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Testing the light dark matter scenario of the MSSM at the LHC

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Abstract: In the light dark matter (DM) scenario of the MSSM, the DM relic density puts non-trivial requirements on the spectrum of supersymmetric particles. As a result, the direct search for multi-lepton signals at the LHC has great impact on the scenario. In this work, we concentrate on the searches for sleptons and electroweak-inos at the LHC, investigate their constraints on the light DM scenario with the 8 TeV LHC data, and also study their capability to test the scenario at the 14 TeV LHC. For this purpose, we first get the samples of the scenario by scanning the vast parameter space of the MSSM with various available constraints considered. Then for the surviving samples, we simulate the $2l+E_T^{\rm miss}$ signal from slepton pair production process and the $2l+E_T^{\rm miss}$ and $3l+E_T^{\rm miss}$ signals from chargino and neutralino associated production processes at both the 8 TeV LHC and the 14 TeV LHC. Our simulations indicate that the 8 TeV LHC data have excluded a sizable portion of the samples, and the capability of the 14 TeV LHC will be much more powerful in testing the scenario. For example, in case that no excess of the multi-lepton signals is observed at the 14 TeV LHC, most samples of the light DM scenario will be excluded, especially a lower limit on the lightest neutralino mass will be set at 42 GeV and 44 GeV with 30 fb^{-1} and 100 fb^{-1} data respectively, and this limit can be further pushed up to 55 GeV with 300 fb^{-1} data.

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Contents

1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) is one of the most promising new physics model beyond the Standard Model (SM), which can stabilize the electroweak (EW) scale, explain the cosmic dark matter (DM) and achieve the gauge coupling unification simultaneously [1–3]. In recent years, a large number of searches for the supersymmetric particles (sparticles) predicted by the MSSM have been performed at the LHC, and consequently much stronger limits on their spectrum than those from the LEP experiments have been obtained. For example, the null results in the searches for multi-jets plus large missing transverse energy ($E_T^{\rm miss}$) signal have set the lower mass bounds for colored sparticles at TeV scale, i.e. about 1.2 TeV and 0.8 TeV for gluino and degenerate first two generation squarks respectively in optimal cases [4, 5], and although the EW sparticles in the MSSM are less constrained due to their relatively small production rates, the mass limits can still be up to 300 GeV for the sleptons [6, 7] and 700 GeV for the charginos and neutralinos [7, 8]. More strikingly, with the recent operation of the LHC Run-II at $\sqrt{s} = 13$ TeV, it is widely expected that much heavier sparticles will be explored very soon, and this will provide us the opportunities to probe some fundamental questions such as the severe fine tuning problem suffered in the SM. Obviously, discussing the potential of the LHC experiments to detect the sparticles is an important task for both theorists and experimentalists. In fact, such studies have been intensively carried out, e.g. the prospect to search for the EW sparticles were recently discussed in [9–13].

In the MSSM with R-parity, the lightest neutralino $\tilde{\chi}_1^0$ is usually the lightest sparticle, and thus can act as a DM candidate [3]. So far the scenario featured by a moderately light DM has been studied comprehensively [14–46]. One motivation for doing this is that in some fundamental theories such as the minimal supergravity theories [47], the EW sparticles tend to be significantly lighter than the colored sparticles. This pattern of the sparticle spectrum does not conflict with any constraints from low energy processes as well as from the direct searches for the sparticles at the colliders. Instead, it is helpful to solve some experimental anomalies such as the discrepancy of the measured muon anomalous magnetic moment from its SM prediction and the Galactic Center γ-ray excess observed by the Fermi-LAT [48–51]. Another motivation for the scenario is that light higgsinos are the minimal tree-level requirement posed by naturalness. However, a light higgsino-like DM can not solely account for the observed DM relic density since it annihilated too efficiently in early universe [52]. Consequently, simultaneous presence of a light bino and the higgsinos, which mix to form a light DM, is the minimal ingredient of a natural MSSM [53]. In this work, we are particularly interested in the DM lighter than about 100 GeV. In this case, the chargino mass limits from the LEP experiments have required the DM to be bino-dominated. Then the weak interaction of the DM together with its sizable mass splittings from the other sparticles typically lead to the overproduction of the DM in the early universe, unless that an efficient annihilation mechanism was at work [41, 43]. This situation in turn imposes non-trivial requirements on the sparticle spectrum, which serve as an important supplement to the direct search for SUSY at colliders. As a result, only a small corner in the MSSM parameter space is pertinent to the scenario, which makes some signals of the sparticles at the LHC quite distinctive [41, 43]. So requiring $m_{\tilde{\chi}_1^0} \lesssim 100\,\text{GeV}$ is not only of theoretical interest, but also can simplify greatly our analysis to get somewhat definite conclusions.

Recent discussions on the light DM scenario concentrated on the complement of new experimental constraints, such as those from the 125 GeV Higgs data and the direct searches for sparticles at the LHC, and consequently the allowed parameter space of the scenario shrinks significantly [34–41, 43]. For example, it was found that the lower bound of $m_{\tilde{\chi}_1^0}$ could be improved from about 10 GeV to roughly 25 GeV after considering the searches for multi-τ plus large E_T^{miss} signal at the early stage of the LHC Run-I [34]. In this context, we will extend the latest analysis in this subject [43] by relaxing its assumptions on the parameters of the MSSM, and then scanning the vaster parameter space of the MSSM to get more general features of the scenario. We will also study the multi-lepton signals of the sparticles at the LHC, and investigate the capability of the machine to test the scenario. The latter study, especially discussing the sensitivity of the 14 TeV LHC to the scenario, is the main purpose of this work. We think such a study quite necessary due to following two reasons. One is that the light DM scenario as a natural realization of the MSSM is an important scenario, and therefore its exploration at future experiments should be studied in an elaborated way. As we will show below, if the DM is lighter than about 65 GeV, it must annihilate by s-channel exchange of a resonant Z boson or a resonant SM-like Higgs boson to get the measured relic density. In these cases, the effective coupling of the DM with nucleon usually drops drastically, and so is the rate of the DM annihilation in Galactic Center at present day. This will make the direct or indirect DM detection rather difficult. So exploring the scenario at future colliders as an alternative way to prob the scenario should be studied carefully. The second reason is that for most SUSY searches at the LHC, they rely to a great extent on large E_T^{miss} signal contributed by DM and also on the spectrum of light sparticles. Therefore deciphering the property of the light DM scenario, such as its mass spectrum and the interactions of the DM, is important for the searches. As we will show below, if the specific scenario is realized in nature, the future LHC experiment is very powerful to explore its properties, e.g. given that no SUSY signal is seen at the machine with 300 fb^{-1} integrated luminosity, the DM lighter than about 55 GeV is disfavored, and without the presence of light sleptons, its mass is fixed at about one half of the SM-like Higgs boson mass. Within our knowledge, these conclusions are rather new.

The rest of this paper is organized as follows. In section 2 we review the features of the electroweak-inos in the MSSM, and point out that the DM relic density can impose non-trivial constraints on the higgsino mass μ in light DM scenario. In section 3 we scan the parameter space of the MSSM by considering the constraints available in literatures to obtain the samples of the scenario. Then we pay special attention to the important constraints from the direct searches for $2l + E_T^{\rm miss}$ and $3l + E_T^{\rm miss}$ signals at the 8 TeV LHC by detailed simulation, and check whether the samples can survive them in section 4. In section 5 we extend the simulation study to the 14 TeV LHC and discuss its capability to prob the scenario. As a useful supplement to the direct searches, we also briefly examine the capabilities of the future DM direction experiments to detect the scenario in section 6. Finally, we draw our conclusions in section 7.

