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Cornering light Neutralino Dark Matter at the LHC

Lorenzo Calibbi ⋆1, Jonas M. Lindert †2, Toshihiko Ota ‡3, Yasutaka Takanishi ∗4

⋆ *Service de Physique Théorique, Université Libre de Bruxelles, Bld du Triomphe, CP225, B-1050 Brussels, Belgium*

† *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805 München, Germany*

‡ *Department of Physics, Saitama University, Shimo-Okubo 255, 338-8570 Saitama-Sakura, Japan*

∗ *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*

Abstract

We investigate the current status of the light neutralino dark matter scenario within the minimal supersymmetric standard model (MSSM) taking into account latest results from the LHC. A discussion of the relevant constraints, in particular from the dark matter relic abundance, leads us to a manageable simplified model defined by a subset of MSSM parameters. Within this simplified model we reinterpret a recent search for electroweak supersymmetric particle production based on a signature including multi-taus plus missing transverse momentum performed by the ATLAS collaboration. In this way we derive stringent constraints on the light neutralino parameter space. In combination with further experimental information from the LHC, such as dark matter searches in the monojet channel and constraints on invisible Higgs decays, we obtain a lower bound on the lightest neutralino mass of about 24 GeV. This limit is stronger than any current limit set by underground direct dark matter searches or indirect detection experiments. With a mild improvement of the sensitivity of the multi-tau search, light neutralino dark matter can be fully tested up to about 30 GeV.

[1]E-mail: `lcalibbi@ulb.ac.be`
[2]E-mail: `lindert@mppmu.mpg.de`
[3]E-mail: `toshi@mppmu.mpg.de`
[4]E-mail: `yasutaka@mpi-hd.mpg.de`

1 Introduction

Searches for supersymmetry (SUSY) performed by the Large Hadron Collider (LHC) experiments on the center-of-mass energy $\sqrt{s} = 7, 8$ TeV run data have started to set stringent constraints to the strongly-interacting SUSY particles. They translate to limits on the SUSY masses up to $1 \div 1.5$ TeV for gluinos and squarks of the first family [1] and $600 \div 700$ GeV for third generation squarks [2]. Comparatively weaker constraints were obtained for the states that can be only produced through electroweak (EW) interactions, such as sleptons, EW gauginos and Higgsinos. The resulting bounds are up to $200 \div 300$ GeV for selectrons and smuons [3] and up to 600 GeV for charginos [4]. They often depend on the assumption of available on-shell decays. Nevertheless, it is remarkable that the LHC experiments have started – especially with the 2012 run data at $\sqrt{s} = 8$ TeV – to go considerably beyond LEP in testing the EW sector of the theory. Such direct searches for EW production of SUSY particles are of major importance, as the EW-interacting particles can be in principle much lighter than the strongly-interacting ones.

In this paper, we want to discuss how the 8 TeV run data constrain the parameter space that is compatible with a light neutralino as candidate for cold dark matter (DM). In other words, we aim at answering the following question: how light can the lightest neutralino still be after the 8 TeV run of the LHC?[1]

The framework we adopt for our study can be defined as follows:

- only the field content of the MSSM is considered;
- DM is a thermal relic and a standard history of the universe is assumed;
- the abundance of the lightest MSSM neutralino, whose stability is guaranteed by R-parity conservation, is required to not exceed the observed DM relic abundance.

We are not going to make any assumption on the origin and the relations among the SUSY-breaking parameters: in particular we drop the hypothesis of gaugino mass unification that would imply the lower bound for the lightest neutralino mass reported by the PDG [8]: $m_{\tilde{\chi}_1^0} > 46$ GeV. Instead, we treat all SUSY soft-masses as free low-energy parameters.

As we discuss in the next section, relic density constraints from cosmic microwave background (CMB) observations identify the parameter space compatible with light neutralino dark matter and thus the features of the SUSY spectrum and the LHC phenomenology. In particular, we are going to argue that, under the assumptions listed above, neutralino DM with

$$m_{\tilde{\chi}_1^0} \lesssim 30 \text{ GeV} \tag{1}$$

is only possible in a specific region of the supersymmetric parameter space, featuring relatively light staus and Higgsinos. Hence, searches based on multi-tau plus missing energy events are particularly promising in order to test such a scenario, as we are going to discuss in detail. A similar study has been presented last year in Ref. [9]. Here, we want to generalize the approach

[1] For early works addressing this question, see e.g. [5, 6, 7].

of Ref. [9], by considering a simplified model defined only by the subset of SUSY parameters relevant for the determination of the relic abundance. The rest of the spectrum is allowed to be heavy, so that our study is very conservative as it considers only EW production of staus and neutral and charged Higgsinos. Moreover, the ATLAS collaboration has recently performed a search for new physics in a final state with at least two taus and large missing transverse momentum [10], that we will translate into a stringent test of the light neutralino parameter space.[2]

The rest of this paper is organized as follows. In section 2 we qualitatively review the features of the parameter space compatible with light neutralino DM and we define the simplified model we are going to employ in the rest of the study. A quantitative discussion of the relevant constraints and the result of a numerical scan of the parameter space are presented in section 3.1, while bounds from direct and indirect dark matter searches are briefly discussed in 3.2. Section 4 is dedicated to a discussion of the spectrum of the light DM scenario and the consequences for SUSY searches at the LHC. In section 5, we discuss the indirect limits on the parameter space from invisible Higgs decays and we show the possible impact of direct DM searches at the LHC in the monojet plus missing energy channel. In section 6, we present a Monte Carlo study reproducing the limits from Ref. [10]. Afterwards we translate these limits into bounds on the light neutralino parameter space. We conclude summarizing our results in section 7.

2 Light neutralino DM in the MSSM

In this section, we discuss how the parameter space of the MSSM is constrained by the requirement of neutralino dark matter with $m_{\widetilde{\chi}_1^0} \lesssim 30$ GeV. The first obvious condition is that, due to the LEP bound on the chargino mass [8] that implies for the wino and Higgsino mass parameters M_2, $\mu \gtrsim 90$ GeV, the lightest neutralino is mainly bino-like with the bino mass M_1 approximately:

$$M_1 \lesssim 30 \text{ GeV}. \tag{2}$$

The other SUSY parameters depend strongly on how the DM relic density constraints are fulfilled and hence on the annihilation processes of the lightest neutralino in the early universe. In fact, a bino-like neutralino is typically overproduced in thermal processes so that an efficient annihilation mechanism is required in order to reproduce the observed relic density. There are mainly the following three categories for the annihilation mechanism that select different regions of the parameter space: (i) s-channel Higgs mediation, (ii) co-annihilation with a light sfermion, (iii) t-channel sfermion mediation.

Higgs-mediated annihilation. Case (i), in which the neutralino pair-annihilation is mediated by Higgs bosons (mainly the CP-odd one, as the s-wave $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ initial state is CP-odd),

[2]After the completion of this work, a similar analysis, based on 19.5 fb^{-1} at $\sqrt{s} = 8$ TeV, has been presented by CMS [11]. The exclusion limit they obtain seems to be perfectly compatible with the results of Ref. [10].

is an attractive possibility, because the parameter space selected by this scenario unavoidably corresponds to a large scattering cross-section with nuclei (up to $\sigma_{\rm SI} \simeq 10^{-41}$ cm^2), so that the signals at DAMA [12, 13], CoGeNT [14], CRESST-II [15] and the three events recently reported by CDMS [16] could be nicely explained [7, 17, 18, 19]. However, recent LHC results exclude light DM in this parameter region of the MSSM. The reason is the following: $m_{\tilde{\chi}_1^0} \approx 10 \div 20$ GeV requires a light CP-odd Higgs boson A (with $m_A \simeq 100$ GeV) and quite large values of $\tan\beta$ ($\gtrsim 35$) to make the annihilation cross-section efficient enough [20, 21, 22, 23, 24]. This setup has been recently excluded by extra Higgs boson searches at the LHC [25, 26]. On the other hand, larger values of $m_{\tilde{\chi}_1^0}$ ($20 \div 30$ GeV) still correspond to a direct detection cross-section $\sigma_{\rm SI} \simeq 10^{-42} \div 10^{-41}$ cm^2 that is excluded by XENON100 [27] for that mass range [24].[3] In other words, LHC searches for the CP-odd Higgs in combination with direct dark matter searches constrain m_A to values that cannot efficiently mediate neutralino annihilation for $m_{\tilde{\chi}_1^0} \lesssim 30$ GeV.

