

$\mathcal{O}(1)$ GeV dark matter in SUSY and a very light pseudoscalar at the LHC

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ABSTRACT: We analyze the prospects of the detection of an $\mathcal{O}(1)$ GeV neutralino dark matter, $\tilde{\chi}_1^0$, in the Next-to-Minimal Supersymmetric Standard Model at the 14 TeV LHC. We perform dedicated scans of the relevant parameter space of the model and find a large number of points where the thermal relic abundance due to such a dark matter is consistent with the PLANCK measurement. We note that this dark matter is highly singlino-dominated and is always accompanied by a pseudoscalar, A_1 , with a mass around twice its own, which is responsible for its resonant annihilation. For two benchmark points from our scan, we then carry out a detector-level signal-to-background analysis of the pair production of a heavier higgsino neutralino and a chargino. The higgsino thus produced decays into the dark matter and either the Z boson or the A_1 . For the Z -associated production of $\tilde{\chi}_1^0$, we investigate the scope of the trilepton search channel. For the A_1 -associated production mode, in order to identify the two collimated muons coming from the decay of the A_1 , we employ an unconventional method, of clustering them together into one jet-like object. Using this method, for certain parameter space configurations, a much larger sensitivity can be obtained at the 14 TeV LHC for the $A_1\tilde{\chi}_1^0$ channel compared to the $Z\tilde{\chi}_1^0$ channel, with an integrated luminosity of 300 fb^{-1} .

KEYWORDS: Supersymmetry Phenomenology

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Contents

1	Introduction	1
2	The singlet sector of the NMSSM	3
3	Parameter space scan and constraints	6
4	Very light DM via higgsino decays at the LHC	11
4.1	The trilepton channel	11
4.2	Collimated muons from an A_1	12
5	Results and discussion	13
6	Conclusions	16

1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) contains three neutral Higgs states. The lightest one of these, h , is one of the main candidates for the Higgs boson, H_{obs} , observed at the Large Hadron Collider (LHC) [1, 2]. The MSSM also contains a total of four neutralino mass eigenstates, the lightest of which, $\tilde{\chi}_1^0$, is an important dark matter (DM) candidate, when it is also the lightest supersymmetric particle (LSP) and R -parity is conserved. Despite its being a theoretically sound and highly predictive model, the absence of any evidence of supersymmetry (SUSY) during Run-I of the LHC has brought the MSSM under increased scrutiny recently. This is because the only way for h to gain a mass close to the one measured for the H_{obs} is through large radiative corrections from the SUSY sector. The most dominant of these corrections come from the stops, which warrants either TeV-scale SUSY-breaking masses for them or a multi-TeV stop mixing parameter, A_t . This in turn leads to excessive fine-tuning of the model parameters such as the soft masses of the two Higgs doublet fields, H_u and H_d , and the Higgs-higgsino mass parameter μ , given the measured mass of the Z boson.

The parameters of the MSSM get further constrained if one requires, in addition to h fulfilling the role of the observed Higgs boson, $\tilde{\chi}_1^0$ to generate the observed *thermal* DM relic density of the universe, Ω_{DM} , as measured by the WMAP [3] and PLANCK [4] telescopes. This condition is strongly dependent on the interplay between the mass and the composition of the $\tilde{\chi}_1^0$, as these quantities govern its annihilation rate into pairs of SM particles. The $\tilde{\chi}_1^0$ is a pure higgsino when $M_1, M_2 \gg \mu$, with M_1 and M_2 being the soft gaugino masses, and can only yield the correct relic abundance if $\mu \sim 1$ TeV. If $\tilde{\chi}_1^0$ is instead a bino-higgsino mixture, it can give sufficient Ω_{DM} for comparatively smaller masses, by annihilating via chargino/neutralino exchanges into pairs of vector bosons. A predominantly bino-like $\tilde{\chi}_1^0$,

on the other hand, can be consistent with the measured Ω_{DM} for much smaller masses, provided one of the third-generation sfermions is not much heavier than itself. In fact, if such a $\tilde{\chi}_1^0$ has a mass $\lesssim 65$ GeV, it can undergo annihilation via h in the s -channel into a $b\bar{b}$ pair (see, e.g., [5, 6]). For even smaller bino masses, the right amount of s -channel annihilation can occur through the Z boson. Evidently, the cross section for annihilation via h or Z falls abruptly as the difference between $m_{\tilde{\chi}_1^0}$ and $m_h/2$ or $m_Z/2$, respectively, increases. Below $m_{\tilde{\chi}_1^0} \lesssim 30$ GeV it is thus generally impossible to obtain sufficient Ω_{DM} in the MSSM due to the absence of a mediator with the correct mass.

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) [7–10] contains a gauge singlet Higgs superfield, \hat{S} , in addition to the two doublet superfields, \hat{H}_d and \hat{H}_u , of the MSSM. This results in two additional neutral mass eigenstates in the Higgs sector besides the three similar to the MSSM ones. Thus, in total there are seven Higgs bosons in the NMSSM; CP-even $H_{1,2,3}$, CP-odd $A_{1,2}$ and a charged pair, H^\pm . Naturally, the two new Higgs bosons are dominated by the scalar component of \hat{S} , which implies that their couplings to the fermions and gauge bosons of the Standard Model (SM) are typically much smaller than those of the doublet-like Higgs bosons. Their masses are thus generally very weakly constrained by the Higgs boson data from the Large Electron Positron (LEP) collider, the Tevatron or the LHC, and can be as low as a GeV or so. Similarly, the neutralino sector of the NMSSM also contains five mass eigenstates, one more than in the MSSM. The fifth neutralino is dominated by the fermion component of \hat{S} , commonly referred to as the singlino.

