

# Testing the higgsino-singlino sector of the NMSSM with trileptons at the LHC

**Ulrich Ellwanger**

*Laboratoire de Physique Théorique, UMR 8627, CNRS and Université de Paris-Sud,  
F-91405 Orsay, France*

*E-mail:* [ulrich.ellwanger@th.u-psud.fr](mailto:ulrich.ellwanger@th.u-psud.fr)

**ABSTRACT:** We propose a simplified light higgsino-singlino scenario in the NMSSM, in which the masses of the chargino and the lightest neutralino determine the masses and couplings of all 3 lightest neutralinos. This scenario is complementary to the simplified wino-like chargino/neutralino scenario used conventionally for the interpretation of results from trilepton searches, and motivated by lower bounds on the gluino mass in the case of GUT relations between the wino and gluino masses. We present all masses and mixing angles necessary for the determination of production cross sections of the chargino and the 3 neutralinos in the form of tables in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane, assuming Higgs mass motivated values for  $\tan\beta = 2$  and  $\lambda = 0.6$ . We show that this scenario leads to considerable signal rates, and present constraints in this plane from recent searches for trileptons at the LHC.

**KEYWORDS:** Supersymmetry Phenomenology

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**1 Introduction**

One of the main tasks of the LHC is the search for supersymmetric (SUSY) particles. These searches have been without success so far, and have lead to lower bounds in the TeV range on the masses of gluinos and squarks of the first two generations.

The trilepton channel  $pp \rightarrow W^{(*)} \rightarrow \chi^\pm + \chi_i^0$  ( $i > 1$ ) with  $\chi^\pm \rightarrow W^{(*)} + \chi_1^0$ ,  $\chi_i^0 \rightarrow Z^{(*)} + \chi_1^0$  and leptonic decays of both  $W^{(*)}$  and  $Z^{(*)}$  are considered as “gold-plated” for searches for charginos and neutralinos at hadron colliders [1–9]. Corresponding searches at the LHC using leptonic final states, in particular trileptons plus missing transverse energy, have been performed by ATLAS and CMS [10–15]; see [16, 17] for recent results from trilepton searches at  $\sqrt{s} = 8$  TeV. There, the absence of significant excesses of events is interpreted in simplified models, motivated by the SUSY particle content of the Minimal SUSY extension of the Standard Model (MSSM) and assuming simple branching ratios and relations among masses. Interpretations of the present constraints from the trilepton channel in realistic versions of the MSSM have been performed in [18–21] (see [22–24] for the rôle of trilepton final states in some beyond-the-MSSM models).

A particularly challenging MSSM scenario would be the case of light and nearly degenerate higgsinos [25, 26]. Light higgsinos correspond to a relatively small ( $\lesssim 300$  GeV) SUSY Higgs mass parameter  $\mu$ , which is favored by fine-tuning arguments:  $\mu^2$  appears always as a positive mass<sup>2</sup> parameter in the Higgs potential, and must be compensated by negative soft SUSY breaking Higgs mass terms for electroweak symmetry breaking to be possible. This makes large values of  $\mu$  unnatural, since then the required cancellation must be relatively very precise. On the other hand, a dominantly higgsino-like (neutralino) LSP is a difficult candidate for dark matter: its annihilation cross section in the early universe is typically too large so that, assuming a standard cosmological evolution, its relic density today is too small to comply with the WMAP and Planck result  $\Omega h^2 \sim 0.1187$ . Moreover, its direct detection (nucleon) cross section is also too large [21, 27] in view of the latest XENON100 results [28] unless the higgsino component is close to 100%.

In the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [29], a SUSY Higgs mass parameter  $\mu_{\text{eff}}$  is generated dynamically through the vacuum expectation value (vev) of a gauge singlet superfield  $S$ ,  $\mu_{\text{eff}} = \lambda \langle S \rangle$ , where  $\lambda$  denotes the coupling of  $S$  to the MSSM-like Higgs superfields. Again, small values of  $\mu_{\text{eff}}$  are favored by low fine-tuning [30, 31]. However, the problems associated with a higgsino-like LSP in the MSSM do not persist in the NMSSM due to the presence of the additional neutralino (singlino) from the superfield  $S$ , which can well be lighter than the higgsinos. This allows for a dominantly singlino-like LSP, whose annihilation cross section via Higgs bosons in the s-channel (and/or coannihilation or some higgsino component) can lead to the desired relic density (see [29] and refs. therein),<sup>1</sup> and a sufficiently small direct detection cross section [32–35] compatible with present XENON100 bounds.

Hence a scenario with light higgsinos and a light singlino, but heavy electroweak gauginos, is viable in the NMSSM. Assuming GUT relations among the electroweak gauginos and the gluino, heavy electroweak gauginos would be an obvious consequence of lower bounds well above 1 TeV on the gluino mass. Since higgsino-singlino mixing would lift the degeneracy among the neutral and charged higgsinos and in the presence of a light singlino-like LSP, searches for charginos and neutralinos in the trilepton channel would be more promising than in the light higgsino scenario within the MSSM [25].

We emphasize that such a scenario would be complementary to the simplified models used by ATLAS and CMS for the interpretation of the trilepton results up to now: In these models, the lightest chargino and the second lightest neutralino are assumed to be wino-like and degenerate, the lightest neutralino is assumed to be bino-like, and the higgsinos are assumed to be heavy and decoupled. The obvious reason for this choice is that now signal rates depend on only two mass parameters (assuming 100% branching ratios into  $W/Z + \chi_1^0$ ).

In the light higgsino-singlino scenario of the NMSSM (containing one chargino  $\chi_1^\pm$  and 3 neutralinos  $\chi_i^0$ ,  $i = 1, 2, 3$ ) the masses and neutralino mixing angles depend on the higgsino mass parameter  $\mu_{\text{eff}}$ , the singlino mass, the ratio  $\tan \beta$  of Higgs vevs and the coupling  $\lambda$  (see the next section). The value of  $\sim 125$  GeV for the SM-like Higgs mass can be obtained naturally in the NMSSM provided  $\lambda$  is large ( $\approx 0.6$ ) and  $\tan \beta$  is relatively small ( $\approx 2$ ) [23, 36–58]. Fixing  $\tan \beta = 2$  and  $\lambda = 0.6$ , also the light higgsino-singlino scenario of the NMSSM depends on two mass parameters only. These can be chosen as the physical chargino mass  $M_{\chi_1^\pm}$  ( $\sim \mu_{\text{eff}}$ ) and the LSP mass  $M_{\chi_1^0}$ , which have a more direct physical meaning than the higgsino and singlino mass parameters in the Lagrangian.

Assuming heavy sleptons, the chargino  $\chi_1^\pm$  decays with a branching ratio (BR) of 100% into  $W^{(*)} + \chi_1^0$ . The neutralinos  $\chi_{2,3}^0$  will typically decay with a BR of 100% into  $Z^{(*)} + \chi_1^0$ . In some cases, decays  $\chi_{2,3}^0 \rightarrow \chi_1^0 +$  a CP-odd or CP-even Higgs boson are possible. These depend on the masses and couplings of the Higgs bosons. Subsequently we define a

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<sup>1</sup>The relic abundance of a mostly singlino-like LSP depends strongly on the masses and couplings of the Higgs scalars which can be exchanged in the s-channel, and hence on various parameters in the Higgs sector like trilinear soft SUSY breaking terms and top/stop-loop induced couplings which have no influence on the neutralino/chargino sector considered below. Hence, although the parameters in the neutralino/chargino sector appear also in the Higgs sector, the condition of a correct relic abundance would not be sufficient to constrain them.

simplified light higgsino-singlino scenario within which such neutralino-to-Higgs decays are absent. Then, given the above values of  $\tan\beta$  and  $\lambda$ ,  $M_{\chi_1^\pm}$  and  $M_{\chi_1^0}$  determine completely the signal rates for chargino + neutralino production into trilepton final states.