2 The electroweak-inos in the MSSM

In the MSSM, the fields bino $\tilde{B}^0$, wino $\tilde{W}^0$, and higgsinos $\tilde{H}_d^0$ and $\tilde{H}_u^0$ mix to form mass eigenstates, which are usually called neutralinos $\tilde{\chi}_i^0$ $(i = 1, \cdots 4)$. In the basis $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$, the mass matrix of the fields is given by

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}, \tag{2.1}$$

where M_1 and M_2 are the soft masses for bino and wino respectively, μ represents the higgsino mass, $c_\beta = \cos\beta$ and $s_\beta = \sin\beta$ with $\tan\beta \equiv v_u/v_d$ being the ratio of the vacuum expectation values of the two Higgs doublets. This mass matrix can be diagonalized by an unitary 4×4 matrix N so that the interactions of the neutralinos are given by

$$\begin{aligned} \mathcal{L}_{\tilde{\chi}^0} = {} & \tilde{l}_L^* \bar{\tilde{\chi}}_i^0 \left[\frac{e}{\sqrt{2} s_w c_w} (N_{i1} s_w + N_{i2} c_w) P_L + y_l N_{i3}^* P_R \right] l \\ & + \tilde{l}_R^* \bar{\tilde{\chi}}_i^0 \left[\frac{-\sqrt{2} e}{c_w} N_{i1}^* P_R + y_l N_{i3} P_L \right] l + \tilde{\nu}^* \bar{\tilde{\chi}}_i^0 \left[\frac{e}{\sqrt{2} s_w c_w} (N_{i1} s_w - N_{i2} c_w) P_L \right] \nu \\ & + \frac{e}{2 s_w} h \bar{\tilde{\chi}}_i^0 \Big[(N_{i2} - N_{i1} \tan\theta_w)(\sin\alpha N_{j3} + \cos\alpha N_{j4}) + (i \leftrightarrow j) \Big] \tilde{\chi}_j^0 \\ & + \frac{e}{s_w c_w} Z_\mu \bar{\tilde{\chi}}_i^0 \gamma^\mu (\mathcal{O}_{ij}^L P_L + \mathcal{O}_{ij}^R P_R) \tilde{\chi}_j^0 + \cdots, \end{aligned} \tag{2.2}$$

where y_l is the Yukawa coupling coefficient for the lepton l, h denotes the SM-like Higgs boson, $c_W = \cos\theta_W$, $s_W = \sin\theta_W$ and $\mathcal{O}^L_{ij} = -\mathcal{O}^{R*}_{ij} = -\frac{1}{2}N_{i3}N^*_{j3} + \frac{1}{2}N_{i4}N^*_{j4}$. The Lagrangian in eq. (2.2) indicates that the $Z\bar{\tilde{\chi}}^0_i\tilde{\chi}^0_j$ interaction is determined by the higgsino components of the neutralinos, and by contrast the $h\bar{\tilde{\chi}}^0_i\tilde{\chi}^0_j$ interaction is determined by the product of the gaugino component for one of the neutralinos and the higgsino component for the other neutralino.

Assuming $M_1 < |\mu| \ll M_2$, one can expand the matrix N by powers of M_1/μ. Up to the first order of the expansion, the matrix is given by [43]

$$N \simeq \begin{pmatrix} 1 & 0 & \frac{m_Z s_W}{\mu}(s_\beta + c_\beta \frac{M_1}{\mu}) & -\frac{m_Z s_W}{\mu}(c_\beta + s_\beta \frac{M_1}{\mu}) \\ \frac{m_Z s_W (s_\beta + c_\beta)}{\sqrt{2}\mu}(1 + \frac{M_1}{\mu}) & 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{m_Z s_W (s_\beta - c_\beta)}{\sqrt{2}\mu}(1 - \frac{M_1}{\mu}) & 0 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & -1 & 0 & 0 \end{pmatrix}. \tag{2.3}$$

Then for a bino-like $\tilde{\chi}^0_1$ and a higgsino-like $\tilde{\chi}^0_k$, one can conclude that

$$\begin{aligned} &C_{\tilde{l}^*\bar{\tilde{\chi}}^0_1 l} \propto e, \quad C_{\tilde{l}^*\bar{\tilde{\chi}}^0_k l} \propto y_l, && C_{\tilde{\nu}^*\bar{\tilde{\chi}}^0_1 \nu} \propto e, \quad C_{\tilde{\nu}^*\bar{\tilde{\chi}}^0_k \nu} \sim 0, \\ &C_{h\bar{\tilde{\chi}}^0_1\tilde{\chi}^0_1} \propto e\frac{m_Z}{\mu}\left[\cos(\beta+\alpha) + \sin(\beta-\alpha)\frac{M_1}{\mu}\right], && C_{h\bar{\tilde{\chi}}^0_1\tilde{\chi}^0_k} \propto e(\sin\alpha \pm \cos\alpha), \\ &C_{Z\bar{\tilde{\chi}}^0_1\tilde{\chi}^0_1} \propto e\frac{m_Z^2}{\mu^2}\cos 2\beta\left(1 - \frac{M_1^2}{\mu^2}\right), && C_{Z\bar{\tilde{\chi}}^0_1\tilde{\chi}^0_k} \propto e\frac{M_Z}{\mu}(s_\beta \pm c_\beta)\left(1 \pm \frac{M_1}{\mu}\right), \end{aligned} \tag{2.4}$$

where C_{XYZ} represents the coupling coefficient for the interaction involving the particles X, Y and Z. Eq. (2.4) indicates that if the $\tilde{\chi}^0_1$ as the light DM candidate annihilated in early universe mainly by s-channel exchange of a Z boson or a SM-like Higgs boson [41, 43], an upper bound on μ has to be imposed to forbid its overproduction. Similarly an upper bound on slepton mass can be obtained if the DM annihilation proceeded mainly by t/u-channel slepton mediation. On the other side, noting that neutralinos and charginos as well as sleptons will be intensively explored at the 14 TeV LHC, we expect that the light DM scenario considered in this work can be readily tested in future. So it is necessary to discuss the capability of the LHC in this respect. This is the main motivation of this work.

In this work, we focus on the parameter space of the MSSM where the s-channel annihilations play the dominant role. We note that current bound on slepton masses is rather weak, so we also allow for the presence of light sleptons. Obviously, in the case that the sleptons contribute significantly to the annihilations, the bound on μ will be relaxed greatly. Another impact of the light sleptons is that they may affect the decay of the neutralinos, i.e. in addition to the decays $\tilde{\chi}^0_k \to Z\tilde{\chi}^0_1, h\tilde{\chi}^0_1$, the decay mode $\tilde{\chi}^0_k \to \tilde{l}^* l \to \bar{l} l \tilde{\chi}^0_1$ may be open. In this case, the LHC search for the neutralinos becomes quite complicated.

3 Light DM scenario in the MSSM

In our study we get the light DM scenario by scanning the parameter space of the MSSM. To simplify the analysis, we make following assumptions about the involved parameters:

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- The masses of gluino and the first two generation squarks are fixed at 2 TeV, which are above their mass limits set by the LHC searches for SUSY.

- With regard to the third generation squarks, we assume $m_{U_3} = m_{D_3}$ for the right-handed soft breaking masses and $A_t = A_b$ for soft breaking trilinear coefficients, and let the other parameters vary freely to tune the SM-like Higgs boson mass.

- We take a common value $m_{\tilde{l}}$ for all soft parameters in slepton sector, i.e. $m_{L_{1,2,3}} = m_{E_{1,2,3}} = A_{E_{1,2,3}} \equiv m_{\tilde{l}}$, and treat $m_{\tilde{l}}$ as a free parameter since we note that light sleptons can play a role in the DM annihilation.

As shown in previous studies [15–41, 43], these assumptions do not affect the features of the light DM scenario.