In the NMSSM, the role of the H_{obs} can be played by either one of the H_1 and H_2 [11–15] or even by a combination/superposition of these two when both of them lie near 125 GeV [16–18]. Evidently, when H_{obs} is the H_1 , only A_1 can be lighter than it. Conversely, when H_{obs} is the H_2 , there exist the possibilities of either the H_1 alone or both the H_1 and A_1 being lighter than it. Such light H_1 or A_1 can act as mediators for the annihilation of a $\tilde{\chi}_1^0$ as light as a GeV or so in order for it to generate the correct Ω_{DM} — a scenario precluded in the MSSM. Note that the electroweak (EW) baryogenesis may also be accommodated within this framework when the $\tilde{\chi}_1^0$ mass is below 10 GeV [19, 20]. Additionally, a light NMSSM $\tilde{\chi}_1^0$ can explain the galactic centre γ -ray excess [21, 22] observed by the Fermi Large Area Telescope in the presence of a light A_1 [20, 23–25].¹ If the $\tilde{\chi}_1^0$ is even lighter, it has been shown [26, 27] to explain the CDMS-II event excess near 10 GeV [28]. However, further experimental evidence is necessary to confirm whether any of these events are indeed caused by the annihilation of the DM and the jury is still out on its correct mass. While the direct-detection experiments such as DAMA/LIBRA [29], CoGeNT [30, 31], CRESST-II [32], XENON100 [33] and LUX [34] can cover a wide range of the DM mass, it is extremely unlikely for them to reach below ~ 2 GeV [35]. Similarly, while the IceCube neutrino observatory also shows some promise [36] for the indirect detection of the NMSSM DM, the sensitivity for a mass below 10 GeV is very poor.

¹In the case of an H_1 , the s -channel annihilation is p -wave suppressed and hence generally negligible. Furthermore, due to the strong correlation between the masses of H_1 and H_2 , as will be shown later, it is very difficult, although possible, to obtain an H_1 as light as a GeV or so while requiring H_2 to have a mass near 125 GeV.

The Run-II of LHC can prove very crucial in this regard, owing to its potential to probe a very light DM, produced in association with the Z boson or the A_1 in the decays of the heavier neutralinos. In some recent studies [37–41] it has been shown that significant regions of the NMSSM parameter space can be covered by the Z -associated production of the $\tilde{\chi}_1^0$ at the LHC Run-II, with the Z decaying into two leptons. The $\tilde{\chi}_{2,3}^0 \rightarrow A_1 + \tilde{\chi}_1^0$ channel has also shown some promise [42] even for the 8 TeV LHC, with the mass of the A_1 lying above the $\tau^+\tau^-$ production threshold. These search channels can be complemented by those where the light A_1 is not accompanied by the DM. As long as the relic abundance is satisfied for a given SUSY point with a very light DM, observation of the corresponding A_1 , which would be a likely mediator for its annihilation, could serve as a pointer. Such channels include, most importantly, decays of the H_{obs} into $A_1 + A_1$ or $A_1 + Z$ [43–49]. At the Run-I of LHC, light pseudoscalars decaying in the $\mu^+\mu^-$ channel have already been probed, when they are produced either singly in pp collisions [50] or in pairs from the decays of a 125 GeV Higgs boson [51]. These searches thus strongly constrain the parameter space of the NMSSM. Prospects for the observability of A_1 at the 14 TeV LHC have been analyzed in detail recently in [52–54], with the measurement of the mass of H_{obs} providing an additional handle in the kinematic selection of the events. The channels investigated in all these analyses, however, show sufficient sensitivity only for an A_1 heavier than 5 GeV.

In this study we focus on the production of a very light, $\mathcal{O}(1)$ GeV, $\tilde{\chi}_1^0$ via decays of the heavier, higgsino-like, neutralinos of the NMSSM. We perform detailed scans of the NMSSM parameter space to highlight its regions where such a $\tilde{\chi}_1^0$, consistent with the observed relic abundance of the universe, can be obtained in the presence of a SM-like H_2 . We discuss some important characteristics of these parameter regions and of the $\tilde{\chi}_1^0$. We note, in particular, that the $\tilde{\chi}_1^0$ is always accompanied by a pseudoscalar with a mass nearly twice its own. We then carry out comprehensive detector-level analyses of the Z - as well as A_1 -associated productions of the $\tilde{\chi}_1^0$. For the $A_1 + \tilde{\chi}_1^0$ production channel, we adopt an unconventional method for reconstructing the pair of highly collinear muons that result from the subsequent decay of the A_1 . We find that by using our signal reconstruction method the $A_1 + \tilde{\chi}_1^0$ channel can have a better signal strength at the 14 TeV LHC compared to the $Z + \tilde{\chi}_1^0$ channel for certain specific parameter configurations. Therefore, the $A_1 + \tilde{\chi}_1^0$ channel can serve as a crucial probe of new physics, complementing well the $Z + \tilde{\chi}_1^0$ channel for very a low-mass singlino-dominated DM.

The article is organized as follows. In section 2, we will briefly discuss the NMSSM and its singlet sector. In section 3 we will present some details of our findings from the numerical scans of the NMSSM parameter space. In section 4 we will explain our signal-to-background analyses and in section 5 we will show their results. We will present our conclusions in section 6.