It would be very helpful if the ATLAS and CMS collaborations would interpret their results from trilepton searches within such a light higgsino-singlino scenario, as it would allow to test a well motivated region in the parameter space of the NMSSM. It also allows to generalize in a well defined manner the (somewhat unrealistic) assumption  $M_{\chi_1^\pm} = M_{\chi_2^0}$  within the present simplified models, and to study the impact of the lift of this degeneracy.

In the present paper we present the necessary parameters for the determination of the  $pp \rightarrow \chi_1^\pm + \chi_{2,3}^0$  production rates in the light higgsino-singlino scenario in the form of tables in the  $M_{\chi_1^\pm} - M_{\chi_1^0}$  plane: The masses  $M_{\chi_2^0}$  and  $M_{\chi_3^0}$  of the two additional neutralinos, and the mixing angles of  $\chi_2^0$  and  $\chi_3^0$  (relevant for the  $W - \chi_1^\pm - \chi_{2,3}^0$  couplings). As a (preliminary) application we simulated the trilepton event rates in the various signal channels defined in [16], and deduced bounds in the  $M_{\chi_1^\pm} - M_{\chi_1^0}$  plane from the upper limits on the corresponding channel-specific signal cross sections based on  $21 \text{ fb}^{-1}$  integrated luminosity at  $\sqrt{s} = 8 \text{ TeV}$  given there. The tables should allow the ATLAS and CMS collaborations to perform more precise simulations (in particular of the detector responses) and comparisons with data themselves, notably with future data at larger  $\sqrt{s}$  and/or different signal channels.

In the next section we define the simplified light higgsino-singlino scenario in the NMSSM, and comment on the tables given in the appendix. In section 3 we describe the simulations of the trilepton final states and show the resulting bounds in the  $M_{\chi_1^\pm} - M_{\chi_1^0}$  plane. Section 4 is devoted to conclusions and an outlook.

## 2 The light higgsino-singlino scenario in the NMSSM

The NMSSM differs from the MSSM due to the presence of the gauge singlet superfield  $\hat{S}$ . In the simplest realisation of the NMSSM, the SUSY  $\mu \hat{H}_u \hat{H}_d$  Higgs mass term in the MSSM superpotential  $W_{\text{MSSM}}$  is replaced by the coupling  $\lambda$  of  $\hat{S}$  to  $\hat{H}_u$  and  $\hat{H}_d$ , and a self-coupling  $\kappa \hat{S}^3$ . Here,  $\hat{H}_u$  couples to up-type quark superfields, and  $\hat{H}_d$  to down-type quark and lepton superfields. In this version the superpotential  $W_{\text{NMSSM}}$  is scale invariant, and given by:

$$W_{\text{NMSSM}} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \dots \tag{2.1}$$

where the dots denote the Yukawa couplings of  $\hat{H}_u$  and  $\hat{H}_d$  to the quarks and leptons as in the MSSM. Once the scalar component of  $\hat{S}$  develops a vev  $s$ , the first term in  $W_{\text{NMSSM}}$  generates an effective  $\mu$ -term with

$$\mu_{\text{eff}} = \lambda s . \tag{2.2}$$

Amongst others,  $\mu_{\text{eff}}$  generates a Dirac mass term  $\mu_{\text{eff}} \psi_u \psi_d + \text{h.c.}$  for the SU(2)-doublet higgsinos  $\psi_u$  and  $\psi_d$ . The vevs  $v_u$  and  $v_d$  of  $\hat{H}_u$  and  $\hat{H}_d$  generate mixing terms between the singlino  $\psi_S$  and  $\psi_d$ ,  $\psi_u$ , respectively. The second term in the superpotential  $W_{\text{NMSSM}}$  (2.1) generates a Majorana mass term  $M_S$  for  $\psi_S$  with

$$M_S = 2 \kappa s \equiv \frac{2\kappa}{\lambda} \mu_{\text{eff}} . \tag{2.3}$$

The soft SUSY breaking terms include, amongst others, mass terms for the gauginos  $\tilde{B}$  (bino),  $\tilde{W}^a$  (winos) and  $\tilde{G}^a$  (gluinos):

$$-\mathcal{L}_{1/2} = \frac{1}{2} \left[ M_1 \tilde{B} \tilde{B} + M_2 \sum_{a=1}^3 \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^8 \tilde{G}^a \tilde{G}_a \right] + \text{h.c.} . \quad (2.4)$$

Altogether the symmetric  $5 \times 5$  mass matrix  $\mathcal{M}_0$  in the neutralino sector in the basis  $\psi^0 = (-i\tilde{B}, -i\tilde{W}^3, \psi_d^0, \psi_u^0, \psi_S)$  is given by [29]

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & M_S \end{pmatrix} \quad (2.5)$$

leading to mass terms in the Lagrangian of the form

$$\mathcal{L} = -\frac{1}{2} (\psi^0)^T \mathcal{M}_0 (\psi^0) + \text{h.c.} . \quad (2.6)$$

In the limit of heavy decoupled winos and bino considered here,  $M_{1,2} \gg (\mu_{\text{eff}}, 2|\kappa s|)$  (we assume  $\mu_{\text{eff}} > 0$ ), the light higgsino-singlino sector is described by the lower  $3 \times 3$  sub-matrix  $\mathcal{M}_0^{(3)}$  of (2.5). Besides  $\mu_{\text{eff}}$  and  $M_S$ , the elements of  $\mathcal{M}_0^{(3)}$  depend on  $\lambda$  and  $\tan \beta = \frac{v_u}{v_d}$  via  $v_u = \sin \beta \sqrt{v_u^2 + v_d^2} = \sin \beta (174 \text{ GeV})$ ,  $v_d = \cos \beta \sqrt{v_u^2 + v_d^2}$ . As stated in the introduction, we define subsequently the simplified light higgsino-singlino scenario by  $\lambda = 0.6$ ,  $\tan \beta = 2$ .

$\mathcal{M}_0^{(3)}$  is diagonalized by an orthogonal real matrix  $N_{ij}$ ,  $i = 1, 2, 3$ ,  $j = 3, 4, 5$  such that the physical masses  $M_{\chi_i^0}$  ordered in  $|M_{\chi_i^0}|$  are real, but not necessarily positive. Denoting the 3 eigenstates by  $\chi_i^0$ , we have

$$\chi_i^0 = N_{ij} \psi_j^0 \quad (2.7)$$

where  $\psi_3^0 = \psi_d^0$ ,  $\psi_4^0 = \psi_u^0$ ,  $\psi_5^0 = \psi_S$ .

The Dirac mass  $M_{\chi_1^\pm}$  of the higgsino-like charginos  $\chi_1^\pm$  is simply  $M_{\chi_1^\pm} = \mu_{\text{eff}}$ .

The calculations of the masses and mixing angles as function of the parameters  $\lambda$ ,  $\kappa$  (which determines  $M_S$ ),  $\mu_{\text{eff}}$  and  $\tan \beta$  are performed with the help of the public code NMSSMTools [59, 60]. Due to the radiative corrections to the pole masses,  $M_{\chi_1^\pm}$  differs slightly from  $\mu_{\text{eff}}$ . For the soft SUSY breaking squark and slepton masses we choose 2 TeV, and  $M_1 = 1 \text{ TeV}$ ,  $M_2 = 2 \text{ TeV}$ ,  $M_3 = 6 \text{ TeV}$ . (These SUSY breaking parameters determine implicitly the SUSY breaking scale which has a mild impact on the radiative corrections.)

The soft SUSY breaking parameters  $A_\lambda$  and  $A_\kappa$  [29] have no impact on the neutralino/-chargino sector. They can be chosen such that the SM-like Higgs mass is near 125 GeV; in any case they must be chosen such that all physical Higgs masses<sup>2</sup> are positive.

Subsequently we consider  $M_{\chi_1^\pm}$  in the range  $M_{\chi_1^\pm} = 100 \dots 400 \text{ GeV}$  in steps of 20 GeV. The corresponding values of  $\mu_{\text{eff}}$  are tabulated in table 1 in the appendix.

