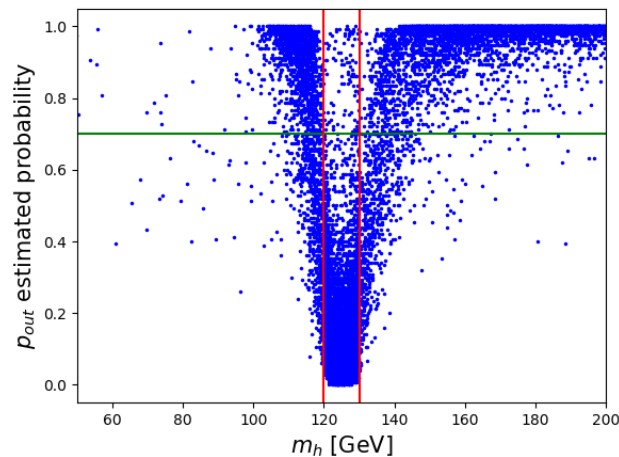


Figure 15: Distribution of the estimated probability for p_{out} as function of m_h obtained from the RFC. Points with an estimated probability above 70% (green line) of being outside the desired $120 < m_h < 130$ range (red lines) are discarded. Values in the $m_h > 200$ GeV and $m_h < 50$ GeV ranges are not depicted for clarity reasons.

944 where m_{SR} and m_{TP} are the tree-level masses of the singlet and triplet scalars, respectively,
 945 and are given large values to avoid a significant suppression on the Higgs mass¹⁶.

946 To overcome this issue, we have implemented Random Forest Classifiers (RFCs) that pre-
 947 dict, from the initial input values, if the parameter point has a m_h inside (p_{in}) or outside (p_{out})
 948 the desired our $120 < m_h < 130$ GeV range. A sample of 50623 points was chosen so as to
 949 have an even distribution of inside/outside range points. The data was then divided as train-
 950 ing and test data in a 67:33 split. We trained the classifier using the RFC algorithm in the
 951 `scikit-learn` python module with 150 trees in the forest (`n_estimators=150`).

952 The obtained mean accuracy score for the trained RFC was 93.75%. However, we are in-
 953 terested in discarding as many points with m_h outside of range as possible while keeping all the
 954 p_{in} ones. To do so we have rejected only the points with a 70% estimated probability of being
 955 p_{out} . In this way, we obtained an improved 98.8% on the accuracy for discarding p_{out} points
 956 while still rejecting 86% of them. The cut value of estimated probability for p_{out} was chosen
 957 as an approximately optimal balance between accuracy and rejection percentage. Above the
 958 70% value there is no significant improvement in the accuracy, but the rejection percentage
 959 depreciates. This behaviour is schematised in Figure 15, where the estimated probability of
 960 p_{out} is shown as a function of m_h .

961 Finally, to estimate the overall improvement on the scan efficiency, we multiplied the per-
 962 centage of real p_{out} (roughly 88%) by the p_{out} rejection percentage (86%) and obtained an
 963 overall 75% rejection percentage. Hence, the inclusion of the classifier yields a scan approxi-
 964 mately four times faster.

965 A.4 Recast of ATLAS-SUSY-2019-08

ATLAS reported a search in final states with E_T^{miss} , 1 lepton (e or μ) and a Higgs boson decaying into $b\bar{b}$, with 139 fb^{-1} in [107]. This is particularly powerful for searching for winos with a lighter LSP (such as a bino or higgsino) and so we implemented a recast of this analysis in MadAnalysis 5 [113–116]. The analysis targets electroweakinos produced in the combination

¹⁶See for instance, Sec. 2.4 of [69] for a discussion on the effects of electroweak soft terms on the tree-level Higgs mass in DG models.

Table 5: Number of events expected in each signal region in [107] (columns labelled “ATLAS”) against result from recasting in MadAnalysis 5 (columns labelled “MA”) for different parameter points. The quoted error bands are *Monte Carlo* uncertainties, but the cross-section uncertainties can also reach 10% for some regions.

$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)[\text{GeV}]$	Region	$m_{\text{CT}} \in [180, 230]$		$m_{\text{CT}} \in [230, 280]$		$m_{\text{CT}} > 230$	
		ATLAS	MA	ATLAS	MA	ATLAS	MA
(300, 75)	LM	6	7.1 \pm 2.2	11	8.5 \pm 2.5	11	12.8 \pm 3.0
(500, 0)	MM	2.5	1.6 \pm 0.4	3.5	2.6 \pm 0.5	5.5	4.8 \pm 0.7
(750, 100)	HM	2	2.0 \pm 0.2	2.5	2.7 \pm 0.2	6	5.4 \pm 0.3