2 The singlet sector of the NMSSM

The scale-invariant superpotential of the NMSSM (see, e.g., [55, 56] for reviews) is written as

$$W_{\text{NMSSM}} = \text{MSSM Yukawa terms} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3, \quad (2.1)$$

where λ and κ are dimensionless Yukawa couplings. The above superpotential observes a discrete Z_3 symmetry, which forbids the $\mu\widehat{H}_u\widehat{H}_d$ term present in the MSSM superpotential and at the same time breaks the dangerous Peccei-Quinn (PQ) symmetry [57, 58]. Here, an effective μ -term is generated upon spontaneous symmetry breaking, when \widehat{S} develops a vacuum expectation value (VEV), $s \equiv \langle \widehat{S} \rangle$, so that $\mu_{\text{eff}} = \lambda s$. The soft SUSY-breaking terms in the scalar Higgs sector are then given by

$$V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right). \quad (2.2)$$

Through the minimization conditions of the complete tree-level Higgs potential, the soft masses m_{H_u} , m_{H_d} and m_S can be traded for the respective VEVs, v_u , v_d and s , of the corresponding Higgs fields.

The neutral scalar and pseudoscalar Higgs mass matrices are obtained from the Higgs potential evaluated at the vacuum. Diagonalization of these matrices yields the mass expressions for the five neutral Higgs bosons. The tree-level masses of the two lightest CP-even Higgs bosons, which are of our interest here, can be approximated, for moderate-to-large $\tan\beta$ ($\equiv v_u/v_d$) and EW-scale dimensionful parameters, by [59]

$$m_{H_{1,2}}^2 \approx \frac{1}{2} \left\{ m_Z^2 + 4(\kappa s)^2 + \kappa s A_\kappa \mp \sqrt{[m_Z^2 - 4(\kappa s)^2 - \kappa s A_\kappa]^2 + 4\lambda^2 v^2 [2\lambda s - (A_\lambda + \kappa s) \sin 2\beta]^2} \right\}, \quad (2.3)$$

where $v \equiv \sqrt{v_u^2 + v_d^2} \simeq 174$ GeV. Thus there is a strong correlation between the masses of H_1 and H_2 , implying that requiring one of these to lie near 125 GeV constrains the other also. Similarly, the tree-level mass of the singlet-like pseudoscalar can be given, assuming negligible singlet-doublet mixing, by the approximate expression

$$m_{A_1}^2 \simeq \lambda(A_\lambda + 4\kappa s) \frac{v^2 \sin 2\beta}{2s} - 3\kappa s A_\kappa. \quad (2.4)$$

The neutralino mass matrix in the NMSSM is written as

$$\mathcal{M}_{\widetilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_W \tan \theta_W \cos \beta & m_W \tan \theta_W \sin \beta & 0 \\ 0 & M_2 & m_W \cos \beta & -m_W \sin \beta & 0 \\ -m_W \tan \theta_W \cos \beta & m_W \cos \beta & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ m_W \tan \theta_W \sin \beta & -m_W \sin \beta & -\mu_{\text{eff}} & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & 2\kappa s \end{pmatrix}, \quad (2.5)$$

with m_W being the mass of the W boson and θ_W being the weak mixing angle. This symmetric mass matrix can be diagonalized by a unitary matrix N to obtain the five neutralino states, $\widetilde{\chi}_{1-5}^0$, ordered by their masses, implying that the $\widetilde{\chi}_1^0$ is the LSP. This mass eigenstate is given by the linear combination

$$\widetilde{\chi}_1^0 = N_{11} \widetilde{B}^0 + N_{12} \widetilde{W}_3^0 + N_{13} \widetilde{H}_d^0 + N_{14} \widetilde{H}_u^0 + N_{15} \widetilde{S}^0. \quad (2.6)$$

We define the gaugino fraction in $\widetilde{\chi}_1^0$ as $Z_g = |N_{11}|^2 + |N_{12}|^2$, the higgsino fraction as $Z_h = |N_{13}|^2 + |N_{14}|^2$ and the singlino fraction as $Z_s = |N_{15}|^2$. The composition of $\widetilde{\chi}_1^0$ thus depends on the values of the various model parameters appearing in the above mass matrix.

In the MSSM, the fifth row and column, corresponding to the singlino and hence containing the λ -dependent terms, do not exist. There, the smaller the μ compared to the $\min[M_1, M_2]$, the larger the higgsino fraction in $\tilde{\chi}_1^0$. Since the mass of the higgsino-like chargino, which is the lighter $\tilde{\chi}_1^\pm$ in this case, is also proportional to μ , the value of this parameter is bounded from below to around 100 GeV by the non-observation of a chargino at the large electron positron (LEP) collider. On the other hand, in order to avoid excessive fine-tuning of the model parameters for obtaining the correct Higgs boson mass, μ ought not to be too large. However, a purely higgsino LSP does not give the correct thermal relic density for masses below ~ 1 TeV, as the annihilation cross section becomes too large. Therefore, the only way for the $\tilde{\chi}_1^0$ in the MSSM to give good relic abundance with a mass $\mathcal{O}(10)$ GeV is to have a sizable bino component [6, 60].