For  $M_{\chi_1^0}$  we consider the range  $M_{\chi_1^0} = 0 \dots 100 \text{ GeV}$  in steps of 10 GeV. For fixed  $\lambda$ ,  $\tan \beta$  and for each given  $\mu_{\text{eff}}$ , the desired values for  $M_{\chi_1^0}$  can be obtained by suitable

values of  $\kappa$ . Actually, low values of  $M_{\chi_1^0}$  require negative values for  $\kappa$  (we recall that we assume  $\mu_{\text{eff}} > 0$ ). Along a strip around  $\kappa \sim 0$ , negative and positive values of  $\kappa$  (of different absolute values) can lead to the same values of  $M_{\chi_1^0}$ . We chose the convention  $\kappa > 0$  whenever possible, which lifts this ambiguity. The corresponding values for  $\kappa$  are tabulated in table 2 in the appendix. Note that  $M_{\chi_1^0} = M_{\chi_1^\pm} (= 100 \text{ GeV})$  is not possible for  $M_S \leq \mu_{\text{eff}}$  as considered here, since even for  $M_S = \mu_{\text{eff}}$  mixing in the neutralino sector will always imply  $M_{\chi_1^0} < M_{\chi_1^\pm}$  (by at least 3 GeV).

Now the masses and mixing angles of  $\chi_2^0$  and  $\chi_3^0$  are uniquely determined. In the tables 3 and 4 in the appendix we list  $M_{\chi_2^0}$  and  $M_{\chi_3^0}$  in the considered range of  $M_{\chi_1^\pm}$  and  $M_{\chi_1^0}$ . We see that  $M_{\chi_2^0}$  is close to  $M_{\chi_1^\pm} \sim \mu_{\text{eff}}$ , whereas  $M_{\chi_3^0}$  is significantly larger due to mixing. (For  $M_{\chi_1^0} \gtrsim M_{\chi_1^\pm} - 20 \text{ GeV}$  in the lower left-hand corner, the mixing angles differ considerably from the other part of the plane.)

The mixing angles  $N_{i,j}$  with  $i = 2, 3, j = 3, 4$  appear in the Feynman rule for the vertex in  $W^+ \rightarrow \chi_1^+ + \chi_{2,3}^0$  corresponding to an incoming  $W_\mu^+$ , an outgoing higgsino-like chargino  $\chi_1^+$  and outgoing neutralinos  $\chi_{2,3}^0$ ; the projectors  $P_L, P_R$  act on the neutralino 4-spinors:

$$ig_2 \gamma_\mu (N_{i,3} P_R - N_{i,4} P_L) / \sqrt{2}. \tag{2.8}$$

Note that the last factor  $1/\sqrt{2}$  is absent in the coupling of  $W$  to wino-like charginos and neutralinos (not shown here); as a consequence the production rates of higgsino-like charginos and neutralinos considered here are smaller than those of wino-like charginos and neutralinos assumed in the simplified models used by ATLAS and CMS. The mixing angles  $N_{2,3}, N_{2,4}, N_{3,3}$  and  $N_{3,4}$  are tabulated in the tables 5, 6, 7 and 8, respectively, in the appendix. Since the signs of physical spinors can be flipped without affecting the cross sections, we used this freedom to simplify the tables in the lower left-hand corner where frequent sign changes appear as consequence of the numerical diagonalisation routine.

Given the decoupled winos and bino, the (absolute values of) the singlino components of  $\chi_i^0$ ,  $i = 2, 3$ , are given by  $|N_{i,5}| = \sqrt{1 - N_{i,3}^2 - N_{i,4}^2}$ , and are typically quite small with the exception of  $N_{3,5}$  for  $M_{\chi_1^0} \lesssim M_{\chi_1^\pm}$  (in the lower left-hand corner of the tables). Likewise, the (absolute values of) the higgsino components  $N_{1,i}$  ( $i = 3, 4$ ) of  $\chi_1^0$  are given by  $|N_{1,i}| = \sqrt{1 - N_{2,i}^2 - N_{3,i}^2}$ , from which the singlino component  $N_{1,5}$  of  $\chi_1^0$  (typically dominant) can be deduced as before.

Assuming BRs of 100% for the decays  $\chi_2^0 \rightarrow Z^{(*)} + \chi_1^0$ ,  $\chi_3^0 \rightarrow Z^{(*)} + \chi_1^0$  and  $\chi_1^\pm \rightarrow W^{(*)} + \chi_1^0$ , the masses and the  $W - \chi_1^\pm - \chi_{2,3}^0$  vertices suffice to determine the production cross sections and signal rates into trilepton channels in this light higgsino-singlino scenario. Hence this scenario is now well defined (on the points given in the tables), and can be used to interpret results from searches for trileptons and missing energy. If desired, the parameters of additional points in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane can be provided.

### 3 Present LHC constraints on the light higgsino-singlino scenario

Recent results from searches for trileptons and missing energy at the LHC at  $\sqrt{s} = 8 \text{ TeV}$  and  $\sim 20 \text{ fb}^{-1}$  of integrated luminosity have been published in [16, 17]. Subsequently we

use the upper bounds (at the 95% confidence level) on event rates in the specific search channels given by ATLAS in the table 1 in [16]. For the simulation we proceed as follows:

The cross sections for  $pp \rightarrow \chi_1^\pm + \chi_2^0$  and  $pp \rightarrow \chi_1^\pm + \chi_3^0$  production are obtained from Prospino at next-to-leading order (NLO) [61–63]. The matrix elements are generated by MadGraph/MadEvent 5 [64], which includes Pythia 6.4 [65]. The output is given to the fast detector simulation DELPHES [66, 67]. We have verified that the cut flows given in table 5 in [16] are reproduced reasonably well (within 10 – 30% for the final signal rate).

The strongest constraints on the light higgsino-singlino scenario originate from the search channels SRnoZc and SRZc in [16], which are defined as follows:  $m_{\text{SFOS}}$  denotes the invariant mass of a same-flavour opposite-sign (SFOS) lepton pair (closest to the  $Z$ -boson mass). For SRnoZc one requires  $m_{\text{SFOS}} < 81.2 \text{ GeV}$  or  $m_{\text{SFOS}} > 101.2 \text{ GeV}$ , whereas for SRZc one requires  $81.2 \text{ GeV} < m_{\text{SFOS}} < 101.2 \text{ GeV}$ . For  $p_T^l$  of the third leading lepton one requires  $p_T^l > 30 \text{ GeV}$  for SRnoZc, and  $p_T^l > 10 \text{ GeV}$  for SRZc. For the missing transverse energy  $E_T^{\text{miss}}$  one requires  $E_T^{\text{miss}} > 75 \text{ GeV}$  for SRnoZc, and  $E_T^{\text{miss}} > 120 \text{ GeV}$  for SRZc. The transverse mass  $m_T$  is defined by  $m_T = \sqrt{2 \cdot E_T^{\text{miss}} \cdot p_T^l \cdot (1 - \cos \Delta\Phi_{l, E_T^{\text{miss}}})}$ , and required to be above 110 GeV in all cases. The upper bounds on the number of signal events are 6.8 for SRnoZc, and 6.5 for SRZc (for more details, see [16]).

The resulting constraints in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane are shown as a red curve in figure 1. The black dashed line in figure 1 indicates where  $M_{\chi_2^0} - M_{\chi_1^0} = M_Z$ . Above the black dashed line,  $\chi_2^0$  (with a significantly larger production cross section than  $\chi_3^0$ ) undergoes 3-body decays  $\chi_2^0 \rightarrow \chi_1^0 + Z^* \rightarrow \dots$ , and the search channel SRnoZc is most relevant, whereas below the black dashed line  $\chi_2^0$  undergoes 2-body decays  $\chi_2^0 \rightarrow \chi_1^0 + Z \rightarrow \dots$ , and the search channel SRZc is relevant.