Co-annihilation with sfermions. The co-annihilation scenario (ii) with a light stau has recently awaken a great interest, because the parameter choice can be also compatible with an enhancement of the $h \to \gamma\gamma$ decay rate, as discussed in Ref. [31]. However, in order to have an efficient co-annihilation for a neutralino lighter than 30 GeV, one would need $m_{\tilde{\tau}} \lesssim 80$ GeV [31], below the limit set by the LEP experiments [8]. On the other hand, if the stau-neutralino mass splitting is small enough to evade direct LEP searches, the scenario is seriously challenged by Z width measurements implying $m_{\tilde{\tau}} \gtrsim 40$ GeV [8] (unless the stau left-right mixing is tuned such that the coupling to Z is strongly suppressed) and would anyway correspond to a too efficient annihilation, i.e. to a DM relic density way below the observed value. As we will discuss in the following, neutralino DM with $m_{\tilde{\chi}_1^0} \lesssim 30$ GeV also requires a light stau. However, the selected parameter space requires small values of the Higgsino mass parameter μ, while very large values of the stau left-right mixing $\mu \tan\beta$ are needed in order to have an effective enhancement of $\Gamma(h \to \gamma\gamma)$ [32, 31]. We have checked that the parameter region we consider does not drive the co-annihilation process and does not give a significant enhancement of $\Gamma(h \to \gamma\gamma)$. Nevertheless, the current LHC measurements of the Higgs decay rates, especially $\Gamma(h \to \text{invisible})$ still provide important information for our scenario. We will come back to this point later.

Sfermion mediation. The only option left is t-channel sfermion mediation (iii). Light neutralino DM is indeed possible in presence of a light stau, as recently shown in Refs. [33, 34]. The reasons why the exchange of other sfermions cannot give enough enhancement to the annihilation cross-section are twofold: (a) LEP and LHC searches put severe limits on the masses of the other sfermions, (b) efficient annihilation of very light neutralinos requires the contribution of Yukawa interactions.

[3]In addition, the recent LHCb evidence for the rare decay $B_s \to \mu^+\mu^-$ with BR $\approx 3 \times 10^{-9}$ [28] and the observation of a SM-like Higgs with $m_h \approx 125$ GeV [29, 30] are also incompatible with the parameter space of the Higgs mediation scenario, as one can see in Ref. [23].

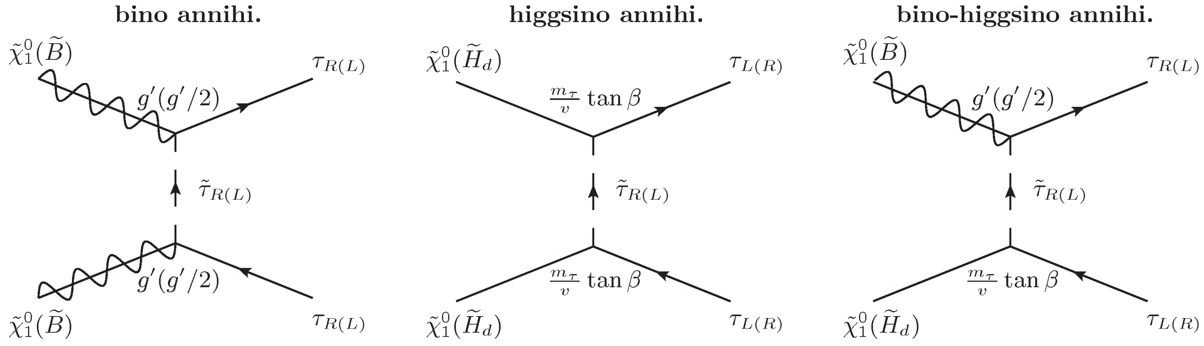

Figure 1: Relevant neutralino annihilation processes mediated by a light stau.

The annihilation cross-section is inverse-proportional to the mass of the mediating sfermion. Therefore, it is constrained by the bound on the mass of the mediation field, the so-called Lee-Weinberg bound [35]. The LHC places strong limits on the masses of squarks and first and second generation sleptons. For instance, direct slepton searches with e and μ in final states at the LHC imply $m_{\tilde{\ell}} \gtrsim 275$ GeV ($\widetilde{\ell} = \widetilde{e}, \widetilde{\mu}$) for $m_{\widetilde{\chi}_1^0} \lesssim 30$ GeV [3]. Similarly, the bounds on direct production of stop and sbottom subsequently decaying to the lightest SUSY particle (LSP) are $m_{\tilde{t}}$, $m_{\tilde{b}} \gtrsim 650$ GeV [2]. If the sfermion-neutralino mass-splitting is small enough ($\lesssim 10$ GeV), these collider bounds can be evaded, as the outgoing fermion is too soft to be detected (see e.g. [36]). However, LEP observations of the Z decays imply the lower bound on any sfermion $m_{\tilde{f}} \gtrsim 40$ GeV. This means that for $m_{\widetilde{\chi}_1^0} \lesssim 30$ GeV it is anyway not possible to have efficient annihilation mediated by light sfermions and to evade at the same time the collider constraints. This justifies *a posteriori* our choice of concentrating on a neutralino lighter than 30 GeV.[4]

The only option left is that the lightest neutralino, that is mainly bino, does pair-annihilate into $\tau^+\tau^-$ via the t-channel stau exchange diagram driven by gauge interactions shown in the left panel of Fig. 1. Since the amplitude is proportional to the square of the hypercharge of the mediating sfermion, the right-handed stau mediation is much more efficient than the left-handed one, giving a factor 16 larger cross-section. As a consequence, the relic density constraints select the mass of the right-handed stau to be not far above the LEP lower bound [33]:

$$m_{\widetilde{\tau}_R} \sim 100 \text{ GeV}. \tag{3}$$

However, the gauge interaction diagram might not be enough to have an efficient neutralino annihilation, especially for even lower neutralino masses, e.g. $\lesssim 20$ GeV. If the lightest neutralino has a sizeable Higgsino component, this can contribute through Higgsino-bino and Higgsino-pair annihilation diagrams (shown as the middle and the right diagrams in Fig. 1). These further contributions assist in realizing the correct relic density with a very light neutralino, in particular for large values of $\tan\beta$.[5] A significant Higgsino component in the lightest

[4]In principle, one could have a tuned scenario with few GeV of neutralino-sbottom mass splitting and left-right sbottom mixing such that the $Z\tilde{b}\tilde{b}$ interaction gets strongly suppressed [36]. This possibility might be challenged by indirect DM searches through antiproton and gamma-ray production [37]. See however [38].

[5]Instead, a light wino does not increase the annihilation cross-section enough, if Higgsinos are not light too.

neutralino requires a small μ-term. This implies that, in addition to the lightest $\widetilde{\tau}$, the lightest chargino $\widetilde{\chi}_1^{\pm}$ and two Higgsino-like neutralinos ($\widetilde{\chi}_2^0$ and $\widetilde{\chi}_3^0$, if $M_2 \gg \mu$) are necessarily light.

In short, in order to enhance the annihilation process driven by the Higgsino component in the lightest neutralino, the following values of the above parameters are selected:

$$m_{\widetilde{\chi}_1^0} \lesssim 30\,(20)\ \text{GeV} \qquad \Rightarrow \qquad \mu \sim 100\ \text{GeV}, \qquad \tan\beta \gtrsim 10\,(30)\ . \tag{4}$$

In summary, the parameter space compatible with light neutralino DM we aim at studying is essentially determined by the values of the four parameters given in Eqs. (2-4), (M_1, μ, $m_{\widetilde{\tau}_R}$, and $\tan\beta$) and does not depend on the detail of the other SUSY parameters. In the following we illustrate numerically the parameter space qualitatively sketched above. We then make use of the simplified model defined by this subset of the parameters in order to discuss the limits set by the LHC on neutralino DM.