In the NMSSM, the presence of the singlino leads to some additional possibilities in the context of DM phenomenology. In the limit $\mu_{\text{eff}} \ll \min[M_1, M_2]$, the term $[\mathcal{M}_{\tilde{\chi}^0}]_{55} = 2\kappa s = 2\frac{\kappa\mu_{\text{eff}}}{\lambda}$ in eq. (2.5) implies that the LSP is singlino-dominated for $2\kappa/\lambda < 1$. The singlino fraction in $\tilde{\chi}_1^0$ can be increased by reducing κ . One could alternatively increase λ , while keeping μ_{eff} fixed, to reduce the size of the $[\mathcal{M}_{\tilde{\chi}^0}]_{55}$ term, but this also enlarges the sizes of the off-diagonal mixing terms. Eq. (2.4) shows that the mass of A_1 also scales with κs . Thus a light singlino-like $\tilde{\chi}_1^0$ can be naturally accompanied by a light A_1 . Note that the strong correlation, eq. (2.3), between the H_2 mass, which is required to be around 125 GeV, and the H_1 mass generally prevents the latter from taking very low values, although it also scales mainly with κs . Importantly though, even if H_1 has a mass close to $2\tilde{\chi}_1^0$, the $\tilde{\chi}_1^0$ annihilation via s -channel H_1 is p -wave suppressed, which would make it extremely difficult to generate the correct thermal relic abundance. We therefore focus only on a light A_1 here, which can result in the singlino-like $\tilde{\chi}_1^0$ yielding the correct relic density even with its mass around a GeV.

As noted in the Introduction, the light $\tilde{\chi}_1^0$ can be produced in the decays of the heavier neutralinos. In particular, the $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ as well as the $\tilde{\chi}_1^\pm$ in this scenario with a light singlino-like DM are predominantly higgsinos [42]. Their main production channel is $pp \rightarrow \tilde{\chi}_{2,3}^0 + \tilde{\chi}_1^\pm$, which is followed by the decays $\tilde{\chi}_{2,3}^0 \rightarrow Z/A_1 + \tilde{\chi}_1^0 \rightarrow \ell^+\ell^- + \cancel{E}_T$ and $\tilde{\chi}_1^\pm \rightarrow W^\pm + \tilde{\chi}_1^0 \rightarrow \ell^\pm + \cancel{E}_T$, where \cancel{E}_T implies missing transverse energy. The complete processes are shown in figure 1, (a) and (b). The $Z + \tilde{\chi}_1^0$ decay channel of the $\tilde{\chi}_{2,3}^0$ is by far the dominant one, while $\tilde{\chi}_{2,3}^0 \rightarrow A_1 + \tilde{\chi}_1^0$ is generally suppressed. The $Z + W + \cancel{E}_T$ production, which results in trileptonic final states, is therefore the preferred search channel for the higgsinos, also since it has minimal dependence on $m_{\tilde{\chi}_1^0}$. Dedicated searches carried out by both the CMS and ATLAS collaborations [61–63] have either already put strong constraints on significant regions of the NMSSM parameter space or are likely to cover large portions of it, where the $\tilde{\chi}_1^0$ can be as light as a GeV, at the LHC Run-II.

It is, however, important to note that, for sufficiently large values of the parameter λ , the branching ratio (BR) for the $\tilde{\chi}_{2,3}^0 \rightarrow A_1 + \tilde{\chi}_1^0$ decay channel, while still subdominant, can become sizable. For A_1 masses of interest here, i.e., below the $\tau^+\tau^-$ threshold, the decay mode with the largest BR is $A_1 \rightarrow c\bar{c}$. The main leptonic decay channel, $A_1 \rightarrow \mu^+\mu^-$, is highly subdominant, with its BR never exceeding 9%, as we shall see below. This value is still larger than twice that of the $\text{BR}(Z \rightarrow \mu^+\mu^-) (\simeq 0.034)$. But one challenge that arises

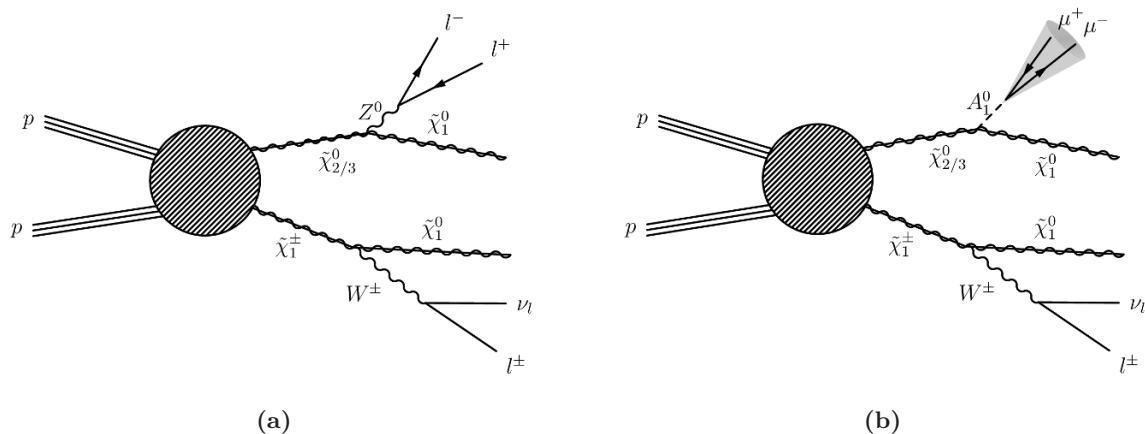


Figure 1. Production process for the $\tilde{\chi}_{2,3}^0 \tilde{\chi}_1^\pm$ pair, with the $\tilde{\chi}_{2,3}^0$ decaying via (a) $Z + \tilde{\chi}_1^0$ and (b) $A_1 + \tilde{\chi}_1^0$.

in this context is the reconstruction of the very light A_1 from two highly collinear muons it decays into and the isolation of this signal from the background. As long as this complication can be overcome, the two observations above imply that the $A_1 + \tilde{\chi}_1^0$ search channel can possibly complement the $Z\tilde{\chi}_1^0$ channel for certain specific NMSSM parameter space points. In the following sections we will analyze such parameter combinations and also introduce our method for reconstructing the very light A_1 from two collinear muons. We should point out here that while in principle the same method can alternatively be used to probe these A_1 's in the decays of the heavy CP-even Higgses, our requirement of the presence of \cancel{E}_T in the final state, as an indication of light DM, renders these channels irrelevant here.