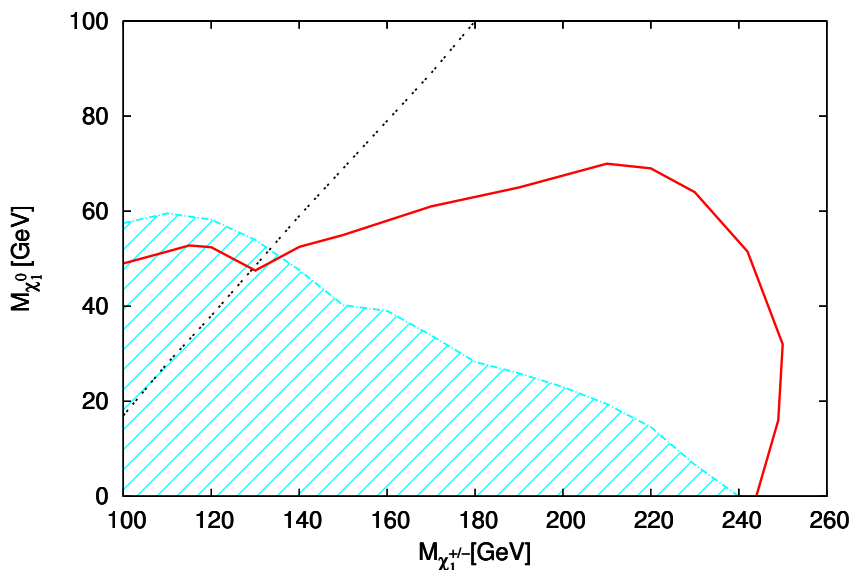
We note that the bounds in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane are significantly weaker than the bounds in figure 8(b) in [16]. The reason hereof is the significantly lower production cross section for higgsino-like charginos and neutralinos compared to wino-like charginos and neutralinos assumed in the simplified model in [16]. The fact that here we include in addition the production of  $\chi_3^0$  does not compensate for the smaller couplings to  $W^*$  (also due to mixings with the singlino), moreover  $M_{\chi_3^0}$  is substantially larger than  $M_{\chi_2^0}$ .

Searches for  $e^+e^- \rightarrow Z^{(*)} \rightarrow \chi_2^0\chi_1^0$  had already been performed at LEP, notably by the DELPHI [68] and OPAL [69] collaborations. Since the  $Z - \chi_2^0 - \chi_1^0$  vertex is equally well defined in the present scenario, corresponding constraints (as implemented in NMSSMTools [59, 60]) can be applied and lead to the excluded blue hashed region in figure 1. Actually, inside the blue hashed region (for  $M_{\chi_1^0} < M_Z/2$  and low  $M_{\chi_1^\pm}$  where the higgsino components of  $\chi_1^0$  are not negligibly small), some points are also excluded by a too large contribution to the invisible  $Z$  width from  $Z \rightarrow \chi_1^0\chi_1^0$ .

Hence, even in this somewhat delicate light higgsino-singlino scenario, already the present LHC constraints are significantly stronger than the bounds from LEP.

## 4 Conclusions and outlook

The main purpose of the present paper is the presentation of a simplified, but well-motivated light higgsino-singlino scenario in the NMSSM. It is complementary to the sim-



**Figure 1.** Red curve: boundary of the excluded region in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane from searches for trileptons by ATLAS [16]. The black dashed line indicates  $M_{\chi_2^0} - M_{\chi_1^0} = M_Z$ . Above the black dashed line,  $\chi_2^0$  undergoes 3-body decays  $\chi_2^0 \rightarrow \chi_1^0 + Z^* \rightarrow \dots$ . The blue hashed region is excluded by searches for  $\chi_2^0 + \chi_1^0$  production at LEP [68, 69].

plified wino-like chargino/neutralino scenario used conventionally by ATLAS and CMS for the interpretation of results from trilepton searches, but leads equally to considerable signal rates. (Assuming GUT-like relations among the gaugino mass parameters, the wino mass term is bounded from below by about 1/3 of the lower limit on the gluino mass, disfavoring light winos.) Hence present and future searches for chargino/neutralino production at the LHC merit to be interpreted in this scenario as well.

We have presented all necessary masses and mixing angles for the determination of production cross sections of the chargino and the 3 neutralinos in the form of tables in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane, assuming Higgs mass motivated values (in the NMSSM) for  $\tan \beta = 2$  and  $\lambda = 0.6$ ; however, as long as  $\lambda$  remains sizeable and  $\tan \beta$  small, the masses and mixing angles depend little on these specific values. Masses and mixing angles for additional points in this plane can be provided by the author, or be obtained with the help of the public code NMSSMTools [59, 60].

The present constraints in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane from the ATLAS search for trileptons [16] (assuming heavy sleptons) have been obtained using the simplified detector simulation DELPHES [66, 67]; this simulation should actually be redone by the LHC collaborations themselves. In any case it shows that the signal rates in this scenario are measurably large, and that relevant constraints are obtained in the absence of signals.

In addition to the trilepton final state, the simplified higgsino-singlino scenario can also be tested in searches for four leptons plus  $E_T^{\text{miss}}$  [17, 70]. The relevant processes would be  $pp \rightarrow Z^* \rightarrow \chi_i^0 \chi_j^0$  with  $i, j = 2, 3$ ,  $\chi_{i,j}^0 \rightarrow \chi_1^0 + Z^{(*)}$  and leptonic decays of  $Z^{(*)}$  (or, alternatively, hadronic decays of one of the  $Z^{(*)}$ ) [17, 71]. Again, the masses and mixing angles given here allow for the determination of the production cross sections. These are



$M_{\chi_1^\pm}$	100.0	120.0	140.0	160.0	180.0	200.0	220.0	240.0	260.0	280.0	300.0	320.0	340.0	360.0	380.0	400.0
$\mu_{\text{eff}}$	99.3	118.8	138.4	157.9	177.5	197.2	216.8	236.5	256.1	275.8	295.6	315.3	335.0	354.8	374.6	394.3

**Table 1.** Values for  $\mu_{\text{eff}}$  leading to the specific values of  $M_{\chi_1^\pm}$  used below.

dominated by  $\chi_2^0 + \chi_3^0$  production with, however, a cross section of only  $\sim 20 - 25\%$  of the one for trileptons. At present, the results of these searches are interpreted in SUSY models with gauge mediation where  $\chi_1^0$  is replaced by a practically massless gravitino. Hence, re-analyses of these (and future) results are desirable in the context of the present scenario.

In how far does this simplified light higgsino-singlino scenario differ from more general regions in the parameter space of the NMSSM? First, if the wino mass parameter  $M_2$  is not as large as assumed here (2 TeV), the lightest chargino and neutralinos can have sizeable wino components which lead typically to an increase of the production cross sections. Hence the present scenario is conservative in this respect. On the other hand, the neutralinos  $\chi_{2,3}^0$  will not necessarily have branching ratios of 100% into  $Z^{(*)} + \chi_1^0$ , notably if decays into some of the lighter of the 5 CP-even or CP-odd neutral Higgs states of the NMSSM are frequent. Clearly such decays would reduce the signal rate in the trilepton channel considered here — even if  $\chi_{2,3}^0$  decay into a light pseudoscalar  $A_1$  with  $M_{A_1} < 2M_b$  and  $A_1$  decays dominantly into  $A_1 \rightarrow \tau^+\tau^-$  [72, 73]. Decays of  $\chi_{2,3}^0$  into heavier Higgs states (decaying into  $b\bar{b}$ ), however, start also to be constrained by corresponding searches [74]. Implications of these latter results on more general regions in the parameter space of the NMSSM remain to be worked out.

## Acknowledgments

It is a pleasure to thank A. Teixeira for discussions. We acknowledge support from the French ANR LFV-CPV-LHC, the European Union FP7 ITN INVISIBLES (Marie Curie Actions, PITN-GA-2011-289442) and the ERC advanced grant Higgs@LHC.