3 Scan of the parameter space and experimental constraints

In order to investigate the parameter space selected by requiring light neutralino dark matter, we perform a numerical scan by means of the `SuSpect` [39] and `micrOMEGAs` codes [40]. The low-energy values of the four parameters identified above were randomly varied in the following ranges:

$$\begin{aligned} 10\ \text{GeV} \leq\ & M_1 \ \leq 45\ \text{GeV}, \quad 65\ \text{GeV} \leq\ m_{\widetilde{\tau}_R} \ \leq 200\ \text{GeV}, \\ 90\ \text{GeV} \leq\ & \mu \ \leq 400\ \text{GeV}, \quad 5 \leq\ \tan\beta \ \leq 60\,, \end{aligned} \tag{5}$$

and the SUSY breaking scale within `SuSpect` is set to the approximate scale of the relevant low-mass states (100 GeV). The other SUSY parameters have a marginal role in fulfilling the relic density constraints and they were set to the following constant values:

$$m_{\widetilde{f}} = M_3 = m_A = 2\ \text{TeV},\ M_2 = 1\ \text{TeV},\ A_t = 1.5 \times m_{\widetilde{f}}\,, \tag{6}$$

where $m_{\widetilde{f}}$ denotes all sfermion soft masses besides $m_{\widetilde{\tau}_R}$, M_i are the gaugino masses, m_A the CP-odd Higgs mass. The values chosen for A_t and $m_{\widetilde{f}}$ give the Higgs mass consistent with the LHC measurements, $m_h \approx 125$ GeV. All other A-terms are set to zero.

In the following we describe various (possible) constraints on the resulting parameter space, where, as motivated above, we limit our discussion on the light neutralino regime defined in Eq. (1).

3.1 Relic density, LEP and other standard constraints

DM relic density. Assuming a standard thermal history of the universe, we compute with `micrOMEGAs` [40] the neutralino relic density and impose a conservative 3σ upper bound taken from Ref. [41],

$$\Omega_{\text{DM}} h^2 \leq 0.124\,. \tag{7}$$

The reason is mainly that the wino component in $\widetilde{\chi}_1^0$ vanishes if Higgsinos decouple.

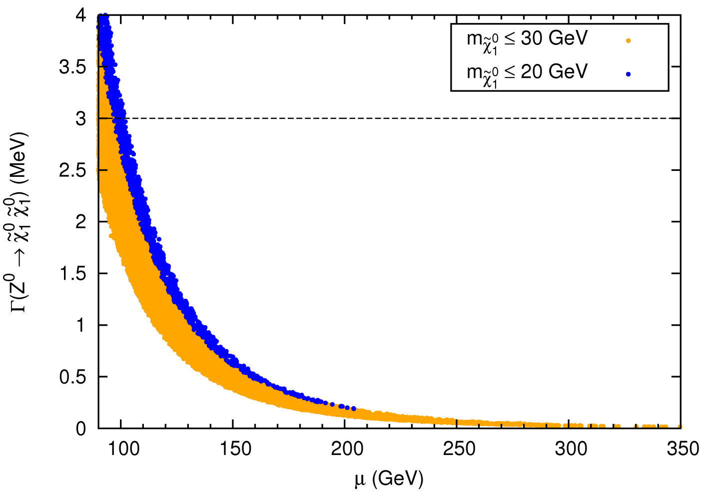

Figure 2: Contribution to the invisible Z width form the process $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ as a function of the Higgsino mass parameter μ. The dashed line corresponds to the LEP limit of Ref. [46].

Direct SUSY searches at LEP. The 95% CL LEP bounds on the lightest stau and chargino masses listed in Ref. [8] are, respectively,

$$m_{\tilde{\tau}_R} \geq 81.9 \text{ GeV}, \quad \text{and} \quad m_{\tilde{\chi}_1^\pm} \geq 94 \text{ GeV}. \tag{8}$$

In addition, we consider bounds from searches of $\tilde{\chi}_1^0 \tilde{\chi}_{2,3}^0$ associated production at LEP, followed by the decay $\tilde{\chi}_{2,3}^0 \to \tilde{\chi}_1^0 Z^{(*)}$. The conservative limit on this process is about 100 fb for the $\tilde{\chi}_1^0$ mass range we are interested in [42]. Explicitly this bound reads

$$\sum_{k=2,3} \sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_k^0) \times \text{BR}(\tilde{\chi}_k^0 \to \tilde{\chi}_1^0 Z^{(*)}) < 100 \text{ fb}. \tag{9}$$

We calculate the associated production cross-sections at LEP using the leading order formulae reported in Refs. [43, 44], the branching fractions were computed by means of the `SUSY-HIT` package [45].

***Z* invisible width.** As discussed above, a sizeable Higgsino $\widetilde{H}_d$ component in $\tilde{\chi}_1^0$ is required. This gives rise to the coupling $\tilde{\chi}_1^0 \tilde{\chi}_1^0 Z$ and also to $\tilde{\chi}_1^0 \tilde{\chi}_1^0 h$ that originates from the gauge vertex $\widetilde{B} H_d \widetilde{H}_d$. As a consequence, the decays $Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ and $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ can occur at relevant rates and we expect stringent constraints from the LEP measurement of the invisible Z width as well as from Higgs observations at the LHC, as recently discussed in Ref. [47]. The decay width of the Z boson into a lightest neutralino pair reads [48]:

$$\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) = \frac{G_F}{\sqrt{2}} \frac{M_Z^3}{12\pi} \left(1 - \frac{4m_{\tilde{\chi}_1^0}^2}{M_Z^2}\right)^{\frac{3}{2}} \left|N_{13}^2 - N_{14}^2\right|^2, \tag{10}$$

where N is the neutralino mixing matrix defined by $\tilde{\chi}_i^0 = N_{i1}\widetilde{B} + N_{i2}\widetilde{W} + N_{i3}\widetilde{H}_d + N_{i4}\widetilde{H}_u$.

In Fig. 2 we plot the resulting $\Gamma(Z \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$ as a function of μ, after applying the other constraints described above. The orange points correspond to $\widetilde{\chi}_1^0$ DM with $m_{\widetilde{\chi}_1^0} \leq 30$ GeV, the blue points to $m_{\widetilde{\chi}_1^0} \leq 20$ GeV. The figure is to be compared to the LEP bound on the new physics contribution to $\Gamma(Z \to \text{invisible})$, $\Delta\Gamma_Z^{\text{inv}}$ [46]:

$$\Delta\Gamma_Z^{\text{inv}} < 3 \text{ MeV} \quad (95\% \text{ CL}). \tag{11}$$

As we see, only a small number of points (corresponding to very low μ and particularly light $\widetilde{\chi}_1^0$ masses) is excluded by this observable.[6] A similar constraint from $h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ will be discussed in section 5.1.

Flavor processes. Rare decays such as $B_s \to \mu^+\mu^-$, recently measured at $\approx 3\sigma$ by LHCb [28], the partially correlated processes of the kind $b \to s\gamma$, charged current processes like $B \to \tau\nu$ and $K \to \mu\nu$ set stringent constraints on supersymmetric models with large $\tan\beta$ [50, 51] (for a discussion in the context of light neutralino DM, see [23]). Nevertheless, these processes are mediated by the charged or CP-odd Higgs boson (and also squarks in the case of $b \to s\gamma$), hence the rates depend on the mass-scale of the extended Higgs sector (and squarks). These parameters can be set to arbitrarily high values, as the $\widetilde{\chi}_1^0$ annihilation cross-section is not affected by them. As a consequence, in general flavor processes do not constrain the light neutralino parameter space we consider here.

LHC searches. Recent limits from chargino searches in multi-leptons + missing transverse energy $\not{E}_T$ events at the LHC [4, 3] depend on the mass of the first and second generation sleptons and assume wino-like charginos. Hence they do not apply to our scenario. Bounds from LHC searches based on at least one pair of hadronically decaying taus [10] are not applied to the scan we are presenting. They will be discussed in detail in the next sections.

The resulting parameter space compatible with light neutralino dark matter and the bounds listed above is shown in Fig. 3, for the physical masses $m_{\widetilde{\tau}_1}$ and $m_{\widetilde{\chi}_3^0}$. Again the orange points correspond to $m_{\widetilde{\chi}_1^0} \leq 30$ GeV, the blue points to $m_{\widetilde{\chi}_1^0} \leq 20$ GeV. The upper boundary of the relevant parameter space is set by the CMB constraint, Eq. (7), that requires low values for either $m_{\widetilde{\tau}_1}$ or $\mu \approx m_{\widetilde{\chi}_3^0}$. Hence, light neutralino dark matter implies upper bounds on the stau and Higgsino masses:

$$m_{\widetilde{\tau}_1} \lesssim 210 \text{ GeV}, \quad m_{\widetilde{\chi}_1^\pm} \approx m_{\widetilde{\chi}_2^0} \approx m_{\widetilde{\chi}_3^0} \lesssim 380 \text{ GeV}. \tag{12}$$

Notice that, below the threshold where $\widetilde{\chi}_{2,3}^0$ decays into a real stau are possible, some points are excluded by the limit from LEP neutralino searches stated in Eq. (9). This is a consequence of the fact that, as far as $\widetilde{\chi}_{2,3}^0$ decays into a real Z are kinematically allowed while the decays into a real stau are forbidden, one obtains $\text{BR}(\widetilde{\chi}_{2,3}^0 \to \widetilde{\chi}_1^0 Z) \approx 1$, so that the LEP bound is maximized. On the other hand, for very low $m_{\widetilde{\chi}_{2,3}^0}$, where this decay is not open, or where this decay competes with on-shell decays into staus, constraints from Eq. (9) vanish.