3 Parameter space scan and constraints

Due to the presence of the additional singlet superfield, the NMSSM contains several new parameters besides the 115 or so of the MSSM at the EW scale. However, assuming the sfermion mass matrices and the scalar trilinear coupling matrices to be diagonal reduces the parameter space of the model considerably. In this study, since our main focus is the higgsino-singlino sector, we further assume the following universality conditions.

$$\begin{aligned}
 M_0 &\equiv M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = M_{L_{1,2,3}} = M_{E_{1,2,3}}, \\
 M_{1/2} &\equiv 2M_1 = M_2 = \frac{1}{3}M_3, \\
 A_0 &\equiv A_t = A_b = A_\tau,
 \end{aligned}
 \tag{3.1}$$

where $M_{Q_{1,2,3}}$, $M_{U_{1,2,3}}$, $M_{D_{1,2,3}}$, $M_{L_{1,2,3}}$ and $M_{E_{1,2,3}}$ are the soft masses of the sfermions, $M_{1,2,3}$ those of the gauginos and $A_{t,b,\tau}$ the trilinear Higgs-sfermion couplings. Along with M_0 , $M_{1/2}$ and A_0 , the model then contains λ , κ , μ_{eff} , $\tan\beta$, A_λ and A_κ as the only free parameters, which are input at the SUSY-breaking scale, $M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, with $m_{\tilde{t}_{1,2}}$ being the physical masses of the two stops.

Parameter	Scanned range
M_0 (GeV)	500–2000
$M_{1/2}$ (GeV)	300–1000
A_0 (GeV)	0–4000
μ_{eff} (GeV)	100–300
$\tan \beta$	6–25
λ	0.01–0.4
κ	10^{-5} – 10^{-1}
A_λ (GeV)	0–5000
A_κ (GeV)	–100–0

Table 1. Ranges of the NMSSM input parameters scanned for obtaining $\tilde{\chi}_1^0$ with a mass below 2 GeV.

We performed a scan of the above mentioned nine parameters using the nested sampling package MULTINEST-v2.18 [64], which was interfaced with NMSSMTOOLS-v4.5.0 [65–68] for calculation of the SUSY mass spectrum and BRs for each model point sampled. The scanned ranges of the parameters are given in table 1 and were chosen, based loosely on the findings of [42], to maximally yield points with $m_{\tilde{\chi}_1^0} \lesssim 2$ GeV as well as the H_2 having a mass near the one measured for the H_{obs} at the LHC. The H_2 was additionally required to have SM-like signal rates. The signal rate, obtained from NMSSMTOOLS as an output, is defined, for a given decay channel X , as

$$R^X \equiv \frac{\sigma(gg \rightarrow H_2) \times \text{BR}(H_2 \rightarrow X)}{\sigma(gg \rightarrow h_{\text{SM}}) \times \text{BR}(h_{\text{SM}} \rightarrow X)}, \quad (3.2)$$

where h_{SM} is the SM Higgs boson with a mass equal to m_{H_2} .

A very light A_1 is subject to constraints from direct collider searches as well as from flavor physics [69]. The program NMSSMTOOLS intrinsically takes into account the exclusion limits on pseudoscalars from LEP and BaBar as well as from the 4μ searches at the CMS [51]. Additionally, It ensures that the LEP limit on the $\tilde{\chi}_1^\pm$ mass and the perturbativity constraints on the various Higgs boson couplings are satisfied and that the $\tilde{\chi}_1^0$ is the LSP. We further required each scanned point to satisfy the following constraints:

- $2.63 \times 10^{-4} \leq \text{BR}(\bar{B} \rightarrow X_s \gamma) \leq 4.23 \times 10^{-4}$,
- $0.71 \times 10^{-4} \leq \text{BR}(B_u \rightarrow \tau \nu) \leq 2.57 \times 10^{-4}$,
- $1.3 \times 10^{-9} \leq \text{BR}(B_s \rightarrow \mu^+ \mu^-) \leq 4.5 \times 10^{-9}$,
- $0.107 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.131$,
- $122 \text{ GeV} \leq m_{H_2} \leq 128 \text{ GeV}$.