## A Neutralino masses and mixing angles

Below we list in the form of tables in the  $M_{\chi_1^0} - M_{\chi_1^\pm}$  plane various parameters relevant for the simplified light higgsino-singlino scenario in the NMSSM. First, in table 1 we show the values of  $\mu_{\text{eff}}$  leading to specific values for  $M_{\chi_1^\pm}$  (which do not depend on  $M_{\chi_1^0}$ ). In table 2 we give the values of  $\kappa$  which lead to the corresponding values of  $M_{\chi_1^0}$ . In the tables 3 and 4 we list  $M_{\chi_2^0}$  and  $M_{\chi_3^0}$ , and in the tables 5, 6, 7 and 8 we list  $N_{2,3}$ ,  $N_{2,4}$ ,  $N_{3,3}$  and  $N_{3,4}$ , respectively.

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$M_{\chi_1^\pm}$ :	100.0	120.0	140.0	160.0	180.0	200.0	220.0	240.0	260.0	280.0	300.0	320.0	340.0	360.0	380.0	400.0
$M_{\chi_1^0}$	$\kappa$															
0	-.242	-.170	-.126	-.097	-.077	-.063	-.052	-.044	-.037	-.032	-.028	-.025	-.022	-.020	-.018	-.016
10	-.185	-.129	-.095	-.072	-.056	-.044	-.036	-.029	-.024	-.020	-.017	-.015	-.013	-.011	-.009	-.008
20	-.130	-.090	-.064	-.047	-.035	-.026	-.020	-.015	-.011	-.008	-.006	-.004	-.003	-.002	-.001	-.000
30	-.077	-.051	-.034	-.022	-.014	-.008	-.004	-.089	0.002	0.003	0.005	0.006	0.006	0.007	0.007	0.008
40	-.025	-.013	-.004	0.003	0.007	0.010	0.012	0.014	0.015	0.015	0.016	0.016	0.016	0.016	0.016	0.016
50	0.029	0.025	0.026	0.027	0.028	0.028	0.028	0.028	0.027	0.027	0.026	0.026	0.025	0.025	0.024	0.023
60	0.088	0.064	0.055	0.051	0.048	0.046	0.044	0.042	0.040	0.039	0.037	0.036	0.035	0.033	0.032	0.031
70	0.159	0.105	0.086	0.075	0.068	0.063	0.059	0.056	0.053	0.050	0.048	0.046	0.044	0.042	0.041	0.039
80	0.264	0.151	0.117	0.100	0.089	0.081	0.075	0.070	0.066	0.062	0.059	0.056	0.053	0.051	0.049	0.047
90	0.539	0.207	0.150	0.125	0.110	0.099	0.091	0.084	0.079	0.074	0.070	0.066	0.063	0.060	0.057	0.055
100	—	0.293	0.188	0.152	0.131	0.117	0.107	0.098	0.091	0.086	0.080	0.076	0.072	0.069	0.066	0.063

**Table 2.**  $\kappa$  as function of  $M_{\chi_1^0}$  and  $M_{\chi_1^\pm}$ .

$M_{\chi_1^\pm}$ :	100.0	120.0	140.0	160.0	180.0	200.0	220.0	240.0	260.0	280.0	300.0	320.0	340.0	360.0	380.0	400.0
$M_{\chi_1^0}$	$M_{\chi_2^0}$															
0	105.9	125.1	144.4	163.7	183.2	202.7	222.3	241.9	261.5	281.2	300.9	320.6	340.3	360.1	379.9	399.7
10	107.1	125.9	145.0	164.2	183.5	203.0	222.5	242.1	261.7	281.4	301.0	320.7	340.5	360.2	379.9	399.7
20	108.5	126.9	145.7	164.7	184.0	203.3	222.8	242.3	261.9	281.5	301.2	320.9	340.6	360.3	380.0	399.8
30	110.4	128.1	146.5	165.3	184.4	203.7	223.0	241.3	262.1	281.7	301.3	321.0	340.7	360.4	380.1	399.9
40	112.8	129.6	147.5	166.0	184.9	204.1	223.4	242.8	262.3	281.9	301.5	321.1	340.8	360.5	380.3	399.9
50	116.3	131.5	148.7	166.9	185.6	204.6	223.7	243.1	262.5	282.1	301.6	321.3	340.9	360.6	380.4	400.1
60	121.7	134.0	150.2	167.9	186.3	205.1	224.1	243.4	262.8	282.3	301.8	321.4	341.1	360.7	380.5	400.1
70	130.9	137.7	152.2	169.1	187.1	205.7	224.6	243.8	263.1	282.5	302.0	321.6	341.2	360.9	380.5	400.2
80	-145.5	143.2	154.8	170.6	188.1	206.4	225.1	244.2	263.4	282.8	302.3	321.8	341.4	361.0	380.7	400.3
90	-134.4	152.7	158.5	172.6	189.3	207.2	225.7	244.6	263.8	283.1	302.5	322.0	341.5	361.1	380.8	400.5
100	—	-158.9	164.1	175.2	190.9	208.2	226.5	245.2	264.2	283.4	302.8	322.2	341.7	361.3	380.9	400.6

**Table 3.**  $M_{\chi_2^0}$  as function of  $M_{\chi_1^0}$  and  $M_{\chi_1^\pm}$ .

$M_{\chi_1^\pm}$ :	100.0 120.0 140.0 160.0 180.0 200.0 220.0 240.0 260.0 280.0 300.0 320.0 340.0 360.0 380.0 400.0
$M_{\chi_1^0}$	$-M_{\chi_3^0}$
0	194.2 200.2 210.0 222.1 235.9 250.9 266.8 283.4 300.4 317.9 335.7 353.7 372.0 390.5 409.2 428.0
10	185.8 194.3 205.5 218.7 233.2 248.7 264.9 281.8 299.1 316.7 334.7 352.9 371.3 389.8 408.5 427.4
20	178.5 189.0 201.6 215.6 230.7 246.6 263.2 280.3 297.8 315.6 333.7 352.0 370.5 389.1 407.9 426.8
30	172.3 184.5 198.0 212.8 228.4 244.8 261.6 289.0 296.6 314.6 332.8 351.2 369.8 388.5 407.3 426.3
40	166.7 180.4 194.9 210.3 226.3 243.0 260.1 277.7 295.5 313.6 331.9 350.4 369.1 387.9 406.8 425.8
50	161.6 176.7 192.0 208.0 224.4 241.4 258.8 276.5 294.5 312.7 331.1 349.7 368.4 387.3 406.3 425.3
60	156.8 173.3 189.4 205.8 222.7 239.9 257.5 275.4 293.5 311.8 330.4 349.0 367.8 386.7 405.8 424.8
70	151.7 170.0 186.9 203.9 221.0 238.5 256.3 274.3 292.6 311.0 329.6 348.4 367.2 386.2 405.3 424.4
80	-150.7 166.8 184.6 202.0 219.5 237.2 255.2 273.4 291.7 310.3 329.0 347.7 366.7 385.7 404.8 423.9
90	-223.5 163.3 182.4 200.3 218.1 236.0 254.1 272.4 290.9 309.5 328.3 347.1 366.1 385.2 404.3 423.6
100	— -173.2 180.1 198.6 216.7 234.9 253.1 271.6 290.1 308.8 327.7 346.6 365.6 384.7 403.9 423.1

**Table 4.**  $-M_{\chi_3^0}$  as function of  $M_{\chi_1^0}$  and  $M_{\chi_1^\pm}$ . (The negative sign is chosen only to keep the linewidths reasonably short.)