[6] We verified that these results are hardly affected by NLO corrections, as presented in Ref. [49], where a factor of 1/2 is missing in the tree-level result stated in Eq. (51).

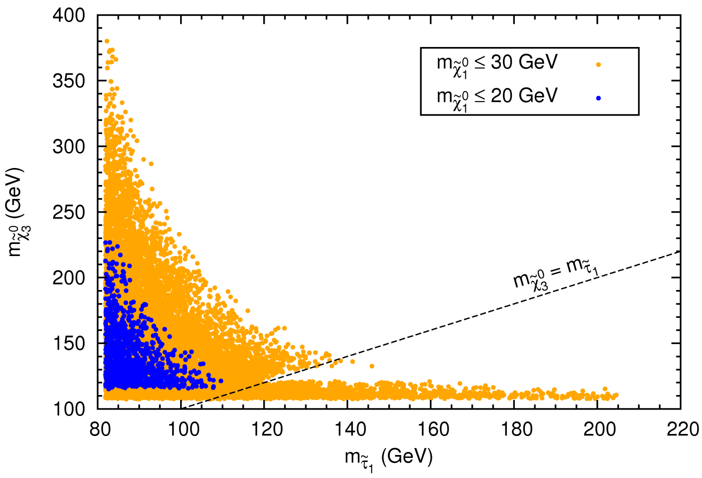

Figure 3: Viable parameter space after applying the constraints discussed in the text, displayed on the $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_3^0}$ plane.

In Fig. 4, the same parameter space is shown in the $\tan\beta - m_{\tilde{\chi}_1^0}$ plane. Different ranges for μ are displayed in different colors. As a consequence of the Higgsino contribution to the $\tilde{\chi}_1^0$ annihilation, the larger $\tan\beta$ is, the smaller $m_{\tilde{\chi}_1^0}$ can be. Taking $\tan\beta < 60$ GeV, required for perturbativity of the bottom Yukawa coupling, one then gets the following lower bound on the mass of neutralino dark matter:

$$m_{\tilde{\chi}_1^0} \gtrsim 11 \text{ GeV}. \tag{13}$$

From the figure we see that neutralino masses close to this lower limit require a particularly light Higgsino sector, namely $\mu \lesssim 150$ GeV.

In sections 4-6, we are going to discuss the consequences for SUSY searches at the LHC of the spectrum discussed above, including all constraints listed here. But first, let us briefly discuss the possible impact of direct and indirect DM searches on the light neutralino parameter space.

3.2 Direct and indirect Dark Matter searches

Several works have been recently dedicated to light neutralinos (see e.g. [20, 21, 22, 19, 23, 36, 52]), aiming at a possible explanation of the annual modulation signal at DAMA/LIBRA [12, 13] and also reported by CoGeNT [14] and the excess of nuclear recoil events observed by CoGeNT itself and CRESST [15]. Recently, three signal events have been also reported by CDMS [16]. Although the situation is not conclusive yet (the above claims are not consistent with the XENON100 results [27] and do not even seem to be perfectly compatible with each other [53, 54, 55]), the above results might be broadly accounted for by a light WIMP with a mass in the range of $\mathcal{O}(10)$ GeV and a spin-independent (SI) elastic DM-nucleon cross-section, $\sigma_{\rm SI}$, of the order of 10^{-42} to 10^{-40} cm^2. As previously mentioned, it is not possible to realize

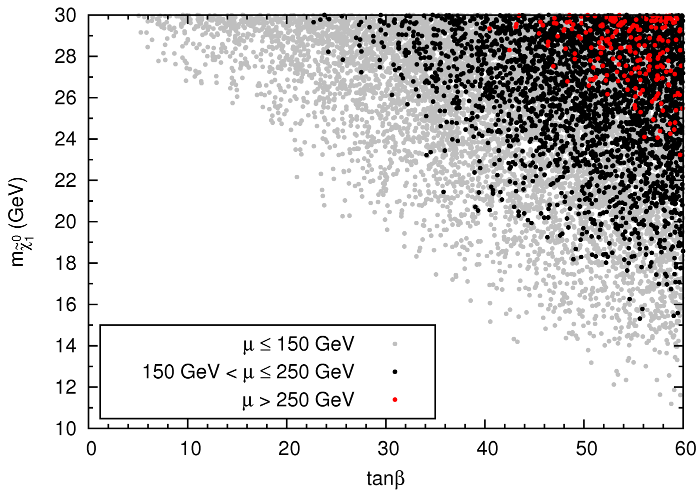

Figure 4: Viable parameter space after applying the constraints discussed in the text, displayed on the $\tan\beta - m_{\tilde{\chi}_1^0}$ plane.

the above configuration within the MSSM [23, 24, 22]: in fact, such a relatively large spin-independent cross-sections require a light extended Higgs sector, which is now excluded for moderate to large $\tan\beta$ by (i) searches at the LHC for extra Higgs bosons decaying into pairs of taus [25, 26], and (ii) the recent observation of the decay $B_s \to \mu^+\mu^-$ at LHCb [28] with a branching fraction compatible with the SM prediction [56].

Direct detection experiments might still set relevant constraints on the region we are exploring, as there is an irreducible contribution to $\sigma_{\rm SI}$ mediated by the exchange of the light Higgs h, whose coupling with the lightest neutralino is set by the relic density bound. Other contributions, such as the squark-mediated ones, are model-dependent as they are controlled by parameters that are not constrained by $\Omega_{\rm DM}$. The calculation of the scattering cross-section is still affected by a residual model dependence, coming from the fact that the decoupling of the contribution mediated by the heavy CP-even Higgs H is very slow: in fact both h and H contributions are enhanced by a small value of μ (that implies a large Higgsino component in $\tilde{\chi}_1^0$), though solely the H contribution is enhanced by large $\tan\beta$. Therefore, if one keeps, as in our scan, $m_H \approx m_A \approx \mathcal{O}(1)$ TeV (which might be a reasonable choice in the light of our SUSY spectrum) and large values of $\tan\beta$ (as required by the relic density constraint), the size of the two contributions is comparable, and the SI cross-section can be a powerful probe of the corner of the parameter space with small values of μ. Indeed, such a region is difficult to directly probe at the LHC, as we will see in section 6. As an illustration, in the left panel of Fig.5 we plot $\sigma_{\rm SI}$ (weighted by $\xi \equiv \Omega_{\rm DM}h^2/0.119$) versus $m_{\tilde{\chi}_1^0}$ for $m_A = 2$ TeV and the default `micrOMEGAs` value of the quark masses and the hadronic matrix elements.[7] As we can see, XENON100 already represents a relevant constraint on the light neutralino parameter space and the expected sensitivity of XENON1T has the potential of completely testing our scenario.

[7] A variation of these parameters in the ranges reported in Ref. [40] can lower the prediction for $\sigma_{\rm SI}$ by about a factor of two.

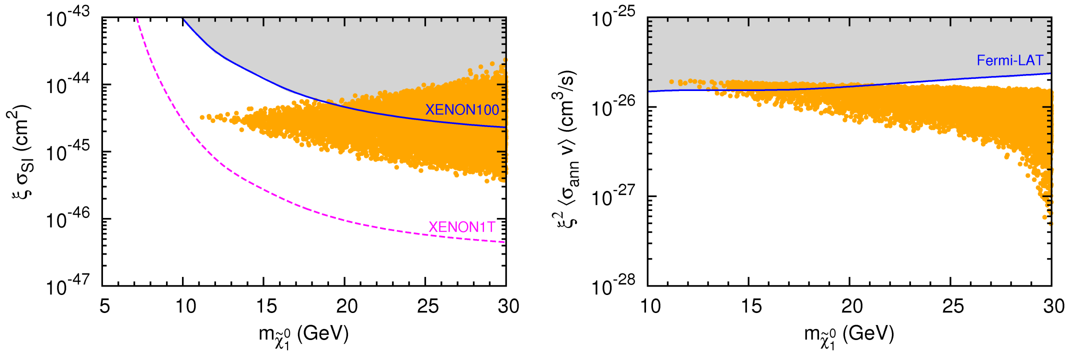

Figure 5: Model predictions and experimental limits on the SI scattering cross-section with nuclei (left panel) and the velocity-averaged annihilation cross-section (right panel) as a function of $m_{\widetilde{\chi}_1^0}$. The rescaling factor $\xi \equiv \Omega_{\rm DM}h^2/0.119$ is taken into account. See the text for the details.