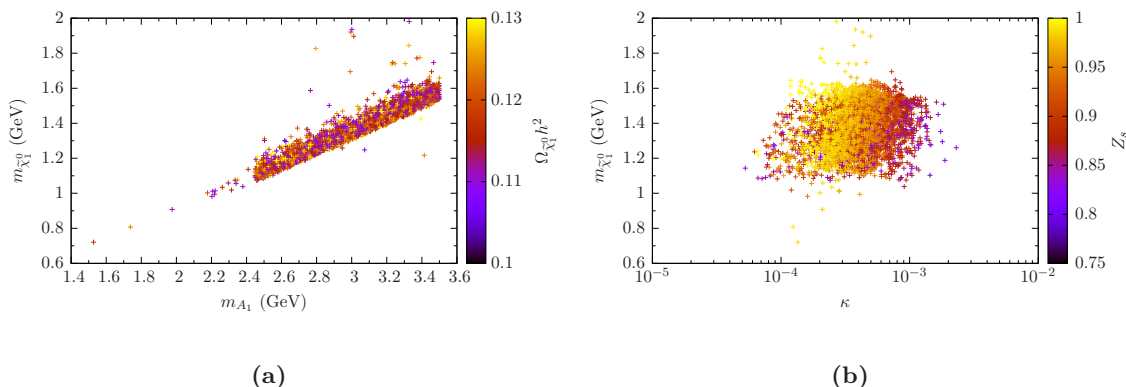


Figure 2. (a) The distribution of the $\tilde{\chi}_1^0$ mass vs. that of the A_1 mass, with the heat map corresponding to the relic abundance. (b) The dependence of $m_{\tilde{\chi}_1^0}$ on the parameter κ . The heat map shows the singlino fraction in the $\tilde{\chi}_1^0$.

The b -physics observables above were calculated using the package SUPERISO-v3.4 [70] and the relic density using the MICROMEAS-v4.1.5 [71] package. The allowed range of $\Omega_{\tilde{\chi}_1^0}$ assumes a $\pm 10\%$ theoretical error around the central value of 0.119 measured by the PLANCK telescope [4]. Similarly an error of ± 3 GeV is allowed in the theoretical estimation of the H_2 mass, given the H_{obs} mass measurement of 125 GeV at the LHC. Consistency with the LEP and LHC exclusion limits on the non-SM-like Higgs bosons, including the A_1 , was further ensured by testing each point that passed the above constraints with the program HIGGSBOUNDS-v4.2.0 [72–75].

In figure 2(a) we show the ranges of the A_1 and $\tilde{\chi}_1^0$ masses obtained for the good points from our scan. The heat map corresponds to the $\tilde{\chi}_1^0$ relic density. One can see a strong correlation between $m_{\tilde{\chi}_1^0}$ and m_{A_1} , with the former almost always being half of the latter in order for the resonant annihilation of the $\tilde{\chi}_1^0$ via the A_1 . The tiny $\tilde{\chi}_1^0$ masses are a result of vanishing κ as seen in figure 2(b), implying an almost PQ-symmetric model. The heat map in the figure shows the distribution of the singlino fraction in the $\tilde{\chi}_1^0$ which increases as κ decreases and is always larger than 0.75. A large singlino component implies a small higgsino fraction, which is necessary to prevent an under abundance of the $\tilde{\chi}_1^0$ from too much annihilation. Figure 3(a) illustrates that the A_1 is restricted to a lower mass, needed for satisfying the relic density constraint, by adjusting A_κ to a narrow range of low negative values. This is in agreement with eq. (2.4), along with the fact that λ , illustrated by the heat map in the figure, also generally tends to be small. In figure 3(b) the distributions of the parameters A_λ and μ_{eff} are shown against the H_1 mass range obtained in the scan. We see that when both A_λ and $\tan\beta$ are small m_{H_1} is low, while its maximum value, ~ 45 GeV, is obtained for the largest allowed values of A_λ , with $\tan\beta \gtrsim 10$.

Figure 4(a) shows that the mass of the $\tilde{\chi}_2^0$ is almost equal to the parameter μ_{eff} as long the parameter $M_{1/2}$, given by the color map, approaches its maximum allowed value. As the splitting between $M_{1/2}$ and μ_{eff} decreases, the gaugino-higgsino mixing increases,

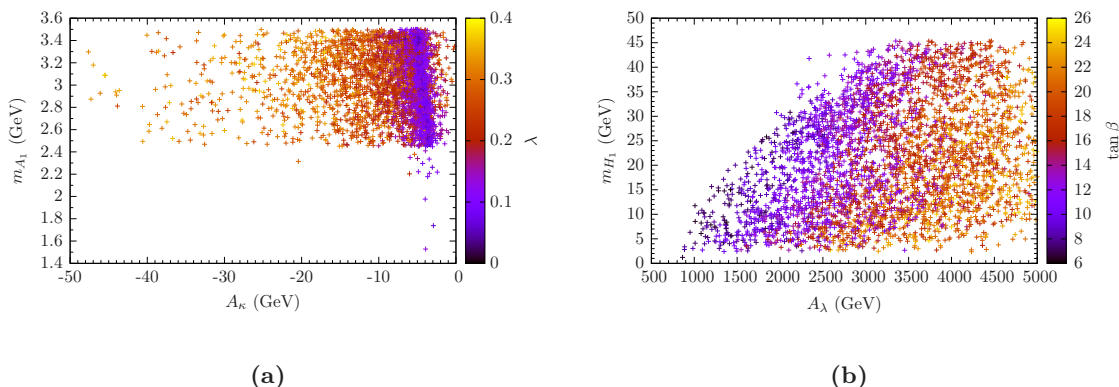


Figure 3. (a) The mass of A_1 as a function of the parameters A_{κ} and λ . (b) The mass of H_1 vs. the distributions of the parameters A_{λ} and $\tan \beta$.