$M_{\chi_1^\pm}$ :	100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
$M_{\chi_1^0}$	$N_{2,3}$
0	.764 .751 .742 .735 .730 .726 .723 .720 .719 .717 .716 .714 .713 .713 .712 .711
10	.767 .753 .743 .736 .730 .726 .723 .721 .719 .717 .716 .715 .714 .713 .712 .711
20	.770 .754 .744 .736 .731 .727 .724 .721 .719 .717 .716 .715 .714 .713 .712 .711
30	.770 .755 .745 .737 .731 .727 .724 .720 .719 .717 .716 .715 .714 .713 .712 .711
40	.768 .755 .745 .738 .732 .727 .724 .721 .719 .718 .716 .715 .714 .713 .712 .711
50	.758 .753 .745 .738 .732 .728 .724 .722 .719 .718 .716 .715 .714 .713 .712 .712
60	.736 .747 .743 .737 .732 .728 .724 .722 .720 .718 .716 .715 .714 .713 .712 .712
70	.689 .734 .739 .736 .732 .728 .724 .722 .720 .718 .716 .715 .714 .713 .712 .712
80	.687 .707 .731 .733 .730 .727 .724 .722 .720 .718 .716 .715 .714 .713 .712 .712
90	.700 .653 .715 .727 .728 .726 .724 .722 .720 .718 .717 .715 .714 .713 .712 .712
100	— .690 .685 .717 .725 .725 .723 .721 .720 .718 .717 .715 .714 .713 .712 .712

**Table 5.**  $N_{2,3}$  as function of  $M_{\chi_1^0}$  and  $M_{\chi_1^\pm}$ .

$M_{\chi_1^\pm}$ :	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
$M_{\chi_1^0}$	$N_{2,4}$															
0	-.600	-.623	-.640	-.652	-.661	-.668	-.674	-.678	-.682	-.684	-.687	-.689	-.690	-.691	-.692	-.693
10	-.583	-.613	-.633	-.647	-.658	-.666	-.672	-.677	-.680	-.683	-.686	-.688	-.690	-.691	-.692	-.693
20	-.562	-.600	-.625	-.642	-.654	-.663	-.670	-.675	-.679	-.682	-.685	-.687	-.689	-.691	-.692	-.693
30	-.535	-.585	-.615	-.636	-.650	-.660	-.668	-.682	-.678	-.681	-.684	-.687	-.688	-.690	-.691	-.692
40	-.499	-.565	-.604	-.628	-.645	-.656	-.665	-.671	-.676	-.680	-.683	-.686	-.688	-.689	-.691	-.692
50	-.450	-.540	-.589	-.619	-.639	-.652	-.662	-.669	-.675	-.679	-.682	-.685	-.687	-.689	-.690	-.692
60	-.380	-.506	-.571	-.608	-.632	-.647	-.659	-.667	-.673	-.677	-.681	-.684	-.686	-.688	-.690	-.691
70	.279	-.459	-.546	-.594	-.623	-.642	-.655	-.664	-.671	-.676	-.680	-.683	-.686	-.688	-.689	-.691
80	.616	-.391	-.513	-.576	-.612	-.635	-.650	-.661	-.668	-.674	-.678	-.682	-.685	-.687	-.689	-.690
90	.648	-.294	-.468	-.553	-.599	-.627	-.645	-.657	-.665	-.672	-.677	-.681	-.684	-.686	-.688	-.690
100	—	.640	-.402	-.521	-.582	-.616	-.638	-.652	-.662	-.670	-.675	-.679	-.683	-.685	-.687	-.689

**Table 6.**  $N_{2,4}$  as function of  $M_{\chi_1^0}$  and  $M_{\chi_1^\pm}$ .

$M_{\chi_1^\pm}$ :	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
$M_{\chi_1^0}$	$N_{3,3}$															
0	.571	.600	.621	.636	.648	.658	.665	.671	.675	.679	.683	.685	.687	.689	.691	.693
10	.591	.614	.632	.645	.655	.662	.669	.674	.678	.681	.684	.687	.689	.690	.692	.693
20	.609	.627	.641	.652	.660	.667	.672	.677	.680	.683	.686	.688	.690	.691	.693	.694
30	.625	.638	.649	.658	.665	.671	.675	.659	.682	.685	.687	.689	.691	.692	.694	.695
40	.638	.648	.656	.663	.669	.674	.678	.681	.684	.686	.689	.690	.692	.693	.694	.695
50	.650	.656	.662	.668	.673	.677	.680	.683	.686	.688	.690	.691	.693	.694	.695	.696
60	.661	.663	.668	.672	.676	.680	.683	.685	.687	.689	.691	.692	.693	.695	.696	.696
70	.672	.670	.673	.676	.679	.682	.685	.687	.689	.690	.692	.693	.694	.695	.696	.697
80	.583	.676	.677	.679	.682	.684	.686	.688	.690	.691	.693	.694	.695	.696	.697	.697
90	.374	.683	.681	.682	.684	.686	.688	.690	.691	.692	.694	.695	.696	.696	.697	.698
100	—	.548	.685	.685	.686	.688	.689	.691	.692	.693	.694	.695	.696	.697	.698	.698

**Table 7.**  $N_{3,3}$  as function of  $M_{\chi_1^0}$  and  $M_{\chi_1^\pm}$ .

$M_{\chi_1^\pm}$ :	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
$M_{\chi_1^0}$	$N_{3,4}$															
0	.468	.515	.550	.578	.600	.616	.630	.641	.649	.657	.662	.667	.672	.675	.678	.681
10	.492	.533	.564	.589	.608	.623	.635	.645	.653	.659	.665	.669	.673	.677	.680	.682
20	.513	.549	.576	.598	.615	.629	.640	.648	.656	.662	.667	.671	.675	.678	.681	.683
30	.532	.563	.587	.606	.622	.634	.644	.625	.659	.664	.669	.673	.676	.679	.682	.684
40	.549	.575	.597	.614	.627	.639	.648	.655	.661	.666	.671	.675	.678	.681	.683	.685
50	.565	.587	.605	.620	.633	.643	.651	.658	.664	.668	.673	.676	.679	.682	.684	.686
60	.581	.597	.613	.626	.638	.647	.654	.661	.666	.670	.674	.677	.680	.683	.685	.687
70	.597	.607	.620	.632	.642	.650	.657	.663	.668	.672	.676	.679	.681	.684	.686	.687
80	-.137	.617	.627	.637	.646	.654	.660	.665	.670	.674	.677	.680	.682	.685	.686	.688
90	.252	.627	.633	.642	.650	.657	.662	.667	.672	.675	.678	.681	.683	.685	.687	.689
100	—	.155	.640	.646	.653	.659	.665	.669	.673	.677	.680	.682	.684	.686	.688	.689

**Table 8.**  $N_{3,4}$  as function of  $M_{\chi_1^0}$  and  $M_{\chi_1^\pm}$ .

## References

- [1] P. Nath and R.L. Arnowitt, *Supersymmetric signals at the Tevatron*, *Mod. Phys. Lett. A* **2** (1987) 331 [[INSPIRE](#)].
- [2] R.L. Arnowitt, R.M. Barnett, P. Nath and F. Paige, *Weak gaugino production at the SSC*, *Int. J. Mod. Phys. A* **2** (1987) 1113 [[INSPIRE](#)].
- [3] R. Barbieri, F. Caravaglios, M. Frigeni and M.L. Mangano, *Production and leptonic decays of charginos and neutralinos in hadronic collisions*, *Nucl. Phys. B* **367** (1991) 28 [[INSPIRE](#)].
- [4] H. Baer and X. Tata, *Probing charginos and neutralinos beyond the reach of LEP at the Tevatron collider*, *Phys. Rev. D* **47** (1993) 2739 [[INSPIRE](#)].
- [5] J.L. Lopez, D.V. Nanopoulos, X. Wang and A. Zichichi, *Supersymmetry tests at Fermilab: a proposal*, *Phys. Rev. D* **48** (1993) 2062 [[hep-ph/9211286](#)] [[INSPIRE](#)].
- [6] H. Baer, C. Kao and X. Tata, *Aspects of chargino-neutralino production at the Tevatron collider*, *Phys. Rev. D* **48** (1993) 5175 [[hep-ph/9307347](#)] [[INSPIRE](#)].
- [7] H. Baer, C.-H. Chen, F. Paige and X. Tata, *Trileptons from chargino-neutralino production at the CERN Large Hadron Collider*, *Phys. Rev. D* **50** (1994) 4508 [[hep-ph/9404212](#)] [[INSPIRE](#)].
- [8] H. Baer, C.-h. Chen, F. Paige and X. Tata, *Signals for minimal supergravity at the CERN Large Hadron Collider. 2: Multi-lepton channels*, *Phys. Rev. D* **53** (1996) 6241 [[hep-ph/9512383](#)] [[INSPIRE](#)].
- [9] H. Baer et al., *WZ plus missing- $E_T$  signal from gaugino pair production at LHC7*, *JHEP* **03** (2012) 092 [[arXiv:1201.5382](#)] [[INSPIRE](#)].
- [10] CMS collaboration, *Search for anomalous production of multilepton events in pp collisions at  $\sqrt{s} = 7$  TeV*, *JHEP* **06** (2012) 169 [[arXiv:1204.5341](#)] [[INSPIRE](#)].
- [11] ATLAS collaboration, *Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in  $13.0 \text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *ATLAS-CONF-2012-154* (2012).