We checked, however, that, if we allow m_A to be $\mathcal{O}\,(10)$ TeV, the H contribution would finally decouple and the SI cross-section would be decreased by almost a factor of three, so that most of the points would escape from the XENON100 bound, although probably still being within the future XENON1T sensitivity.

Contrary to $\sigma_{\rm SI}$, the prediction for the spin-dependent (SD) cross-section, $\sigma_{\rm SD}$, is much more robust, as the relevant dimension-6 operator $\bar{\widetilde{\chi}}_1^0\gamma^\mu\gamma_5\widetilde{\chi}_1^0\;\bar{q}\gamma_\mu\gamma_5 q$ is in our case mediated by a Z exchange, which at leading order does not depend on the SUSY parameters except for the neutralino mixing parameters. Bounds on the $\sigma_{\rm SD}$ from direct detection experiments such as PICASSO [57], COUPP [58], SIMPLE [59], KIMS [60] IceCube [61], XENON100 [62] (see also [63]) and the Baksan Neutrino Observatory [64] are not much constraining yet for light neutralino DM. Nevertheless, LHC searches for events with a monojet plus missing transverse momentum [65, 66] can be translated into bounds on neutralino-nucleon scattering cross-sections [67, 68, 69, 70]. In the case of the operator given above, the bounds on $\sigma_{\rm SD}$ translated from the monojet searches are much stronger than the ones obtained from underground direct DM detection experiments. As we are going to see in section 5.2, searches for monojet events performed by CMS and ATLAS might set a strong constraint on the small-μ region of the parameter space.

Let us now briefly discuss indirect detection limits. Our scenario predicts as a unique annihilation channel $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to \tau^+\tau^-$. The most stringent bound on this channel is provided by the observation of gamma-rays from satellite galaxies performed by the Fermi-LAT collaboration [71]. The limit is shown in the right panel of Fig. 5 and it is compared with our parameter space prediction for the velocity-averaged annihilation cross-section (weighted by ξ^2) as computed with `micrOMEGAs`. As we can see, the Fermi-LAT limit slightly increases the lower bound of the neutralino mass to about 13 GeV. Still, a conservative estimate of about 30% of possible uncertainties affecting the theoretical computation and the experimental limit could easily make such a bound milder. Nevertheless, the model predictions lie certainly on the border of the current Fermi-LAT sensitivity so that the light neutralino scenario might be tested independently in the near future by gamma-ray observations.

A detailed discussion of experimental and theoretical uncertainties affecting direct and indirect DM searches is beyond the scope of this paper. What we can conclude from this brief discussion is that direct and indirect DM searches are approaching the sensitivity for testing the light neutralino scenario, so that we can expect this to be achieved in the upcoming years, but at the moment we can conservatively consider most of our parameter space unconstrained by such searches. Therefore, we are not going to impose the bounds from XENON100 and Fermi-LAT further in this study and concentrate on the constraints that can be obtained from the LHC data.

4 Spectrum and LHC phenomenology

As illustrated in the previous sections, light neutralino DM in the MSSM is only consistent with WMAP and Planck observations in a region of the parameter space with peculiar features: a small soft mass for the right-handed stau, a small Higgsino mass parameter μ and moderate to large $\tan\beta$. This leads us naturally to the following spectrum at the electroweak scale: besides the lightest neutralino that is assumed to have mass $m_{\widetilde{\chi}_1^0} \lesssim 30$ GeV, there are only the lighter stau (mainly right-handed), the Higgsino-dominated neutralinos $\widetilde{\chi}_{2,3}^0$, and the lighter chargino $\widetilde{\chi}_1^\pm$, which take masses that are not much above ≈ 100 GeV. More specifically, these states are assumed to be in the range between the LEP lower bounds given in Eq. (8) and the upper limits given in Eq. (12), i.e. 94 GeV $< m_{\widetilde{\chi}_1^\pm} <$ 380 GeV. All the other states (in particular the strong-interacting superpartners) play no role in satisfying the relic density constraint and can be in principle too heavy to be detected by LHC experiments. Still, direct electroweak production for $\widetilde{\tau}_1$, $\widetilde{\chi}_{2,3}^0$ and $\widetilde{\chi}_1^\pm$ with masses of $\mathcal{O}(100)$ GeV can be sizeable, with cross-sections up to the pb level for proton-proton collisions at $\sqrt{s} = 14$ TeV [72, 73]. This represents the only unavoidable contribution to the total SUSY production in our scenario. In order to test light neutralino DM at the LHC, it is therefore sufficient to consider the particle content described above with the following electroweak Drell-Yan production modes:

$$pp \to \widetilde{\tau}_1^+ \widetilde{\tau}_1^- + X, \quad pp \to \widetilde{\chi}_i^0 \widetilde{\chi}_j^0 + X, \quad pp \to \widetilde{\chi}_i^0 \widetilde{\chi}_1^\pm + X, \quad pp \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^- + X, \tag{14}$$

where $i, j = 2, 3$. The decays of these particles clearly depend on the detail of the spectrum.

Let us first consider the hierarchy depicted in Fig. 6, i.e.,

$$m_{\widetilde{\chi}_1^\pm} \simeq m_{\widetilde{\chi}_{2,3}^0} > m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}_1^0}\,,$$

that we typically observe in the parameter region consistent with Planck (cf. the points above the dashed-line in Fig. 3). In this case the stau decays with almost 100% probability into a tau lepton and the LSP,

$$\widetilde{\tau}_1^\pm \to \tau^\pm \widetilde{\chi}_1^0 \quad [\mathrm{BR} \approx 100\%]. \tag{15}$$

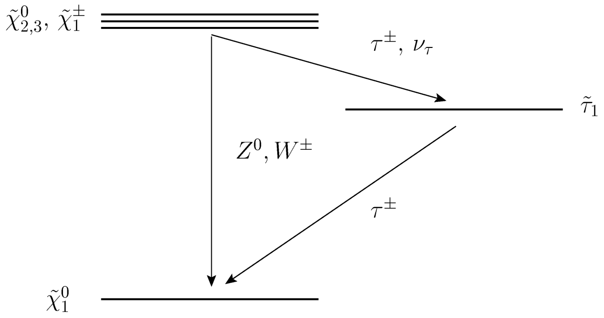

Figure 6: A typical mass spectrum of the light neutralino dark matter scenario. The shown particles masses are mainly controlled by three SUSY parameters: M_1, $m_{\tilde{\tau}_R}$, and μ. All the other fields are assumed to be heavy.

Charginos and heavier neutralinos can instead decay first to an on-shell stau,

$$\widetilde{\chi}^0_{2,3} \to \tau^\mp \widetilde{\tau}^\pm_1 \quad [\text{BR} \approx 90\%], \tag{16}$$

$$\widetilde{\chi}^\pm_1 \to \nu_\tau \widetilde{\tau}^\pm_1 \quad [\text{BR} \approx 75\%], \tag{17}$$

where in parenthesis we show typical values for the branching fractions for the case $m_{\widetilde{\chi}^\pm_1} \simeq m_{\widetilde{\chi}^0_{2,3}} > m_{\widetilde{\tau}_1}$, as computed with the `SUSY-HIT` package [45]. The other possible channels are $Z\widetilde{\chi}^0_1$ for the neutralinos and $W^\pm\widetilde{\chi}^0_1$ for the chargino. From the above, we see that the pair production of Higgsino-like neutralinos can lead with high probability ($\approx 80\%$) to a striking $4\tau + \not{E}_T$ signal at the LHC from the decay chain:

$$\widetilde{\chi}^0_{2,3} \to \tau^\mp \widetilde{\tau}^\pm_1 \to \tau^\mp \tau^\pm \widetilde{\chi}^0_1. \tag{18}$$

Still, event rates for such a signature are suppressed by hadronic tau reconstruction efficiencies, which are typically of the order of $25 \div 40\%$ for each hadronic tau τ_h. Similarly, $\widetilde{\chi}^0_{2,3}\widetilde{\chi}^\pm_1$ production gives about 70% of times events with $3\tau + \not{E}_T$. Other combinations of production and decay modes result in a smaller number of taus (e.g. two from $\widetilde{\chi}^+_1\widetilde{\chi}^-_1$ production followed by $\widetilde{\chi}^\pm_1 \to \widetilde{\tau}^\pm_1 \nu_\tau$), hence they are, in principle, more difficult to disentangle from the SM background. For instance, production and decays of SM gauge bosons and $t\bar{t}$ can copiously give signatures like $2\tau + \not{E}_T$. Nevertheless, the m_{T2} cut, we are going to discuss in the next section, turns out to be very efficient in discriminating between signal and background also in this case. Moreover, we expect a very large number of such events as several combinations of production and decay modes contribute to this category. Thus, $2\tau + \not{E}_T$ events also have an important role in testing our scenario.