Now the free parameters in our study include $tan\beta$, M_1, M_2, μ, m_A, $m_{\tilde{l}}$, M_{Q_3}, M_{U_3} and A_t. We define all these parameters except for $\tan\beta$ at the scale of 2 TeV, and scan the following parameter space:[1]

$$\begin{gathered} 2 < \tan\beta < 60, \quad 10\,\text{GeV} < M_1 < 100\,\text{GeV}, 100\,\text{GeV} < M_2 < 1000\,\text{GeV}, \\ 100\,\text{GeV} < \mu < 1500\,\text{GeV}, \quad 50\,\text{GeV} < M_A < 2\,\text{TeV}, \\ |A_t| < 5\,\text{TeV}, \quad 200\,\text{GeV} < m_{Q_3}, m_{U_3} < 2\,\text{TeV}, \quad 100\,\text{GeV} < m_{\tilde{l}} < 2\,\text{TeV}. \end{gathered} \tag{3.1}$$

In the scan, we consider the constraints usually adopted in pervious literatures

- Firstly, we impose the constraints from the LEP searches for SUSY, which include the lower mass limits of charginos and sleptons, $m_{\tilde{\chi}_i^\pm} > 103.5\,\text{GeV}$ and $m_{\tilde{l}} > 93.2\,\text{GeV}$, the upper bounds on the cross sections for neutralino pair production, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_i^0) \lesssim 0.05\,\text{pb}$ for $i > 1$, and the non-SM invisible decay width of Z boson $\Gamma_{Z\to\tilde{\chi}_1^0\tilde{\chi}_1^0} \leq 1.71\,\text{MeV}$.

- Secondly, we consider the constraints from B-physics, such as the precise measurements of $B \to X_s\gamma$, $B_s \to \mu^+\mu^-$, $B_d \to X_s\mu^+\mu^-$ and the mass differences ΔM_d and ΔM_s at 2σ C.L. [57].

- Thirdly, we require the samples to explain the discrepancy of the measured value for the muon anomalous magnetic moment from its SM prediction at 2σ level, i.e. $12.7 \leq \delta a_\mu^{\text{SUSY}} \leq 44.7$ [57].

- Fourthly, we implement the constraints of various collider data on the Higgs sector of the MSSM with the packages HiggsBounds [58, 59] and HiggsSignal [60–62]. Briefly speaking, these data have required $m_h \simeq 125\,\text{GeV}$ and $\text{Br}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \lesssim 26\%$ (at 95% C. L. from our analysis) with h denoting the SM-like Higgs boson in the MSSM, and they also have set a lower mass bound on the CP-odd Higgs boson, $m_A \gtrsim 250\,\text{GeV}$.

[1] We note that in the limit $\lambda, \kappa \to 0$ of the Next-to-Minimal Supersymmetric Standard Model (NMSSM), the phenomenology of the NMSSM is same as that of the MSSM for fixed value of μ. So we use the multipurpose package NMSSMTools [54–56] to perform the scan. As pointed out by the authors of the package, it can reproduce correctly the results of the MSSM.

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- Fifthly, we require the bino-dominated $\tilde{\chi}_1^0$ to take up more than 10% component of the total DM, and meanwhile its relic density smaller than the 3σ upper limit of the PLANCK [63] and WMAP 9-year data [64], i.e. $\Omega h^2 \leqslant 0.131$ where a 10% theoretical uncertainty is included. We also impose the LUX exclusion bound on the DM-nucleon scattering cross section at 90% C.L. [65]. In the case that the $\tilde{\chi}_1^0$ is only a fraction ϵ of the total DM, we assume that the other components of the DM have no interaction with nucleon, and consequently we can implement the constraint of the LUX experiment only by scaling the experimental upper bound of the cross section with a factor $1/\epsilon$. In our analysis, both the relic density and the scattering rate are obtained by the code micrOMEGAs [66].

- Finally, we impose constraints from the LHC searches for third generation squarks by the code FastLim [67]. This code contains the results of various experimental analyses in the search for third generation squarks, and thus provides a fast way to implement the constraints.

We remind that, in comparison with [43] which is one of the latest studies in this subject, we relaxed the assumptions on the slepton mass and m_A in the scan, and also considered more constraints.

The samples surviving above constraints are projected on the $\mu - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$ planes in figure 1 (we will explain the meanings of the samples marked by different colors later). This figure shows that the bino-like $\tilde{\chi}_1^0$ must be heavier than about 37 GeV after considering the constraints, and a large portion of the samples are characterized either by $m_{\tilde{\chi}_1^0} \simeq m_Z/2$ or by $m_{\tilde{\chi}_1^0} \simeq m_h/2$. Moreover, we find that the surviving samples can be classified into following three types:

- Type-I samples: those featured by $m_{\tilde{l}} \lesssim 350$ GeV. For this type of samples, the DM could annihilate by the t/u-channel mediation of the sleptons in early universe.

- Type-II samples: those featured by $m_{\tilde{l}} \gtrsim 350$ GeV and $m_{\tilde{\chi}_1^0} \simeq m_Z/2$. This type of samples annihilated mainly by s-channel exchange of a Z boson, and to satisfy the relic density constraint, μ should be less than about 470 GeV.

- Type-III samples: those featured by $m_{\tilde{l}} \gtrsim 350$ GeV and $m_{\tilde{\chi}_1^0} \simeq m_h/2$. This type of samples annihilated mainly by s-channel exchange of the SM-like Higgs boson, and the density requires $\mu \lesssim 800$ GeV.

Moreover, we checked that the stops in the surviving samples must be heavier than about 300 GeV. For the samples with $m_{\tilde{t}_1} \simeq 300$ GeV, $\tilde{t}_1$ mainly decays into higgsino-dominated neutralinos or chargino as the first step, and the higgsinos subsequently decay into the $\tilde{\chi}_1^0$. Due to the lengthened decay chain, the constraint from the direct searches for stops at the LHC is weakened.

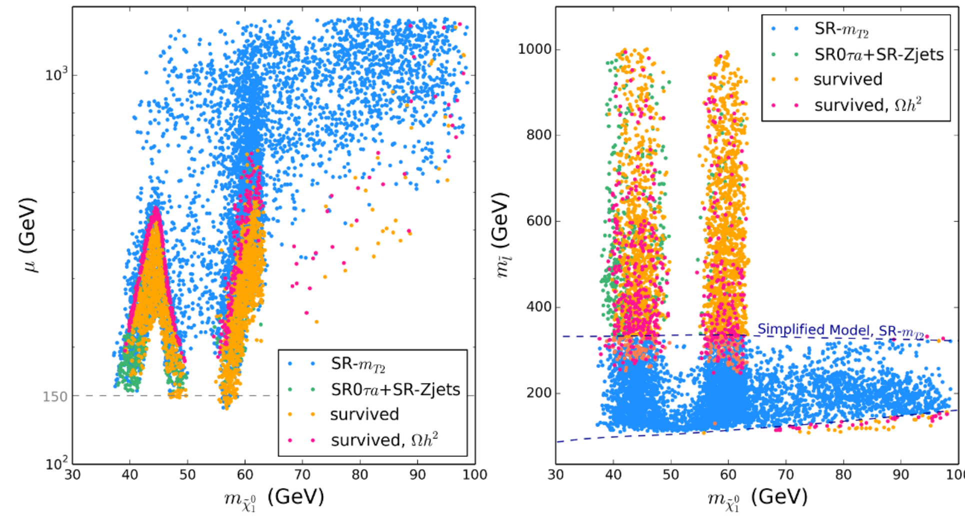

Figure 1. Samples surviving the constraints considered in section 3, which are projected on the $\mu - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$ planes. The blue ones are further excluded by the signal region of SR-m_{T2} in the direct search for sleptons with $2l + E_T^{\rm miss}$ signal at the 8 TeV LHC, and the green ones are further excluded by the combination of the signal regions SR0τa and SR-Z jets, which were adopted in the search for $3l + E_T^{\rm miss}$ and $2l + E_T^{\rm miss}$ signals from the charginos and neutralinos associated production processes at the 8 TeV LHC. The red and orange ones are the remaining sample with the former being able to get the measured DM relic density at 3σ level and the latter only satisfying the 3σ upper bound of the density.