- [12] ATLAS collaboration, *Search for supersymmetry in events with three leptons and missing transverse momentum in  $\sqrt{s} = 7$  TeV pp collisions with the ATLAS detector*, *Phys. Rev. Lett.* **108** (2012) 261804 [[arXiv:1204.5638](#)] [[INSPIRE](#)].
- [13] ATLAS collaboration, *Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in  $\sqrt{s} = 7$  TeV pp collisions with the ATLAS detector*, *Phys. Lett. B* **718** (2013) 841 [[arXiv:1208.3144](#)] [[INSPIRE](#)].
- [14] CMS collaboration, *Search for electroweak production of charginos and neutralinos using leptonic final states in pp collisions at  $\sqrt{s} = 7$  TeV*, *JHEP* **11** (2012) 147 [[arXiv:1209.6620](#)] [[INSPIRE](#)].
- [15] CMS collaboration, *Search for direct EWK production of SUSY particles in multilepton modes with 8 TeV data*, *CMS-PAS-SUS-12-022* (2012).
- [16] ATLAS collaboration, *Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in  $21 \text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, *ATLAS-CONF-2013-035* (2013).
- [17] CMS collaboration, *Search for electroweak production of charginos, neutralinos and sleptons using leptonic final states in pp collisions at 8 TeV*, *CMS-PAS-SUS-13-006* (2013).
- [18] S.S. AbdusSalam, *LHC-7 supersymmetry search interpretation within the pMSSM*, *Phys. Rev. D* **87** (2013) 115012 [[arXiv:1211.0999](#)] [[INSPIRE](#)].
- [19] A. Bharucha, S. Heinemeyer and F. von der Pahlen, *Direct chargino-neutralino production at the LHC: interpreting the exclusion limits in the complex MSSM*, [arXiv:1307.4237](#) [[INSPIRE](#)].
- [20] K. Kowalska and E.M. Sessolo, *Natural MSSM after the LHC 8 TeV run*, *Phys. Rev. D* **88** (2013) 075001 [[arXiv:1307.5790](#)] [[INSPIRE](#)].
- [21] G. Bélanger et al., *LHC constraints on light neutralino dark matter in the MSSM*, *Physics Letters B* **726** (2013) , pp. 773–780 [[arXiv:1308.3735](#)] [[INSPIRE](#)].
- [22] M. Frank, L. Selbuz and I. Turan, *Neutralino and chargino production in  $U(1)'$  at the LHC*, [arXiv:1212.4428](#) [[INSPIRE](#)].
- [23] T. Cheng, J. Li, T. Li and Q.-S. Yan, *Natural NMSSM confronting with the LHC7-8*, [arXiv:1304.3182](#) [[INSPIRE](#)].
- [24] A. Alloul, M. Frank, B. Fuks and M. Rausch de Traubenberg, *Chargino and neutralino production at the Large Hadron Collider in left-right supersymmetric models*, *JHEP* **10** (2013) 033 [[arXiv:1307.5073](#)] [[INSPIRE](#)].
- [25] H. Baer, V. Barger and P. Huang, *Hidden SUSY at the LHC: the light higgsino-world scenario and the role of a lepton collider*, *JHEP* **11** (2011) 031 [[arXiv:1107.5581](#)] [[INSPIRE](#)].
- [26] S. Bobrovskiy, F. Brummer, W. Buchmüller and J. Hajer, *Searching for light higgsinos with b-jets and missing leptons*, *JHEP* **01** (2012) 122 [[arXiv:1111.6005](#)] [[INSPIRE](#)].
- [27] M. Perelstein and B. Shakya, *Fine-tuning implications of direct dark matter searches in the MSSM*, *JHEP* **10** (2011) 142 [[arXiv:1107.5048](#)] [[INSPIRE](#)].
- [28] XENON100 collaboration, E. Aprile et al., *Dark matter results from 225 live days of XENON100 data*, *Phys. Rev. Lett.* **109** (2012) 181301 [[arXiv:1207.5988](#)] [[INSPIRE](#)].
- [29] U. Ellwanger, C. Hugonie and A.M. Teixeira, *The next-to-minimal supersymmetric standard model*, *Phys. Rept.* **496** (2010) 1 [[arXiv:0910.1785](#)] [[INSPIRE](#)].
- [30] U. Ellwanger, G. Espitalier-Noel and C. Hugonie, *Naturalness and fine tuning in the NMSSM: implications of early LHC results*, *JHEP* **09** (2011) 105 [[arXiv:1107.2472](#)] [[INSPIRE](#)].

- [31] M. Perelstein and B. Shakya, *XENON100 implications for naturalness in the MSSM, NMSSM and  $\lambda$ -SUSY*, *Phys. Rev. D* **88** (2013) 075003 [[arXiv:1208.0833](#)] [[INSPIRE](#)].
- [32] D. Cerdeno, C. Hugonie, D. Lopez-Fogliani, C. Muñoz and A. Teixeira, *Theoretical predictions for the direct detection of neutralino dark matter in the NMSSM*, *JHEP* **12** (2004) 048 [[hep-ph/0408102](#)] [[INSPIRE](#)].
- [33] D. Cerdeno, E. Gabrielli, D. Lopez-Fogliani, C. Muñoz and A. Teixeira, *Phenomenological viability of neutralino dark matter in the NMSSM*, *JCAP* **06** (2007) 008 [[hep-ph/0701271](#)] [[INSPIRE](#)].
- [34] V. Barger et al., *Recoil detection of the lightest neutralino in MSSM singlet extensions*, *Phys. Rev. D* **75** (2007) 115002 [[hep-ph/0702036](#)] [[INSPIRE](#)].
- [35] G. Bélanger, C. Hugonie and A. Pukhov, *Precision measurements, dark matter direct detection and LHC Higgs searches in a constrained NMSSM*, *JCAP* **01** (2009) 023 [[arXiv:0811.3224](#)] [[INSPIRE](#)].
- [36] L.J. Hall, D. Pinner and J.T. Ruderman, *A natural SUSY Higgs near 126 GeV*, *JHEP* **04** (2012) 131 [[arXiv:1112.2703](#)] [[INSPIRE](#)].
- [37] U. Ellwanger, *A Higgs boson near 125 eV with enhanced di-photon signal in the NMSSM*, *JHEP* **03** (2012) 044 [[arXiv:1112.3548](#)] [[INSPIRE](#)].
- [38] A. Arvanitaki and G. Villadoro, *A non standard model Higgs at the LHC as a sign of naturalness*, *JHEP* **02** (2012) 144 [[arXiv:1112.4835](#)] [[INSPIRE](#)].
- [39] S.F. King, M. Muhlleitner and R. Nevzorov, *NMSSM Higgs benchmarks near 125 GeV*, *Nucl. Phys. B* **860** (2012) 207 [[arXiv:1201.2671](#)] [[INSPIRE](#)].
- [40] Z. Kang, J. Li and T. Li, *On naturalness of the MSSM and NMSSM*, *JHEP* **11** (2012) 024 [[arXiv:1201.5305](#)] [[INSPIRE](#)].
- [41] J.-J. Cao, Z.-X. Heng, J.M. Yang, Y.-M. Zhang and J.-Y. Zhu, *A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM*, *JHEP* **03** (2012) 086 [[arXiv:1202.5821](#)] [[INSPIRE](#)].
- [42] U. Ellwanger and C. Hugonie, *Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT scale*, *Adv. High Energy Phys.* **2012** (2012) 625389 [[arXiv:1203.5048](#)] [[INSPIRE](#)].
- [43] K.S. Jeong, Y. Shoji and M. Yamaguchi, *Singlet-doublet Higgs mixing and its implications on the Higgs mass in the PQ-NMSSM*, *JHEP* **09** (2012) 007 [[arXiv:1205.2486](#)] [[INSPIRE](#)].
- [44] L. Randall and M. Reece, *Single-scale natural SUSY*, *JHEP* **08** (2013) 088 [[arXiv:1206.6540](#)] [[INSPIRE](#)].
- [45] R. Benbrik et al., *Confronting the MSSM and the NMSSM with the discovery of a signal in the two photon channel at the LHC*, *Eur. Phys. J. C* **72** (2012) 2171 [[arXiv:1207.1096](#)] [[INSPIRE](#)].
- [46] B. Kyae and J.-C. Park, *A singlet-extension of the MSSM for 125 GeV Higgs with the least tuning*, *Phys. Rev. D* **87** (2013) 075021 [[arXiv:1207.3126](#)] [[INSPIRE](#)].
- [47] J. Cao, Z. Heng, J.M. Yang and J. Zhu, *Status of low energy SUSY models confronted with the LHC 125 GeV Higgs data*, *JHEP* **10** (2012) 079 [[arXiv:1207.3698](#)] [[INSPIRE](#)].
- [48] K. Agashe, Y. Cui and R. Franceschini, *Natural islands for a 125 GeV Higgs in the scale-invariant NMSSM*, *JHEP* **02** (2013) 031 [[arXiv:1209.2115](#)] [[INSPIRE](#)].
- [49] G. Bélanger et al., *Higgs bosons at 98 and 125 GeV at LEP and the LHC*, *JHEP* **01** (2013) 069 [[arXiv:1210.1976](#)] [[INSPIRE](#)].