Let us now consider the case that neutralinos cannot decay to a real stau:

$$m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}^0_{2,3}} > m_{\widetilde{\chi}^0_1} \quad \text{or} \quad m_{\widetilde{\chi}^0_3} > m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}^0_2} > m_{\widetilde{\chi}^0_1}.$$

Such hierarchies are consistent with the relic density bound in a corner of the parameter space, as shown with the points below the dashed-line in Fig. 3. The 3-body decays $\widetilde{\chi}^0_{2,3} \to \tau^+\tau^-\widetilde{\chi}^0_1$

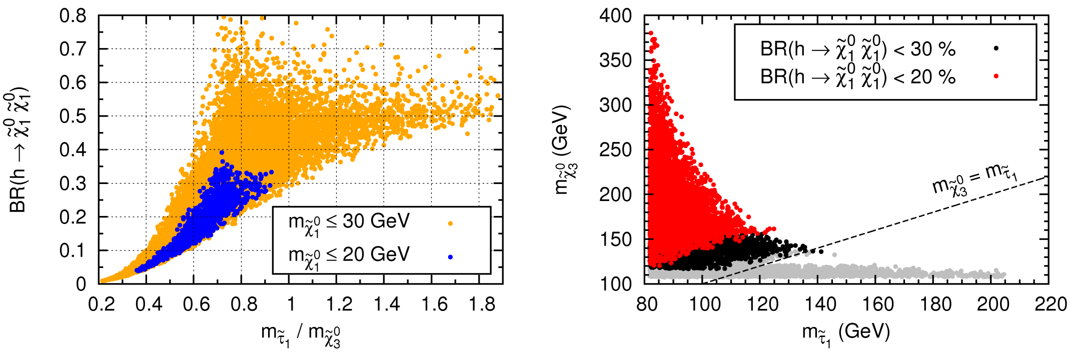

Figure 7: Left: $\mathrm{BR}(h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$ versus the mass ratio $m_{\widetilde{\tau}_1}/m_{\widetilde{\chi}_3^0}$, all the constraints of section 3.1 are applied. Right: different values for $\mathrm{BR}(h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$ displayed on the same $m_{\widetilde{\tau}_1} - m_{\chi_3}$ plane of Fig. 3.

through an off-shell $\widetilde{\tau}_1$ can still give multi-tau events. In this case, the exact branching ratios depend on the masses of the other sfermions that can mediate 3-body decays at comparable rates even if much heavier than $\widetilde{\tau}_1$. We checked that even for squarks and sleptons above the TeV scale, the branching ratio $\mathrm{BR}(\widetilde{\chi}_{2,3}^0 \to \tau^+\tau^-\widetilde{\chi}_1^0)$ does typically not exceed the $15 \div 20\%$ level. Furthermore, the decay of $\widetilde{\chi}_{2,3}^0$ into $\widetilde{\chi}_1^0 Z$ will dominate, if kinematically allowed. This further suppresses a possible multi-tau signal. However, corresponding parameter regions are partly already covered by the limit stated in Eq. (9). The remaining corner of this parameter region at very small μ should be much more difficult to directly probe at the LHC. Nevertheless, other LHC observables already disfavor this scenario, as we illustrate in the following.

5 Limits from $h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ and monojet searches at the LHC

5.1 Invisible Higgs decays

As discussed in section 3, relic density constraints require sizeable Higgsino components in $\widetilde{\chi}_1^0$ that can induce large branching ratios for the decay $h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ [74, 75, 47]. This is in particular the case for heavier $\widetilde{\tau}_1$ and thus for the hierarchy $m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}_{2,3}^0} > m_{\widetilde{\chi}_1^0}$. Here, fulfilling the relic density bound requires a larger Higgsino component (small μ) to contribute to $\widetilde{\chi}_1^0$ annihilation. The light Higgs decay width into the lightest neutralinos is given by [74]:

$$\Gamma(h \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0) = \frac{G_F M_W^2 m_h}{2\sqrt{2}\pi}\left(1 - \frac{4m_{\widetilde{\chi}_1^0}^2}{m_h^2}\right)^{3/2} \left|C_{h\widetilde{\chi}_1^0\widetilde{\chi}_1^0}\right|^2 , \tag{19}$$

where in the decoupling regime $m_A \gg m_h$

$$C_{h\widetilde{\chi}_1^0\widetilde{\chi}_1^0} = \left(N_{12} - \tan\theta_W\ N_{11}\right)\left(\sin\beta\ N_{14} - \cos\beta\ N_{13}\right) . \tag{20}$$

Thus, we see that, in contrast to $\Gamma(Z \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0)$, the contribution from the $\widetilde{H}_u$ component is dominant as it is $\tan\beta$ enhanced with respect to the $\widetilde{H}_d$ one.

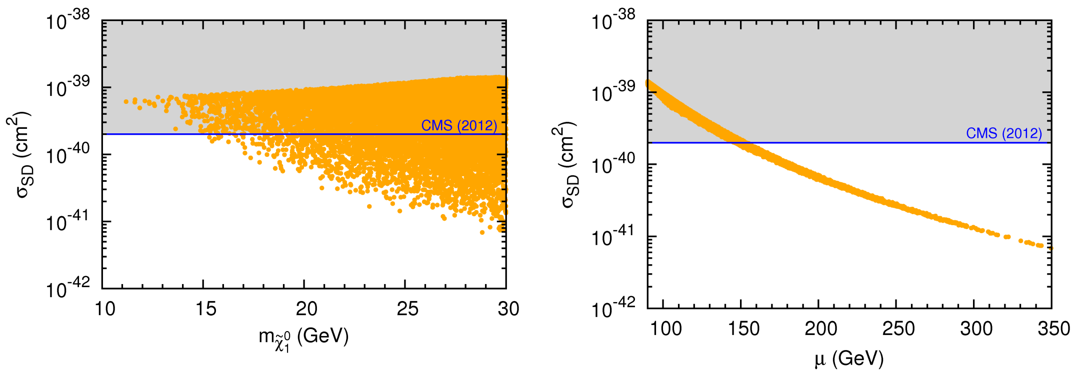

Figure 8: Model prediction for the SD scattering proton-neutralino cross-section as a function of the neutralino mass (left) and the Higgsino mass parameter μ (right), compared to the current bound from monojet searches at the LHC.

In Fig. 7 (left) we plot BR($h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$) versus $m_{\widetilde{\tau}_1}/m_{\widetilde{\chi}_3^0}$ using the parameter scan illustrated in section 3. BR($h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$) has been computed using `SUSY-HIT` [45]. We find that amost all the allowed points with $m_{\widetilde{\tau}_1}/m_{\widetilde{\chi}_3^0} > 1$ (i.e. the points below the dashed-line in the right plot of Fig. 7) correspond to a branching ratio larger than 30%. This is to be compared to the constraints from fits of $\text{BR}_h^{\text{inv}} \equiv \text{BR}(h \to \text{invisible})$ to the observed Higgs decay rates [76, 77]:

$$\text{BR}_h^{\text{inv}} \lesssim 20\% \quad (95\% \text{ CL}). \tag{21}$$

From this we see that the case $m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}_{2,3}^0}$ is strongly disfavored, while $m_{\widetilde{\chi}_{2,3}^0} > m_{\widetilde{\tau}_1}$ is still viable but partly constrained, as shown in Fig. 7 (right).[8]

5.2 Monojet searches

As anticipated in section 3.2, direct DM searches at the LHC, based on monojet + $\not{E}_T$ events, can be displayed as limits on the neutralino scattering cross-section with nuclei. As we discussed above, the prediction for the spin-dependent cross-section, σ_{SD}, is not too sensitive to the SUSY spectrum under consideration. Indeed, the effective proton-neutralino interaction is mediated by a Z boson and hence is solely determined by the size of the Higgsino components in $\widetilde{\chi}_1^0$. We expect that the larger the components are – corresponding to small values of μ –, the stronger the bound from LHC searches becomes. We computed σ_{SD} by means of `micrOMEGAs`, checking that variations of the hadronic matrix elements affect the results only at the level of $10 \div 12$ %.In the interpretation of the ATLAS [65] and CMS [66] analyses – the latter giving a slightly stronger limit – in terms of σ_{SD}, we take into account the fact that neutralinos are Majorana particles and thus the published limits are in our case weaker by a phase-space factor of two [79, 80].