4 Constraints from the multi-lepton signals at the 8 TeV LHC

From figure 1, one can learn that most of the surviving samples are characterized by predicting either moderately light sleptons or moderately low μ. This motivates us to further constrain these samples by the direct searches for sleptons and neutralinos/charginos at the 8 TeV LHC.[2] In the rest of this section, we consider following experimental analyses:

- The search for $2l + E_T^{\rm miss}$ signal from slepton pair production process or electroweakino pair production process at the 8 TeV LHC with 20.3 fb^{-1} integrated luminosity [6]. In this analysis, seven signal regions (SRs) were defined. The first three, collectively referred to as SR-m$_{T2}$, were designed to provide sensitivity to the process $pp \to \tilde{l}^* \tilde{l} \to 2l + E_T^{\rm miss}$. The next three usually called SR-WW were designed to be sensitive to the process $pp \to \bar{\tilde{\chi}}_i^{\pm} \tilde{\chi}_j^{\pm} \to (\tilde{\chi}_1^0 W^{\mp})(\tilde{\chi}_1^0 W^{\pm}) \to 2l + E_T^{\rm miss}$. The last SR called SR-Zjets was designed specifically for the process $pp \to \bar{\tilde{\chi}}_i^0 \tilde{\chi}_j^{\pm} \to (\tilde{\chi}_1^0 Z)(\tilde{\chi}_1^0 W^{\pm}) \to 2l2j + E_T^{\rm miss}$. About these analyses, we note that the bounds on the chargino mass from the SR-WW are much weaker than those from the SR-Zjets in simplified model [6]. Considering that we have kept more than three thousands surviving samples in the scan and consequently the involved simulations are rather time consuming, we in this study only consider the SR-m_{T2} for direct slepton pair production and the SR-Zjets for chargino and neutralino associated productions to save time.

[2]We note that, since the $\tilde{\chi}_1^0$ in our scenario is bino dominated and $m_{\tilde{\chi}_1^0} \gtrsim 37$ GeV, the constraint from the mono-jet search presented in [68] should be very weak since the production rate for the process $pp \to \bar{\tilde{\chi}}_1^0 \tilde{\chi}_1^0 j$ is small.

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SR	N_j	$\Delta m_{ll,Z}$	$E_{T,\mathrm{rel}}^{\mathrm{miss}}$	P_T^{ll}	m_{T2}	ΔR_{ll}	m_{jj}	WW	ZV	Other	Total
m_{T2}^{90}	0	> 10	–	–	> 90	–	–	1.71	1.36	0.26	3.33
m_{T2}^{120}	0	> 10	–	–	> 120	–	–	0.12	0.44	0.00	0.57
m_{T2}^{150}	0	> 10	–	–	> 150	–	–	0.02	0.19	0.00	0.21
Zjets	≥ 2	< 10	>80	>80	–	[0.3,1.5]	[50,100]	0.02	0.14	0.03	0.19

Table 1. The selections of N_j, $\Delta m_{ll,Z}$, $E_{T,\mathrm{rel}}^{\mathrm{miss}}$, P_T^{ll}, m_{T2}, ΔR_{ll} and m_{jj} for different SRs of the SR-m_{T2} and the SR-Zjets. The expected cross sections of the SM backgrounds for each SR at the 14 TeV LHC are also presented, which will be used later. Quantities with mass dimension and the cross sections are in units of GeV and fb respectively.

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Both the SR-m_{T2} and the SR-Zjets require that the signal events contain exactly two same flavor opposite sign (SFOS) leptons with p_T >35 GeV and > 20 GeV, and their invariant mass m_{ll} must be larger than 20 GeV. Events containing any of central ($|\eta| < 2.4$) b-jets, forward ($2.4 < |\eta| < 4.5$, $p_T > 30$ GeV) jets or τ-jet candidates are rejected. Further selections are applied for the different SRs, which are summarized in table 1. In this table N_j represents the number of the central light jets which are defined as $|\eta| < 2.4$ and $P_T > 20(45)$ GeV for SR-m_{T2} (SR-Zjets), and $\Delta m_{ll,Z}$ denotes the mass difference between the SFOS lepton pair and the Z boson. Note that in order to suppress the backgrounds containing two W bosons for the SR-m_{T2}, the 'stransverse' mass m_{T2} is introduced. This quantity is defined by

$$m_{T2} = \min_{\mathbf{q}_T} \left[\max(m_T(\mathbf{p}_T^{l1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{l2}, \mathbf{p}_T^{\mathrm{miss}} - \mathbf{q}_T) \right], \tag{4.1}$$

where $\mathbf{p}_T^{l1}$ and $\mathbf{p}_T^{l2}$ stand for the transverse momenta of the two leptons, and a varying momentum $\mathbf{q}_T$ is introduced to minimize the larger one of the two transverse masses, which are defined by $m_T(\mathbf{p}_T^A, \mathbf{p}_T^B) = \sqrt{2(p_T^A p_T^B - \mathbf{p}_T^A . \mathbf{p}_T^B)}$. By contrast, in order to suppress the background Z + jets production for the SR-Zjets, the cuts on the transverse momentum P_T^{ll}, the separation angle $\Delta R_{ll} = \sqrt{(\Delta\phi_{ll})^2 + (\Delta\eta_{ll})^2}$ of the two leptons, and $E_{T,\mathrm{rel}}^{\mathrm{miss}}$ are imposed. Here the $E_{T,\mathrm{rel}}^{\mathrm{miss}}$ is a variant of E_T^{miss}, and it is defined by

$$E_{T,\mathrm{rel}}^{\mathrm{miss}} = \begin{cases} E_T^{\mathrm{miss}} & \mathrm{if} \Delta\phi_{l,j} \geqslant \pi/2 \\ E_T^{\mathrm{miss}} \times \sin\Delta\phi_{l,j} & \mathrm{if} \Delta\phi_{l,j} \leqslant \pi/2 \end{cases}, \tag{4.2}$$

where $\Delta\phi_{l,j}$ is the azimuthal angle between the direction of $\mathbf{p}_T^{\mathrm{miss}}$ and that of the nearest lepton or central jet.

- The search for $3l + E_T^{\mathrm{miss}}$ signal from the chargino and neutralino associated production at the 8 TeV LHC with 20.3 fb^{-1} integrated luminosity [8]. Signal events in this analysis were required to contain exactly three leptons and no b-tagged jets. The leptons must be separated from each other by $\Delta R > 0.3$, include at least one electron or muon, fire at least one of the single- and double-lepton triggers and also satisfy the P_T-threshold requirements [8]. Then according to the flavor and charge of the leptons, five SRs, namely SR0τa, SR0τb, SR1τ, SR2τa and SR2τb, were defined, and

SR0τa	$m_{\rm SFOS}$	m_T	$E_T^{\rm miss}$	m_{3l}	VVV	WZ	ZZ	t	h	$t\bar{t}$	Total
1	12–40	0–80	50–90	no	0.03	1.11	0.11	0.02	0.07	1.05	2.41
2	12–40	0–80	>90	no	0.01	0.28	0.01	0.01	0.03	0.11	0.45
3	12–40	>80	50–75	no	0.02	0.66	0.03	0.00	0.07	0.22	1.00
4	12–40	>80	>75	no	0.06	0.45	0.02	0.02	0.05	0.48	1.08
5	40–60	0–80	50–75	yes	0.02	0.52	0.13	0.01	0.04	0.65	1.37
6	40–60	0–80	>75	no	0.02	0.33	0.02	0.00	0.04	0.33	0.76
7	40–60	>80	50–135	no	0.08	0.64	0.05	0.00	0.11	0.61	1.49
8	40–60	>80	>135	no	0.02	0.04	0.00	0.02	0.04	0.08	0.20
9	60–81.2	0–80	50–75	yes	0.02	1.40	0.12	0.02	0.03	0.79	2.40
10	60–81.2	>80	50–75	no	0.04	1.09	0.05	0.02	0.02	0.29	1.51
11	60–81.2	0–110	>75	no	0.06	1.75	0.07	0.07	0.04	0.99	2.98
12	60–81.2	>110	>75	no	0.07	0.34	0.01	0.02	0.02	0.16	0.63
13	81.2–101.2	0–110	50–90	yes	0.14	52.16	2.60	0.56	0.23	10.73	66.41
14	81.2–101.2	0–110	>90	no	0.10	19.95	0.56	0.44	0.15	0.42	21.62
15	81.2–101.2	>110	50–135	no	0.11	5.13	0.35	0.13	0.04	0.21	5.98
16	81.2–101.2	>110	>135	no	0.05	0.47	0.01	0.02	0.00	0.03	0.59
17	>101.2	0–180	50–210	no	0.34	4.80	0.24	0.12	0.13	2.01	7.65
18	>101.2	>180	50–210	no	0.06	0.28	0.01	0.02	0.01	0.04	0.44
19	>101.2	0–120	>210	no	0.02	0.13	0.00	0.00	0.00	0.08	0.24
20	>101.2	>120	>210	no	0.02	0.02	0.00	0.00	0.00	0.04	0.09