- [50] Z. Heng, *A 125 GeV Higgs and its di-photon signal in different SUSY models: a mini review*, *Adv. High Energy Phys.* **2012** (2012) 312719 [[arXiv:1210.3751](#)] [[INSPIRE](#)].
- [51] K. Choi, S.H. Im, K.S. Jeong and M. Yamaguchi, *Higgs mixing and diphoton rate enhancement in NMSSM models*, *JHEP* **02** (2013) 090 [[arXiv:1211.0875](#)] [[INSPIRE](#)].
- [52] S.F. King, M. Mühlleitner, R. Nevzorov and K. Walz, *Natural NMSSM Higgs bosons*, *Nucl. Phys. B* **870** (2013) 323 [[arXiv:1211.5074](#)] [[INSPIRE](#)].
- [53] T. Gherghetta, B. von Harling, A.D. Medina and M.A. Schmidt, *The scale-invariant NMSSM and the 126 GeV Higgs boson*, *JHEP* **02** (2013) 032 [[arXiv:1212.5243](#)] [[INSPIRE](#)].
- [54] R. Barbieri, D. Buttazzo, K. Kannike, F. Sala and A. Tesi, *Exploring the Higgs sector of a most natural NMSSM*, *Phys. Rev. D* **87** (2013) 115018 [[arXiv:1304.3670](#)] [[INSPIRE](#)].
- [55] M. Badziak, M. Olechowski and S. Pokorski, *New regions in the NMSSM with a 125 GeV Higgs*, *JHEP* **06** (2013) 043 [[arXiv:1304.5437](#)] [[INSPIRE](#)].
- [56] T. Cheng and T. Li, *Electroweak supersymmetry (EWSUSY) in the NMSSM*, *Phys. Rev. D* **88** (2013) 015031 [[arXiv:1305.3214](#)] [[INSPIRE](#)].
- [57] E. Hardy, *Is natural SUSY natural?*, [arXiv:1306.1534](#) [[INSPIRE](#)].
- [58] C. Beskidt, W. de Boer and D.I. Kazakov, *A comparison of the Higgs sectors of the CMSSM and NMSSM for a 126 GeV Higgs boson*, [arXiv:1308.1333](#) [[INSPIRE](#)].
- [59] U. Ellwanger, J.F. Gunion and C. Hugonie, *NMHDECAY: a Fortran code for the Higgs masses, couplings and decay widths in the NMSSM*, *JHEP* **02** (2005) 066 [[hep-ph/0406215](#)] [[INSPIRE](#)].
- [60] U. Ellwanger and C. Hugonie, *NMHDECAY 2.0: an updated program for sparticle masses, Higgs masses, couplings and decay widths in the NMSSM*, *Comput. Phys. Commun.* **175** (2006) 290 [[hep-ph/0508022](#)] [[INSPIRE](#)].
- [61] W. Beenakker, R. Hopker, M. Spira and P. Zerwas, *Squark and gluino production at hadron colliders*, *Nucl. Phys. B* **492** (1997) 51 [[hep-ph/9610490](#)] [[INSPIRE](#)].
- [62] W. Beenakker, R. Hopker and M. Spira, *PROSPINO: a program for the production of supersymmetric particles in next-to-leading order QCD*, [hep-ph/9611232](#) [[INSPIRE](#)]; for updates see <http://www.thphys.uni-heidelberg.de/~plehn/prospino/>.
- [63] W. Beenakker et al., *The production of charginos/neutralinos and sleptons at hadron colliders*, *Phys. Rev. Lett.* **83** (1999) 3780 [*Erratum ibid.* **100** (2008) 029901] [[hep-ph/9906298](#)] [[INSPIRE](#)].
- [64] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *MadGraph 5: going beyond*, *JHEP* **06** (2011) 128 [[arXiv:1106.0522](#)] [[INSPIRE](#)].
- [65] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [66] S. Ovin, X. Rouby and V. Lemaitre, *DELPHES, a framework for fast simulation of a generic collider experiment*, [arXiv:0903.2225](#) [[INSPIRE](#)].
- [67] J. de Favereau et al., *DELPHES 3, a modular framework for fast simulation of a generic collider experiment*, [arXiv:1307.6346](#) [[INSPIRE](#)].
- [68] DELPHI collaboration, J. Abdallah et al., *Searches for supersymmetric particles in  $e^+e^-$  collisions up to 208 GeV and interpretation of the results within the MSSM*, *Eur. Phys. J. C* **31** (2003) 421 [[hep-ex/0311019](#)] [[INSPIRE](#)].



- [69] OPAL collaboration, G. Abbiendi et al., *Search for chargino and neutralino production at  $\sqrt{s} = 192$  GeV to 209 GeV at LEP*, *Eur. Phys. J. C* **35** (2004) 1 [[hep-ex/0401026](#)] [[INSPIRE](#)].
- [70] ATLAS collaboration, *Search for supersymmetry in events with four or more leptons in  $21\text{ fb}^{-1}$  of pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, [ATLAS-CONF-2013-036](#) (2013).
- [71] ATLAS collaboration, *Search for supersymmetry in final states with jets, missing transverse momentum and a Z boson at  $\sqrt{s} = 8$  TeV with the ATLAS detector*, [ATLAS-CONF-2012-152](#) (2012).
- [72] K. Cheung and T.-J. Hou, *Light pseudoscalar Higgs boson in neutralino decays in the next-to-minimal supersymmetric standard model*, *Phys. Lett. B* **674** (2009) 54 [[arXiv:0809.1122](#)] [[INSPIRE](#)].
- [73] D.G. Cerdeno, P. Ghosh, C.B. Park and M. Peiro, *Collider signatures of a light NMSSM pseudoscalar in neutralino decays in the light of LHC results*, [arXiv:1307.7601](#) [[INSPIRE](#)].
- [74] CMS collaboration, *Search for electroweak production of charginos and neutralinos in final states with a Higgs boson in pp collisions at 8 TeV*, [CMS-PAS-SUS-13-017](#) (2013).