of a chargino and a heavy neutralino, where the neutralino decays by emitting an on-shell Higgs, and the chargino decays by emitting a W -boson, i.e. $WH + E_T^{\text{miss}}$. The Higgs is identified by looking for two b -jets with an invariant mass in the window [100, 140] GeV, while the W -boson is identified through leptonic decays by requiring one signal lepton. Cuts also require $E_T^{\text{miss}} > 240$ GeV, and minimum values of the transverse mass (defined from the lepton transverse momentum and missing transverse momentum). The signal regions are divided into “Low Mass” (LM), “Medium Mass” (MM) and “High Mass” (HM), with four regions for each defined according to the values of the transverse mass and binned according to the *con-transverse mass* of the two b -jets

$$m_{\text{CT}} \equiv \sqrt{2p_T^{b_1} p_T^{b_2} (1 + \cos \Delta\phi_{bb})},$$

966 where there are three bins for exclusion limits ($m_{\text{CT}} \in [180, 230]$, $m_{\text{CT}} \in [230, 280]$,
 967 $m_{\text{CT}} > 230$) and a “discovery” (disc.) region defined for each m_T region (effectively the sum
 968 of the three m_{CT} bins), making twelve signal regions in all.

969 This search should be particularly effective when other supersymmetric particles (such as
 970 sleptons and additional Higgs fields) are heavy. Given constraints on heavy Higgs sectors and
 971 colourful particles, it is rather model independent and difficult to evade in a minimal model.
 972 The ATLAS collaboration made available substantial additional data via HEPData at [136], in
 973 particular including detailed cutflows and tables for the exclusion curves, which are essential
 974 for validating our recast code.

The implementation in MadAnalysis 5 follows the cuts of [107] and implements the lepton isolation and a jet/lepton removal procedure as described in that paper directly in the analysis. Jet reconstruction is performed using fastjet [138] in Delphes 3 [122], where b -tagging and lepton/jet reconstruction efficiencies are taken from a standard ATLAS Delphes 3 card used in other recasting analyses [139–142]. The analysis was validated by comparing signals generated for the same MSSM simplified scenario as in [107]: this consists of a degenerate wino-like chargino and heavy neutralino, together with a light bino-like neutralino. The analysis requires two or three signal jets, two of which must be b -jets (to target the Higgs decay); the signal is simulated by a hard process of

$$p, p \rightarrow \tilde{\chi}_1^+, \tilde{\chi}_2^0 + n \text{ jets}, \quad n \leq 2.$$

975 In the validation, up to 2 hard jets are simulated at leading order in MadGraph5_aMC@NLO,
 976 the parton shower is performed in Pythia 8.2, and the jet merging is performed by the MLM
 977 algorithm using MadGraph5_aMC@NLO defaults. In addition, to select only leptonic decays
 978 of the W -boson, and b -quark decays of the Higgs, the branching ratios are modified in the
 979 SLHA file (with care that Pythia does not override them with the SM values) and the signal
 980 cross-sections weighted accordingly: this improves the efficiency of the simulation by a factor

981 of roughly 8, since the leptonic branching ratio of the W is 0.2157 and the Higgs decays into
 982 b -quarks 58.3% of the time.

983 A detailed validation note will be presented elsewhere, including detailed cutflow analysis
 984 and a reproduction of the exclusion region with that found in [107]. Here we reproduce the
 985 expected (according to the calculated cross-section and experimental integrated luminosity)
 986 final number of events passing the cuts for the “exclusive” signal regions, for the three bench-
 987 mark points where cutflows are available in table 5, where an excellent agreement can be seen.
 988 For each point, 30k events were simulated, leading to small but non-negligible Monte-Carlo
 989 uncertainties listed in the table.

990 Application to the MDGSSM

To apply this analysis to our model, firstly we treat both the lightest two neutralino states as LSP states; we must also simulate the production of all heavy neutralinos ($\tilde{\chi}_i^0$, $i > 2$) and charginos in pairs. It is no longer reasonable to select only leptonic decays of the W , because we can have several processes contributing to the signal. Indeed, in our case, we can have both

$$\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_{1,2}^0 + W, \tilde{\chi}_3^0 \rightarrow \tilde{\chi}_{1,2}^0 + H^0$$

991 and

$$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^- + W, \tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^+ + H^0,$$

for example. Therefore we do not modify the decays of the electroweakinos in the SLHA files, and simulate

$$p, p \rightarrow \tilde{\chi}_{i \geq 1}^\pm, \tilde{\chi}_{j \geq 3}^0 + n\text{jets}, \quad n \leq 2$$

992 as the hard process in MadGraph5_aMC@NLO, before showering with Pythia 8.2 and passing
 993 to the analysis as before.

994 We have not produced an exclusion contour plot for this analysis comparable to the MSSM
 995 case in [107], because a heavy wino with a light bino always leads to an excess of dark matter
 996 unless the bino is near a resonance. We should generally expect the reach of the exclusion to
 997 be better than for the MSSM, due to the increase in cross section from pseudo-Dirac states;
 998 since we can only compare our results directly for points on the Higgs-funnel, for $m_{\tilde{\chi}_1} \approx m_h/2$,
 999 we find a limit on the heavy wino mass of about 800 GeV in our model, compared to 740 GeV
 1000 in the MSSM.

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