Table 2. The details of the 20 bins defined in the SR0τa. For each bin the expected cross sections of its SM backgrounds after cuts at the 14 TeV LHC are also presented for later use. All quantities with mass dimension and cross sections are in units of GeV and fb respectively.

each of them was further designed to detect efficiently a certain type of signal. To be more specific, the SR0τa was optimized for maximum sensitivity to the chargino and neutralino production followed by the $\tilde{l}_L$-mediated or WZ-mediated decay of the sparticles, the SR0τb, SR1τ and SR2τb are all for the Wh-mediated decay, and the SR2τa targets the $\tilde{\tau}$-mediated decay mode. We note that in the simplified model discussed in [8], the constraint from the SR0τa is much stronger than those from the SR0τb, SR1τ and SR2τb in limiting the chargino/neutralino sector mainly because the branching ratios of h decays into leptons are small. We also note that the SR2τa is less efficient for our scenario because the branching ratios of $\tilde{\chi}_1^\pm \to \tau^\pm \nu_\tau \tilde{\chi}_1^0$ and $\tilde{\chi}_i^0 \to \tau^\pm \tau^\mp \tilde{\chi}_1^0$ are usually small. So in our study we only consider the SR0τa for the chargino and neutralino associated production processes.

In the SR0τa, 20 bins were defined by the invariant mass of the SFOS lepton pair closer to the Z boson mass $m_{\rm SFOS}$, $E_T^{\rm miss}$ and $m_T = \sqrt{2p_T^l E_T^{\rm miss} - 2\mathbf{p}_T^l \cdot \mathbf{p}_T^{\rm miss}}$ where $\mathbf{p}_T^l$ is the transverse momentum of the lepton not forming the SFOS lepton pair. The details of the bins are listed in table 2. Note that only in bin-5, 9 and 13, events with $|m_{3l} - m_Z| < 10\,$GeV are vetoed where m_{3l} denotes the trilepton mass.

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About the considered analyses, we note that the SR-m_{T2} focuses on the slepton pair production process, and its SRs are statistically dependent since they overlap with each other. So we use the SR of the SR-m_{T2} with the best exclusion limit to determine whether the model point is excluded. We also note that the SRs targeting the neutralino and chargino associated production processes, i.e. SR0τa and SR-Z jets, are disjoint, which means that their results can be statistically combined to maximize the significance. In our study we combine them together though the CL_s method [69] with RooStats [70], in which the likelihood functions are written as

$$\mathcal{L}(n_i|s_i+b_i) = \prod_{i=1}^{N_{\rm bin}} \frac{1}{\sqrt{2\pi\sigma_{b_i}^2}} \frac{1}{\sqrt{2\pi\sigma_{s_i}^2}} \int db_i' \int ds_i' \frac{(s_i'+b_i')^{n_i} e^{-(s_i'+b_i')}}{n_i!} e^{\frac{(b_i-b_i')^2}{2\sigma_{b_i}^2}} e^{\frac{(s_i-s_i')^2}{2\sigma_{s_i}^2}} \tag{4.3}$$

for signal and

$$\mathcal{L}(n_i|b_i) = \prod_{i=1}^{N_{\rm bin}} \frac{1}{\sqrt{2\pi\sigma_{b_i}^2}} \int db_i' \frac{b_i'^{n_i} e^{-b_i'}}{n_i!} e^{\frac{(b_i-b_i')^2}{2\sigma_{b_i}^2}} \tag{4.4}$$

for backgrounds. In above expressions, n_i, s_i and b_i are the numbers of observed events, predicted signal events and background events in each SR or bin respectively, and σ_{s_i} and σ_{b_i} are the corresponding total systematic uncertainties. In our calculation, we take the values of n_i, b_i and σ_{b_i} from the experimental reports and fix the relative uncertainties of the signals at 10%, i.e. $\sigma_{s_i}/s_i = 10\%$.

In actual calculation, we use MG5_aMC/MadEvents [71, 72] to generate the tree level events for the processes contributing to those SRs, and then pass them through PYTHIA [73] for parton showering and hadronization and DELPHES [74] for fast simulation of the ATLAS detector. The SRs described above have been implemented by CheckMATE [75, 76], and the involved cross sections are calculated by the code PROSPINO2 [77].[3] After these procedures, we can determine whether the model points survive the constraints from the direct searches.

The results of the direct searches at the 8 TeV LHC are showed in figure 1, where the blue points are excluded at 95% C.L. by the SR-m_{T2}, the green ones are excluded by the combination of the SR0τa and the SR-Zjets, and the red and orange ones are the remaining samples with the former being able to get the measured DM relic density at 3σ level and the latter only satisfying the 3σ upper bound of the density. From figure 1, one can learn the following facts:

- After considering the constraints from the SR-m_{T2}, most Type-I samples are excluded, especially for those with $m_{\tilde{\chi}_1^0} \leq 50\,\text{GeV}$. In such a situation, the sleptons are usually heavier than about 250 GeV for $m_{\tilde{\chi}_1^0} \simeq m_Z/2$ and $m_{\tilde{\chi}_1^0} \simeq m_h/2$, and μ is less than 470 GeV and 680 GeV for the two cases respectively.

- The combination of the SR0τa and the SR-Zjets can only exclude the samples with $\mu \lesssim 220\,\text{GeV}$, which is much weaker than the exclusion limit for the chargino mass

[3]About this point we emphasize that we simulate all six neutralino and chargino production processes contributing to the SRs, i.e. $pp \to \tilde{\chi}_i^0 \tilde{\chi}_j^\pm$ with $i = 2, 3, 4$ and $j = 1, 2$, and add their contributions into the signal events for every SR (bin).

reported in [6] and [8]. One reason is that the lighter chargino in our scenario is higgsino-dominated instead of wino-dominated, and consequently the neutralino and chargino associated production rate is relatively small. Another reason is that in our scenario the higgsino-dominated $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ may decay into $Z\tilde{\chi}_1^0$, $h\tilde{\chi}_1^0$ and $\tilde{l}^* l$, and the higgsino-dominated $\tilde{\chi}_1^\pm$ may decay into $W\tilde{\chi}_1^0$ and $\tilde{l}\nu$. As a result, the trilepton signal is suppressed.

- There exist samples with $\mu \sim 150\,\text{GeV}$ on the right bottom of the $m_Z/2$ peak and the left bottom of the $m_h/2$ peak in figure 1 which can not be excluded by the combination of the SR0τa and the SR-Zjets. There also exist some samples with $m_{\tilde{l}} \lesssim 180\,\text{GeV}$ for $m_{\tilde{\chi}_1^0}$ varying from 70 GeV to 100 GeV which can not be excluded by the SR-m_{T2}. For these samples, although the involved sparticles are produced with moderately large rates due to their lightness, the acceptance efficiencies of the signals for the SRs are rather low because of the compressed spectrum of the parent sparticles, i.e the electroweak-inos or sleptons in our discussion, with respect to their decay products. As a result, the direct search experiments can not exclude these samples.