which results in somewhat lowering $m_{\tilde{\chi}_2^0}$ relative to μ_{eff} . Figure 4(b) similarly shows that, since the $\tilde{\chi}_3^0$ and the $\tilde{\chi}_1^{\pm}$ are higgsino-like as well, their masses are also proportional to μ_{eff} . Moreover, the $\tilde{\chi}_1^{\pm}$ is always almost mass-degenerate with $\tilde{\chi}_2^0$, while $\tilde{\chi}_3^0$ is generally heavier than both of them, but only slightly so.² Figure 5(a) illustrates that the $\text{BR}(\tilde{\chi}_2^0 \rightarrow A_1 \tilde{\chi}_1^0)$ increases with λ , shown by the heat map. This is because, for vanishing singlet-doublet mixing in the pseudoscalar mass matrix as well as singlino-higgsino mixing in the neutralino mass matrix, the coupling between the A_1 , $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$, given by eq. (A.14) of [55], can be approximated by the simple relation

$$g_{A_1 \tilde{\chi}_1^0 \tilde{\chi}_2^0} \approx -\frac{i}{20}(\lambda - 2\sqrt{2}\kappa). \quad (3.3)$$

Still, the $\text{BR}(\tilde{\chi}_2^0 \rightarrow A_1 \tilde{\chi}_1^0)$ exceeds 10% only for a few points, reaching as high as about 30% for a couple of them. On the other hand, the $\text{BR}(\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0)$, given on the x -axis, drops quite sharply with increasing λ and can reach as low as about 30%. This is due mainly to the fact that the $\text{BR}(\tilde{\chi}_2^0 \rightarrow H_2 \tilde{\chi}_1^0)$ (not shown here) also rises, much more abruptly than the $\text{BR}(\tilde{\chi}_2^0 \rightarrow A_1 \tilde{\chi}_1^0)$, as λ increases. Figure 5(b) shows that the $\text{BR}(\tilde{\chi}_3^0 \rightarrow A_1 \tilde{\chi}_1^0)$ never exceeds 9% while the $\text{BR}(\tilde{\chi}_3^0 \rightarrow Z \tilde{\chi}_1^0)$ never falls below 50%, implying a relatively weaker dependence on λ . The heat map in the figure shows that the maximum $\text{BR}(A_1 \rightarrow \mu^+ \mu^-)$ achievable is 9%. Note that the $\text{BR}(\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} \tilde{\chi}_1^0)$ is unity for all the points shown in these figures.

We point out here that we also carried out a test scan of the NMSSM with partial universality at the grand unification (GUT) scale. In this model the unified scalar mass parameter, m_0 , the universal gaugino mass, $m_{1/2}$, the universal Higgs-sfermion trilinear couplings, a_0 , as well as the parameters a_{λ} and a_{κ} are input at the GUT scale. The EW scale values of the individual soft scalar and gaugino masses and of all the Higgs trilinear couplings are obtained by the running of these parameters using the renormalization group

²Due to the nature of the neutralino mass matrix, given in eq. (2.5), both positive and negative values of the $\tilde{\chi}_3^0$ mass are possible, although we show here only negative valued solutions. Positivity of $m_{\tilde{\chi}_3^0}$ can be ensured a priori by a phase transformation.

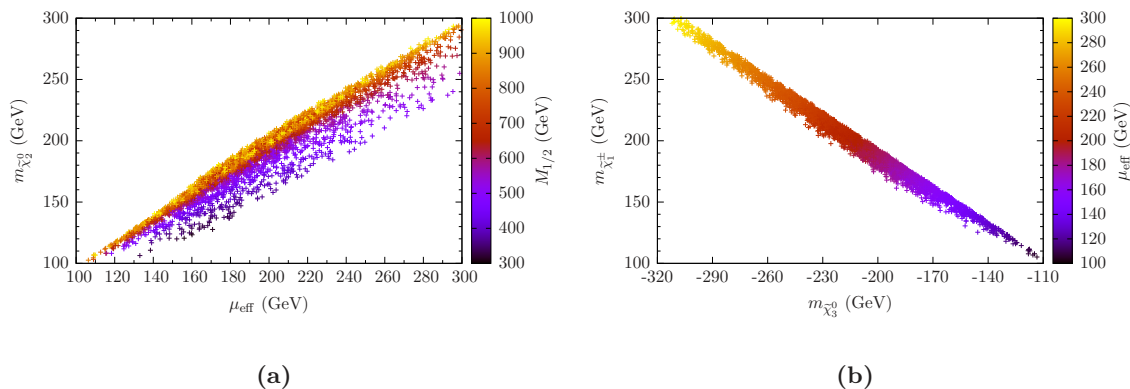


Figure 4. (a) The $\tilde{\chi}_2^0$ mass as a function of the parameter μ_{eff} . The color map shows the dependence on $M_{1/2}$. (b) The distribution of the $\tilde{\chi}_3^0$ and $\tilde{\chi}_1^\pm$ masses vs. μ_{eff} , shown by the heat map.