The result is shown in Fig. 8, from which we see that the parameter space is considerably constrained by the monojet data. In particular, the lower bound of the neutralino mass (left

[8] See, however, the more conservative bound obtained in Ref. [78], considering large theoretical uncertainties: $\text{BR}_h^{\text{inv}} \lesssim 52\%$ (68% CL).

panel) is raised to

$$m_{\tilde{\chi}_1^0} \gtrsim 15 \text{ GeV} \tag{22}$$

and points with low values of the Higgsino mass – namely $\mu \lesssim 150$ GeV – are excluded (right panel). As in the case of the invisible Higgs decay discussed above, this observable is therefore complementary to the multi-tau searches in testing the light neutralino scenario: in fact, the parameter region with $m_{\tilde{\tau}_1} > m_{\tilde{\chi}^0_{2,3}}$, which is kinematically unfavorable for the multi-tau searches, requires $\mu \approx 100 \div 130$ GeV (cf. Fig. 3). From the comparison between Fig. 3 and the left panel of Fig. 8, it is reasonable to conclude that the null result of the monojet searches at the LHC would not be compatible with the parameter region of the light neutralino dark matter scenario with $m_{\tilde{\tau}_1} > m_{\tilde{\chi}^0_{2,3}}$. However, for a conclusive statement of the potential of the LHC monojet searches on direct neutralino production and its relation with direct dark matter detection limits, a detailed study beyond the effective field theory approximation[9] carried out here is necessary.

6 LHC multi-tau limits

6.1 ATLAS multi-tau analysis and Monte Carlo framework

Recently the ATLAS collaboration presented a (preliminary) analysis of a search for new physics in a final state with multi-taus and large missing transverse energy [10] employing a data sample of 20 fb^{-1} at $\sqrt{s} = 8$ TeV. In Ref. [10] at least two reconstructed hadronic taus are required together with a missing transverse energy of $\not{E}_T > 40$ GeV; the final event selection and background suppression are based on a cut on m_{T2} [82, 83] and different jet vetoes. Resulting limits are presented in different simplified models and a parameter region of the "phenomenological MSSM" (pMSSM) with light charginos, neutralinos and staus. The presented analysis is inclusive in the number of reconstructed hadronic taus and relevant for the light neutralino scenario investigated in this study. In the following we reproduce the pMSSM limits presented in Ref. [10] and reinterpret them in the light neutralino parameter space discussed above.

For the signal event simulation we use `Herwig++` [84] and include production of neutralinos, charginos and sleptons. For any scenario we consider, squarks and gluinos are assumed to be heavy and their productions do not contribute. Everywhere full spin correlations in the decays, initial-state-radiation (ISR), final-state-radiation (FSR), hadronization effects, and underlying-event-simulation are included. Obtained event samples are normalized to inclusive NLO cross-sections calculated with `Prospino 2` [85]. Via the `HepMC` format [86] signal events are passed to `Delphes 3` [87] for (fast) detector simulation and event reconstruction. We use the default ATLAS detector card within `Delphes 3` and tune all efficiencies to the values given in Ref. [10]. Signal events are reconstructed and selected, as in Ref. [10], according to the following criteria. Light central jets are required to have transverse momentum $p_j^{\mathrm{T}} > 25$ GeV and pseudorapidity $|\eta_j| < 2.5$. Forward jets must satisfy $p_{j_f}^{\mathrm{T}} > 30$ GeV and $2.5 < |\eta_{j_f}| < 4.5$. For tagged b-jets

[9]For a recent study about the limits of such an approximation, we refer to [81].

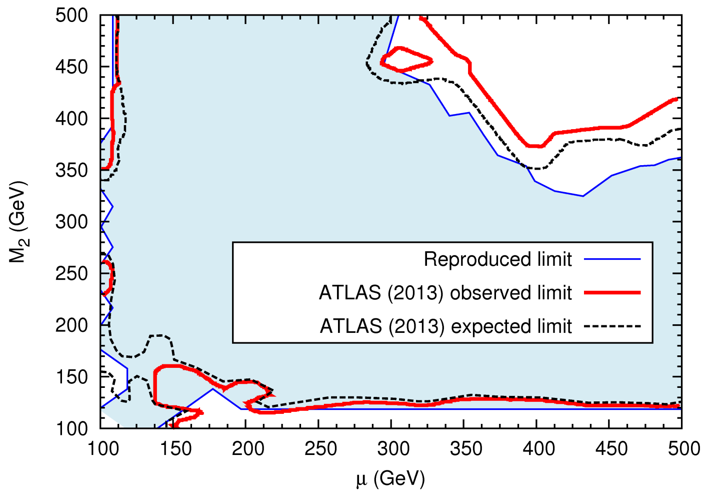

Figure 9: Excluded regions in the $M_2-\mu$ parameter plane of the pMSSM. The bounds obtained by [10] and the limits reproduced by our simulation are shown.

we require $p_{j_b}^{\mathrm{T}} > 20$ GeV and $|\eta_{j_b}| < 2.5$. For electrons and muons we require $p_l^{\mathrm{T}} > 10$ GeV, and $|\eta_e| < 2.47$ and $|\eta_\mu| < 2.4$, respectively. Hadronic tau candidates are required to have $p_{\tau_h}^{\mathrm{T}} > 20$ GeV and $|\eta_j| < 2.5$. Now we select events with at least two opposite sign (OS) taus. Additional light leptons are vetoed and we require $\not{E}_T > 40$ GeV. The variable m_{T2} is calculated using [88] and the assumed mass of the neutralino is set to $m_{\mathrm{inv}} = 0$. In events where more than two taus are reconstructed, m_{T2} is computed taking all possible OS tau pairs into account and then choosing the largest value. For the final event selection two signal regions are defined as in Ref. [10]:

- SR1: veto of central light jets and forward jets, and a cut on $m_{T2} > 90$ GeV,
- SR2: veto of b-jets, and a cut on $m_{T2} > 100$ GeV.

In these signal regions the analysis presented in Ref. [10] sets at 95% CL the following limits on the number of signal events:

$$S_{\mathrm{SR1}}^{95} < 5.6 \qquad \text{and} \qquad S_{\mathrm{SR2}}^{95} < 10.4\,. \tag{23}$$

These limits are then interpreted in an $M_2 - \mu$ plane of the pMSSM with $\tan\beta = 50$, $M_1 = 50$ GeV and $m_{\tilde{\tau}_R} = 84.7$ GeV (together with $A_\tau = 5$ TeV this yields a lighter stau mass of $m_{\tilde{\tau}_1} \approx 95$ GeV). All other parameters are decoupled.

With our Monte Carlo framework we perform a scan in the very same pMSSM plane and compare the resulting number of signal events with the above stated limits at 95% CL. The result is shown in Fig. 9. Besides the exclusions obtained with our framework we show the expected and observed exclusions of Ref. [10]. The agreement between the reproduced exclusions and the ones given in Ref. [10] seems to be sufficient in order to allow a reinterpretation of the underlying limits in the light neutralino parameter space.

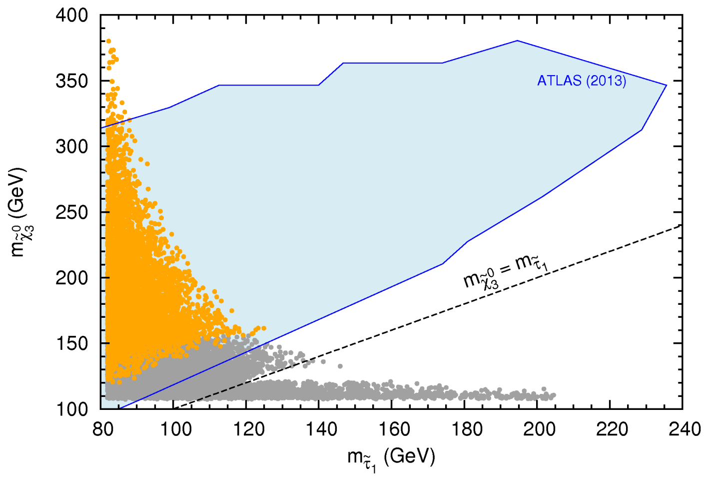

Figure 10: Region excluded by ATLAS in the $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_3^0}$ parameter plane. The light neutralino parameter space is also shown: the gray points fulfill the constraints of section 3.1, the orange points additionally give $\text{BR}(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 20\%$, see section 5.1.