  In order to illustrate this fact in more detail, we first choose two points with same $m_{\tilde{\chi}_1^0} = 47\,\text{GeV}$ from the left panel of figure 1. The first one corresponds to $\mu = 149\,\text{GeV}$ and it is allowed by the direct searches, while the second one corresponds to $\mu = 204\,\text{GeV}$ and it is experimentally excluded by our simulation. Then we compare the predictions of the two points on the total cross section of the neutralino-chargino associated productions, which is defined by

$$\sigma_{\text{tot}} = \sum_{i,j} \sigma(pp \to \bar{\tilde{\chi}}_i^0 \tilde{\chi}_j^\pm) \times \text{Br}(\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 Z) \times \text{Br}(\tilde{\chi}_j^\pm \to \tilde{\chi}_1^0 W^\pm),$$

  and also on the final acceptance efficiency ϵ for the SR-Zjets. We find that $\sigma_{\text{tot}} = 0.75\,\text{pb}$, $\epsilon = 1 \times 10^{-4}$ for the first point, and $\sigma_{\text{tot}} = 0.59\,\text{pb}$, $\epsilon = 9 \times 10^{-4}$ for the second point. This example shows that with the decrease of the mass difference $m_{\tilde{\chi}_i^0} - m_{\tilde{\chi}_1^0} - m_Z$ or $m_{\tilde{\chi}_j^\pm} - m_{\tilde{\chi}_1^0} - m_W$, the acceptance efficiency drops quickly.

At this stage, we'd like to clarify the differences of our study from previous literatures [37] and [42, 43]. In [37], the authors scanned the parameter space of the MSSM by relaxing the slepton masses to get the light DM scenario, which is quite similar to what we did in this work. The main difference of the two works is that the authors of [37] used the package SModelS [78] to implement the constraints of the direct searches on the electroweak-inos and sleptons, while we do it by detailed simulations. Because the feasibility of the SModelS is based on certain assumptions (e.g. the approximate degeneracy of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$) which can not be applied to all of our samples, and also because it considers separately the signals coming from different sparticles that lead to the same final state [78], the constraints of the SModelS on the electroweak-inos should be conservative. In fact, we once compared the difference of the two methods in implementing the constraints, and verified this conclusion. In [43], the authors got the light DM scenario by decoupling all sparticles except for the bino-like $\tilde{\chi}_1^0$ and the higgsino-like $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ and $\tilde{\chi}_1^\pm$. The advantage of such a simplification is that, without the participation of light sleptons, the correlation of $m_{\tilde{\chi}_1^0}$ with μ is rather clear, but as we have shown in this work, the sleptons not only played an important role in the $\tilde{\chi}_1^0$ annihilation, but also affect the decays of the electroweak-inos. So the impact of the light sleptons on the scenario should be taken into account. Another difference of [43] from our work is that the work [43] only considered the trilepton signal to limit the light DM scenario, while we combine the dilepton and trilepton signals to limit the scenario. Moreover, we note that the scenario featured by predicting light bino and sleptons, which is somewhat similar to Type-I samples in this work, was previously studied in [42]. However, our study differs from the work [42] in at least two aspects. One is that the authors of [42] focused on the constraints from the magnetic and electric dipole moments of the electron and muon on the scenario, and they omitted the limitation from the direct search for sleptons at the LHC. By contrast, we require our samples to explain the measured value of the muon magnetic moment, and pay great effort to examine the constraints of the direct search for the sleptons. The other is that the authors of [42] considered the case where there exists large mass splittings between sleptons. In such a situation, the s-wave contribution to the DM annihilation today can be sizable, so they intensively discussed interesting DM signatures at a variety of indirect detection experiments. While we consider the degeneracy of the sleptons in mass, and as a result the s-wave contribution is canceled out (see eq. (8) in [42]).

5 Test the light DM scenario at the 14 TeV LHC

From the discussion in last section, one can learn that the searches for the sleptons and the electroweak-inos at the 8 TeV LHC have important impact on the light DM scenario, e.g. lots of the samples of the scenario have been excluded. Given the ongoing of the upgraded LHC, one may expect that much tighter constraints on the scenario will be obtained, and even some sparticles in this scenario will be discovered in near future.

We investigate this issue by considering the slepton pair production and the neutralino and chargino associated production at the 14 TeV LHC. For simplicity, we adopt the same cuts on the SR-m_{T2}, the SR0τa and the SR-Zjets as those at the 8 TeV LHC, and get the SM backgrounds of the signals by two steps. We first simulate each background process at the 8 TeV LHC, and compare the simulated event number in each SR with its validated number, which was obtained by experimentalists, to get a correction factor (this factor usually varies from 1 to 5 from our simulation). Subsequently we suppose that the dominant backgrounds at the 14 TeV LHC come from the same processes as those at the 8 TeV LHC, which include WW, ZV, Z + jets and top quark production for $2l + E_T^{\rm miss}$, and diboson, $t\bar{t}V$, tZ, VVV and Higgs boson production for $3l + E_T^{\rm miss}$, and simulate each of them at the 14 TeV LHC. Then we take the simulation results for the 14 TeV LHC multiplied by the corresponding correction factors as our predictions of the backgrounds, which are given in table 1 and table 2. We realize that the backgrounds obtained in this way only act as rough estimates of the true backgrounds at the time when we have no detailed information about the ATLAS detector at the 14 TeV LHC.

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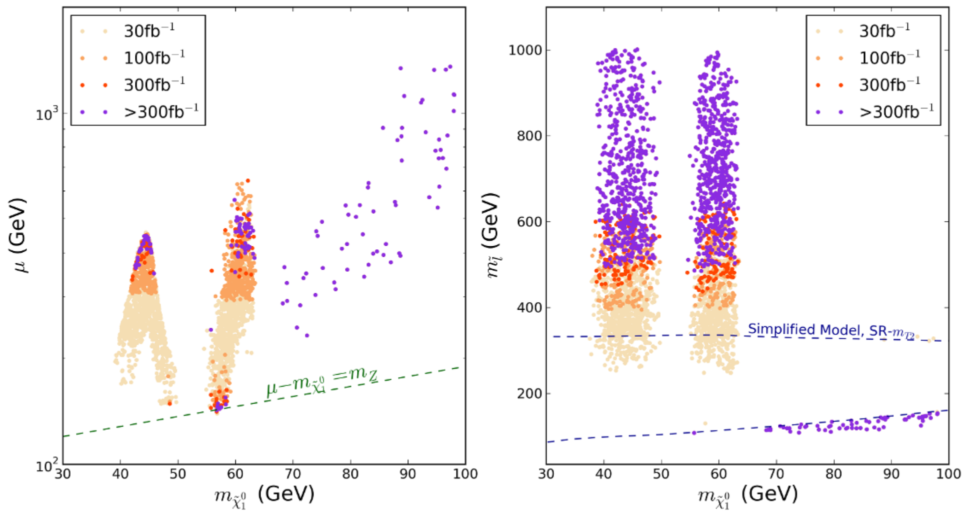

Figure 2. The 95% exclusion bound of the 14 TeV LHC by the combination of the SR0τa and the SR-Zjets (left panel) as well as by the SR-m_{T2} (right panel), which are projected on the $m_{\tilde{\chi}_1^0} - \mu$ plane and the $m_{\tilde{\chi}_1^0} - m_{\tilde{l}}$ plane respectively for the samples surviving the constraints considered in sections 3 and 4. The samples marked by the colors faint yellow, brown and orange will be excluded at 95% C.L. by an integrated luminosity of 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1} respectively, and those marked by the violet color can not be excluded even with 300 fb^{-1} integrated data.

In figure 2, we show our simulation results for the direct production of the charginos and neutralinos at the 14 TeV LHC on the $m_{\tilde{\chi}_1^0} - \mu$ plane and those for the direct production of the sleptons on the $m_{\tilde{\chi}_1^0} - m_{\tilde{l}}$ plane. The samples considered in this figure are those surviving all the constraints listed in sections 3 and 4. The exclusion significance is calculated by the CLs method with the n_i in eq. (4.3) and eq. (4.4) set to be b_i and the total relative systematic uncertainties of the backgrounds and the signals taken same as those at the 8 TeV LHC. The samples marked by the colors faint yellow, brown and orange are those which will be excluded at 95% C.L. with an integrated luminosity of 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1} respectively, and those marked by the violet color denote the samples that can not be excluded with 300 fb^{-1} data.

From the left panel of figure 2, one can clearly see an exclusion line at $\mu \simeq 300$ GeV for 30 fb^{-1} integrated luminosity, and the limit raises with the increase of the luminosity. This means that, except for the compressed spectrum case, a tighter bound on μ can be obtained by the 14 TeV LHC if no excess on the multi-lepton signals is observed. Moreover, we note the existence of a few samples on the top of the $m_Z/2$ peak which are hard to be excluded by the direct search for the electroweak-inos even with 300 fb^{-1} integrated luminosity. For these samples, we checked that they predict relatively light sleptons so that the electroweak-inos can decay into them. From the right panel of figure 2, one can learn that except for the samples with the compressed spectrum, lower bounds of about 400 GeV, 450GeV and 500 GeV on slepton masses can be obtained with an integrated luminosity of 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1} respectively. Especially, we note that for the 300 fb^{-1} luminosity case, the sleptons must be heavier than the higgsino-like $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$

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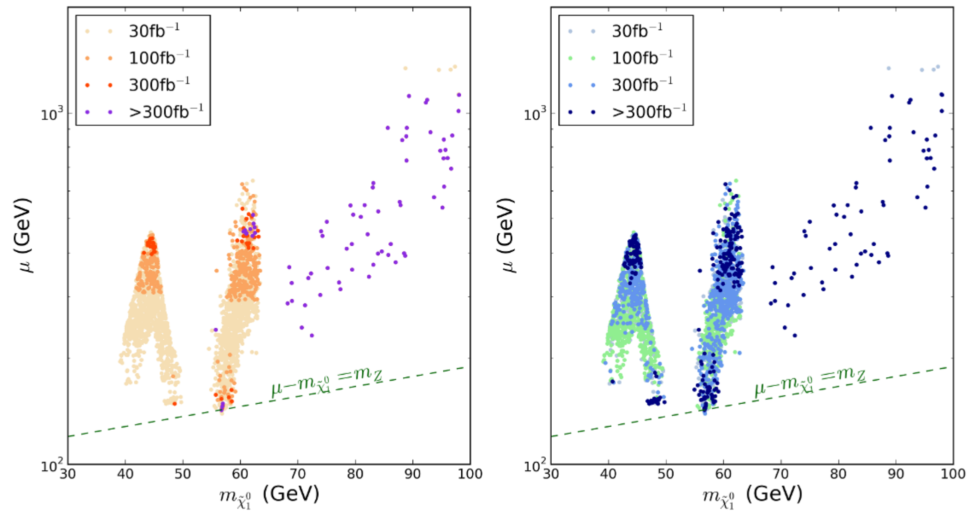

Figure 3. The 95% exclusion capability (left panel) and the discovery capability (right panel) of the multi-lepton searches at the 14 TeV LHC, which are projected on the $m_{\tilde{\chi}_1^0} - \mu$ plane for the samples surviving the constraints considered in sections 3 and 4. The color convention in the left panel is same as that in figure 2. The colors light blue, green and blue in the right panel denote the samples which can be discovered at 5σ C.L. with 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1} data respectively, and the black color represents the difficult case of the light DM scenario, namely the samples that fail to be discovered even with 300 fb^{-1} luminosity.

predicted by the samples around the $m_Z/2$ peak, which means that the neutralinos can not decay into the on-shell sleptons any more.

Next we consider the searches for sleptons and electroweak-inos simultaneously. We again focus on the samples surviving the constraints listed in sections 3 and 4, and project the 95% exclusion capability and the discovery capability of the searches on the $m_{\tilde{\chi}_1^0} - \mu$ planes in figure 3. Here the discovery significance is also calculated by the CLs method, but with the n_i in eq. (4.3) and eq. (4.4) taken to be $b_i + s_i$. The colors in the left panel have same meanings as those in figure 2, while the colors light blue, green and blue in the right panel denote the samples which can be discovered at 5σ C.L. with 30 fb^{-1}, 100 fb^{-1} and 300 fb^{-1} data respectively. Note that the samples marked by black color in the right panel represents the difficult cases of the light DM scenario, namely the samples can not be discovered even with 300 fb^{-1} luminosity. From figure 3, one can learn following facts:

- In case that no excess of the multi-lepton plus $E_T^{\rm miss}$ signals is observed at the 14 TeV LHC, a lower limit on $m_{\tilde{\chi}_1^0}$ will be set at 42GeV and 44 GeV with 30 fb^{-1} and 100 fb^{-1} data respectively, and this limit can be further pushed up to 55GeV with 300 fb^{-1} data.

- If the light DM scenario is chosen by nature, and meanwhile no SUSY multi-lepton signals are observed at the 14 TeV LHC with 300 fb^{-1} data, most samples of the light DM scenario will be excluded. In this case, $\tilde{\chi}_1^0$ must annihilate in early universe either by s-channel exchange of the SM-like Higgs boson or by t/u-channel slepton

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mediation. The latter situation then requires that the sleptons must be lighter than about 170 GeV, and their masses usually differ from the $\tilde{\chi}_1^0$ mass by less than 50 GeV.

- At the 14 TeV LHC with 300 fb^{-1} data, a large portion of the samples in the light DM scenario can be discovered. These samples are characterized by $\mu \lesssim 350$ GeV and a sizable splitting between μ and $m_{\tilde{\chi}_1^0}$.

- We note from the right panel that there exist some samples with $\mu \simeq 700$ GeV at the $m_h/2$ peak which will be discovered at the 14 TeV LHC. For these samples, the wino mass M_2 is smaller than 600 GeV, so it is actually wino-dominated neutralino and chargino that contribute to the multi-lepton signals.

From above discussions, one can learn that the light sleptons can play an important role in the light DM scenario. Here we emphasize that our conclusions are based on a common slepton mass assumption, and if only $\tilde{\tau}$s are assumed to be light, the conclusions may change slightly. Indeed, for the latter case a study similar to what we did must be done, and the experiment pertinent to the $\tilde{\tau}$ search should be considered [34]. We also want to emphasize that the cuts in our simulation at the 14 TeV LHC can be optimized, and meanwhile the pileup effect should be estimated. This is beyond the scope of this work.

Before we end this section, we note that the constraints on the Higgs sector listed in section 3 will be improved at the 14 TeV LHC, and at that time they might impose tighter constraints on the light DM scenario than the direct SUSY searches. Here we consider the impact of the future measured $\mathrm{Br}(h \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$ on the scenario. According to the analyses for the 14 TeV LHC in [79] and [80], the expected exclusion limit of the branching ratio with 300 fb^{-1} integrated luminosity is 14% from global data fit and 17% from the direct search for the process $pp \to Zh \to Z + inv$ under the optimal assumptions on systematic uncertainties. While on the other hand, we checked that, if no excess of the multi-lepton signals is observed at the 14 TeV LHC with only 30 fb^{-1} data, the maximal branching ratio predicted by the surviving samples will drop from 26% to about 12%. So we conclude that the direct searches for sparticles at future LHC can put more stringent constraints on the light DM scenario than the invisible decay.

6 Future DM direct searches

As a supplement to the discussion in section 5, we investigate the capabilities of the future DM direct search experiments in exploring the light DM scenario. For this end, we focus on the effective spin independent (SI) DM-nucleon scattering cross section $\sigma^{SI}_{\mathrm{eff}}$, which is defined by $\sigma^{SI}_{\mathrm{eff}} = \epsilon \times \sigma^{SI}_{\tilde{\chi}_1^0 p}$ with ϵ being the fraction of the $\tilde{\chi}_1^0$ in total DM and $\sigma^{SI}_{\tilde{\chi}_1^0 p}$ being the SI $\tilde{\chi}_1^0 - p$ scattering rate, and calculate it by the package micrOMEGAs [66] with its default setting $\sigma_{\pi N} = 34$ MeV and $\sigma_0 = 42$ MeV.[4] In figure 4, we display $\sigma^{SI}_{\mathrm{eff}}$ versus $m_{\tilde{\chi}_1^0}$ for the samples surviving the constraints considered in section 3 and section 4 together with

[4] We note that if we take $\sigma_{\pi N} = 59$ MeV from [81] and $\sigma_0 = 58$ MeV from [82], the SI cross section will be enhanced by a factor from 20% to 40%.