6.2 Interpretation for the light neutralino scenario

As discussed in detail in section 4, we expect striking multi-tau signals for the considered light neutralino parameter space, and consequently possibly strong constraints on this parameter space from the ATLAS analysis in Ref. [10]. In Fig. 10 we reinterpret the limits of [10] in the $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_3^0}$ plane discussed above. In this reinterpretation, we set $\tan\beta = 55$, $M_1 = 30$ GeV, and as before all other mass parameters with the exception of the relevant stau and Higgsino masses are assumed to be heavy. We checked that limits for an even lighter neutralino are at least as strong as the obtained ones. Moreover, the limits obtained for our simplified model do hardly depend on the choice of $\tan\beta$. From the figure, we see that parameter regions with $m_{\tilde{\chi}_3^0} > m_{\tilde{\tau}_1}$, where the heavier neutralinos can decay into on-shell lighter staus are excluded up to $m_{\tilde{\chi}_1^\pm} \approx m_{\tilde{\chi}_{2,3}^0} \gtrsim 320$ GeV. For $m_{\tilde{\chi}_3^0} \lesssim m_{\tilde{\tau}_1}$ decays of the heavier neutralinos into taus are only possible via off-shell decays, where various decay modes compete and corresponding exclusions limits are much weaker. However, as discussed in section 5.1 and 5.2, such parameter regions are strongly disfavored by recent limits on the invisible width of the light Higgs, h, and potentially by monojet searches at the LHC. In Fig. 10 the orange points give $\text{BR}(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 20\%$ (cf. the right panel of Fig. 3), while the gray points fulfill the relic density constraints (and the other constrains introduced in section 3.1). Additionally, in the region where $m_{\tilde{\chi}_{2,3}^0} - m_{\tilde{\chi}_1^0} > m_Z$ limits from dedicated searches in final states with SM gauge bosons and missing transverse energy could become relevant [89, 90]. Still, in the light neutralino scenario this is a very small parameter region. Multi-tau searches with higher luminosity and center-of-mass energy $\sqrt{s}$, in combination with monojet searches and Higgs decay measurements, are the most promising way to test light neutralino DM up to $m_{\tilde{\chi}_1^0} \approx 30$ GeV. Indeed, only a tiny corner of the parameter space is left unprobed by the different experimental information discussed above: this is better depicted in Fig. 11, where we show the impact of the ATLAS limit on the $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ plane.

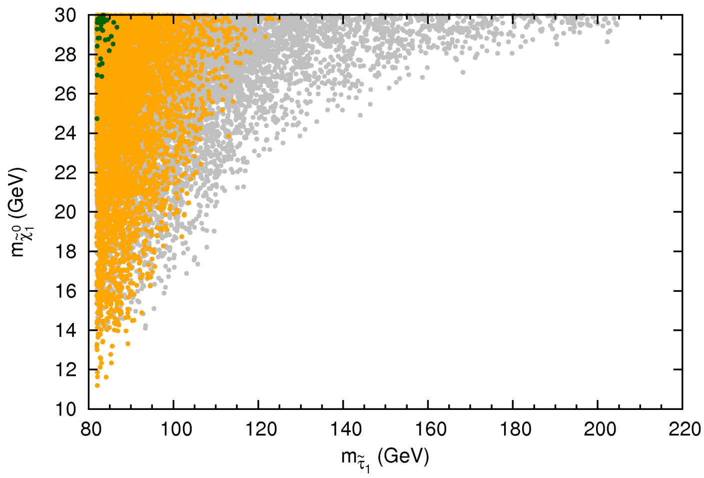

Figure 11: Summary of the LHC searches in $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ plane: the gray points fulfill the constraints of section 3.1, the orange points correspond to $\mathrm{BR}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) < 20\%$, the dark-green points evade the ATLAS multi-tau limit of Fig. 10.

As in Fig. 10, the gray points fulfill the constraints discussed in section 3.1 and the orange points additionally correspond to $\mathrm{BR}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) < 20\%$. The dark-green points are the only ones left after the ATLAS multi-tau search. This allows us to set the present lower bound on the neutralino mass – assuming Eqs. (7) and (21) – at about

$$m_{\tilde{\chi}_1^0} > 24 \div 25 \text{ GeV}. \tag{24}$$

In addition, we see that the few points left require a very light stau with $m_{\tilde{\tau}_1} \lesssim 90$ GeV, a value very close to the LEP exclusion limit reported in Ref. [8].

7 Summary and conclusions

In this paper, we have shown that, assuming a light neutralino as DM candidate and the particle content of the MSSM, the bounds from the DM relic abundance can be fulfilled only in a limited and well-defined region of the parameter space. For a mass of the lightest neutralino smaller than about 30 GeV a handful of parameters suffices to define this parameter space. In turn, this allows to employ current searches for SUSY at the LHC to set definite limits on light neutralino DM and give a lower bound on its mass.

The allowed region of the parameter space is characterized by a relatively light right-handed stau, a light Higgsino-dominated chargino and light Higgsino-dominated neutralinos, cf. Eq. (12). Therefore, the recent search for multi-tau + $\not{E}_T$ events performed by the ATLAS collaboration [10] can be interpreted as a test of the light neutralino DM scenario. By means of a Monte Carlo simulation including fast detector simulation, we have shown how this ATLAS analysis strongly constrains the relevant parameter space. We have also highlighted the complementarity of such tests with other new physics observables at the LHC like the search for the decay $h \to$ invisible, or searches in the monojet + $\not{E}_T$ channel. In combination with this experimental information, the multi-tau ATLAS search excludes most of the parameter space with $m_{\tilde{\chi}_1^0} < 30$ GeV, setting a lower bound on the neutralino DM mass: $m_{\tilde{\chi}_1^0} > 24 \div 25$ GeV. The plots in Figs. 10 and 11 present our final results and show how tiny the remaining parameter space is. Clearly, a small increase of the sensitivity in this channel at the future $\sqrt{s} = 13 \div 14$ TeV run of the LHC can completely test the light neutralino DM scenario up to $m_{\tilde{\chi}_1^0} \approx 30$ GeV.

Larger values of the lightest neutralino mass cannot be probed in such a unique way: in fact, as we argued in section 2, $m_{\tilde{\chi}_1^0} > 30$ GeV would open the possibility of satisfying the relic density constraints with compressed spectra that can, at the same time, (i) evade the LEP searches for light sfermions, (ii) be insensitive to constraints from Z-pole observables, (iii) be very hard to be tested at the LHC. Furthermore, for even larger $m_{\tilde{\chi}_1^0}$, a very efficient neutralino annihilation would be possible through resonant Z and/or h exchange that would just require non-vanishing Higgsino components in $\tilde{\chi}_1^0$. A detailed discussion of such possibilities is beyond the scope of this paper and will be given elsewhere.

A crucial assumption leading to the above results is that the lightest neutralino constitutes (mainly) the observed DM in the universe. Dropping such a hypothesis, as for instance in models with (small) R-parity violation, would clearly change completely the discussion on how light the neutralino can be. Corresponding phenomenology at colliders could be very different, e.g. in the case of a promptly decaying neutralino. For early discussions on (very) light neutralinos without cosmological bounds, we refer to Refs. [91, 92] and references therein.

Concerning direct underground DM searches, we have shown in section 3.2 that the scattering cross-sections with nuclei predicted in the present scenario are in the range 10^{-43} cm$^2 \lesssim \sigma_{\rm SI} \lesssim 10^{-46}$ cm^2. This implies that (i) light MSSM neutralinos cannot account for the signals reported by several direct detection experiments, (ii) the scenario we discussed has cross-sections close to the current XENON100 sensitivity and will be fully tested independently by XENON1T (cf. the left panel of Fig. 5). Similar conclusions can be drawn for indirect searches: the light neutralino scenario lies close to the border of the current Fermi-LAT sensitivity. Thus, it might be complementary tested in the near future also by gamma-ray observations (cf. Fig. 5, right).

To conclude, let us remark that the presented study provides an example of the amazing capability of the LHC experiments to test new physics through pure electroweak interactions, as well as of the complementarity of different collider searches and other experimental information (CMB observations, direct/indirect DM searches, etc.) in shedding light on nature and properties of dark matter and physics beyond the Standard Model in general.

Acknowledgments

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