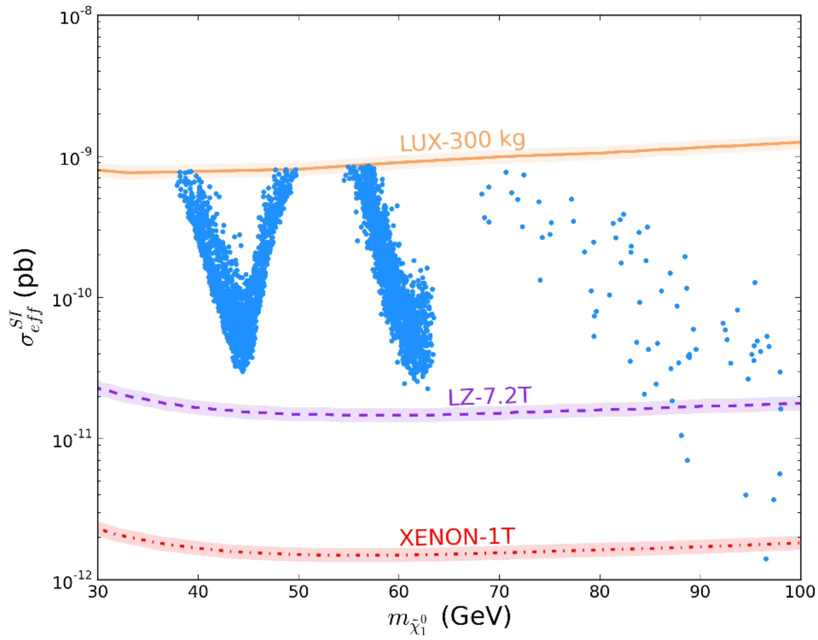

Figure 4. The spin independent DM-nucleon scattering cross section versus the DM mass for the samples surviving the constraints considered in section 3 and section 4. The capabilities of future DM direct detection experiments in probing the cross section are also plotted.

the detection capabilities of future underground DM direct searches LZ-7.2T and XENON-1T [83]. This figure indicates that most samples of the light DM scenario, especially all the Type-II and Type-III samples, will be explored by the experiment LZ-7.2T. This figure also indicates that $\sigma^{\rm SI}_{\rm eff}$ dips greatly at $m_{\tilde{\chi}^0_1} \simeq m_Z/2$ and $m_{\tilde{\chi}^0_1} \simeq m_h/2$. This behavior can be understood by following formulae [84]:

$$\begin{aligned} \sigma^{\rm SI}_{\rm eff} &\propto \left(\frac{C_{h\tilde{\chi}^0_1\tilde{\chi}^0_1} C_{hqq}}{m_h^2} + \frac{C_{H\tilde{\chi}^0_1\tilde{\chi}^0_1} C_{Hqq}}{m_H^2} \right)^2, \\ C_{h\tilde{\chi}^0_1\tilde{\chi}^0_1} &\simeq \frac{m_Z \sin\theta_W \tan\theta_W}{M_1^2 - \mu^2} \left[M_1 + \mu \sin 2\beta \right], \\ C_{H\tilde{\chi}^0_1\tilde{\chi}^0_1} &\simeq -\frac{m_Z \sin\theta_W \tan\theta_W}{M_1^2 - \mu^2} \mu \cos 2\beta, \end{aligned} \tag{6.1}$$

where C_{XYZ} stands for the Yukawa couplings of the CP-even Higgs bosons h and H, and the fact that for the two cases, the value of μ increases rapidly. From eq. (6.1) one can also infer that in the case of a large $\tan\beta$, the H-mediated contribution may still be significant even for a heavy H because C_{Hqq} for down-type quarks is proportional to $\tan\beta$. Anyhow, $\sigma^{\rm SI}_{\rm eff}$ usually decreases as H becomes heavier. We emphasize that the DM direct search experiment and the LHC search for sparticles are two different ways to explore the light DM scenario.

7 Conclusion

In past several years, fruitful results in the search for sparticles have been achieved at the LHC Run I, which set stronger limits on the spectrum of the sparticles than the LEP experiments. Now with the operation of the upgraded LHC, it is widely expected that much heavier sparticles will be tested in near future. Obviously, discussing the potential of the LHC experiments to test the MSSM is an important task for both theorists and experimentalists.

In this work we investigated the impact of the sparticle searches at the LHC on the light DM scenario of the MSSM, for which the DM relic density has put non-trivial constraints on the sparticle spectrum. We started our study by scanning the vast parameter space of the MSSM to get the samples of the scenario. During the scan, we considered the constraints adopted in previous literatures, such as those from the DM relic density, the LUX experiment, the searches for the Higgs bosons at colliders as well as B-physics. Next we paid special attention to the important constraints from the direct searches for the sparticles at the 8 TeV LHC, and investigated how and to what extent the samples are limited. For this end, we simulated the $2l + E_T^{\rm miss}$ signal from slepton pair production process and the $2l + E_T^{\rm miss}$ and $3l + E_T^{\rm miss}$ signals from chargino and neutralino associated production processes, and we found that the 8 TeV LHC has excluded a sizable portion of the samples. Subsequently we extended the simulation study to the 14 TeV LHC and concluded that the 14 TeV LHC is much more powerful than the 8 TeV LHC in testing the scenario. Explicitly speaking, we obtained following conclusions

- In case that no excess of the multi-lepton plus $E_T^{\rm miss}$ signals is observed at the 14 TeV LHC, a lower limit on $m_{\tilde{\chi}_1^0}$ will be set at 42 GeV and 44 GeV with 30 fb^{-1} and 100 fb^{-1} data respectively, and the limit can be further pushed up to 55GeV with 300 fb^{-1} data.

- If the light DM scenario is chosen by nature, and meanwhile no SUSY multi-lepton signals are observed at the 14 TeV LHC with 300 fb^{-1} data, most samples of the light DM scenario will be excluded. In this case, $\tilde{\chi}_1^0$ must annihilate in early universe either by s-channel exchange of the SM-like Higgs boson or by t/u-channel slepton mediation. The latter situation then requires that the sleptons must be lighter than about 170 GeV, and their masses differ from that of the $\tilde{\chi}_1^0$ by less than 50 GeV.

- At the 14 TeV LHC with 300 fb^{-1} data, a large portion of the samples in the light DM scenario can be discovered. These samples are characterized by $\mu \lesssim 350$ GeV and a sizable splitting between μ and $m_{\tilde{\chi}_1^0}$.

At the end of this work, we also discussed the capability of the future DM direct detection experiments to test the scenario. We concluded that, for the parameter space we considered, most samples of the scenario can be explored by the LUX-ZEPLIN 7.2 Ton experiment.

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Note added. At the final stage of this work, the paper [85] appeared, which also studied the impact of the direct search for the multi-lepton signals at the 14 TeV LHC on the light DM scenario in the MSSM. Although we adopted different SRs in the searches from those in [85], we got same conclusion that the samples with $\mu \lesssim 500\,\text{GeV}$ in the light DM scenario will be excluded with $300\,\text{fb}^{-1}$ integrated luminosity data. The main difference of the two works is that in [85], the authors got the light DM scenario by fixing $\Omega_{\tilde{\chi}_1^0} h^2 \simeq 0.120$ and varying M_1 and μ, while we got the scenario by an intensive scan over the much vaster parameter space of the MSSM. As a result, our conclusions are more general.

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