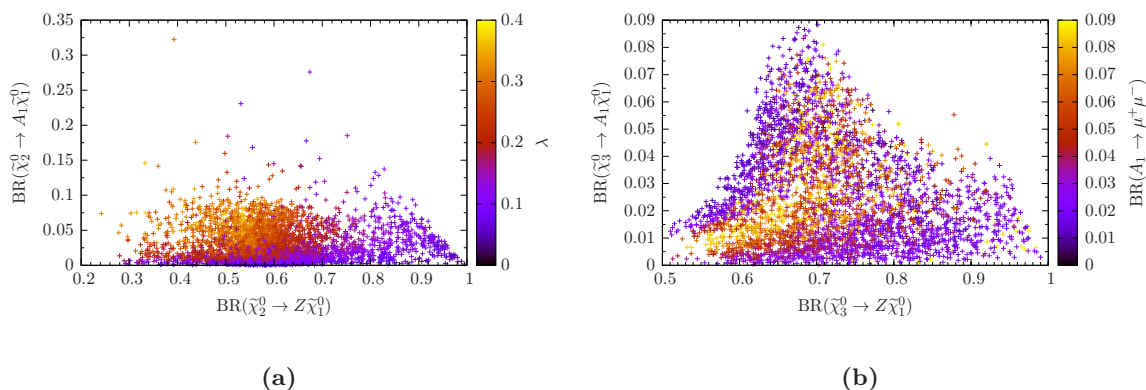


Figure 5. (a) The $\text{BR}(\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0)$ and the $\text{BR}(\tilde{\chi}_2^0 \rightarrow A_1 \tilde{\chi}_1^0)$ as functions of the parameter λ . (b) The $\text{BR}(\tilde{\chi}_3^0 \rightarrow Z \tilde{\chi}_1^0)$ vs. the $\text{BR}(\tilde{\chi}_3^0 \rightarrow A_1 \tilde{\chi}_1^0)$, with the heat map corresponding to the $\text{BR}(A_1 \rightarrow \mu^+ \mu^-)$.

equations. The other Higgs sector parameters, λ , κ , μ_{eff} and $\tan \beta$ are input at M_{SUSY} . But, owing particularly to the GUT scale definition of the parameters a_λ and a_κ , severe fine-tuning is necessary in this model for the scan to find the right combinations of these parameters at M_{SUSY} that yield both H_2 and A_1 with the desired masses.

As noted above in figure 3(a), A_κ at M_{SUSY} is restricted to a narrow range of values, which would imply an even smaller set of its possible values at the GUT scale. Furthermore, the SUSY-preserving parameter κ is also very small due to our requirement of $m_{\tilde{\chi}_1^0} \sim 1.5 \text{ GeV}$, though the approximate PQ symmetry this results in still avoids the cosmological constraints on the PQ axion [76]. Keeping μ_{eff} around the EW scale, κ is typically smaller than 0.01λ . Despite all these limiting conditions, some points with the right masses of the $\tilde{\chi}_1^0$ and A_1 were indeed found. However, they did not cover, for example, the wide range

Selection	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
m_{SFOS}	< 60	$60 - 81.2$	< 81.2 or > 101.2	$81.2 - 101.2$	$81.2 - 101.2$	$81.2 - 101.2$
\cancel{E}_T	> 50	> 75	> 75	$75 - 120$	$75 - 120$	> 120
M_T	–	–	> 110	< 110	> 110	> 110
$p_{T(\ell_3)}$	> 10	> 10	> 30	> 10	> 10	> 10
SR veto	SRnoZc	SRnoZc	–	–	–	–

Table 2. Selection requirements for the six signal regions defined for the trilepton searches by the ATLAS collaboration. All the dimensionful parameters in rows 2 – 5 are in units of GeV.

of the $\text{BR}(\tilde{\chi}_2^0 \rightarrow A_1 \tilde{\chi}_1^0)$ seen in figure 5(a), which stretches beyond 0.1. We therefore opted for the 9-parameter EW-scale NMSSM for this study.

4 Very light DM via higgsino decays at the LHC

For our signal-to-background analyses, we selected two benchmark points, BP1 and BP2, out of the good points from the NMSSM parameter space scan. BP1 is chosen such that the $\text{BR}(\tilde{\chi}_{2,3}^0 \rightarrow Z \tilde{\chi}_1^0)$ is sufficiently large, while BP2 has a relatively enhanced $\text{BR}(\tilde{\chi}_{2,3}^0 \rightarrow A_1 \tilde{\chi}_1^0)$. The parton-level signal and background events for these points were generated with MADGRAPH5_aMC@NLO [77] and passed to PYTHIA 6.4 [78] for hadronization.

4.1 The trilepton channel

As noted earlier, the ATLAS and CMS experiments have separately performed searches for trileptons (3ℓ) [61–63] resulting from the $\tilde{\chi}_{2,3}^0 \tilde{\chi}_1^\pm$ pair production. In the ATLAS 3ℓ search [61], which is the one we will consider in the following, six signal regions (SRs) are defined in terms of the invariant mass of two same flavor leptons with opposite sign (SFOS), m_{SFOS} . These regions also depend on the momentum, $p_{T(\ell_3)}$, of the third lepton, ℓ_3 , that is left after requiring two SFOS leptons to reconstruct m_{SFOS} , \cancel{E}_T and the transverse mass, $M_T = \sqrt{2 \cancel{E}_T p_{T(\ell_3)} (1 - \cos \Delta\phi_{\ell_3, \cancel{E}_T})}$, where $\Delta\phi_{\ell_3, \cancel{E}_T}$ is the azimuthal angle between \cancel{E}_T and the ℓ_3 . The signal regions are divided into three ‘Z-enriched’ ones, SRZ{a,b,c}, where m_{SFOS} lies within 10 GeV of m_Z , and three ‘Z-depleted’ ones, SRnoZ{a,b,c}, where m_{SFOS} lies outside this mass window. Table 2 further shows the selection requirements for each of these six regions.

The irreducible backgrounds include di-boson, tri-boson and $t\bar{t}W/Z$ productions, all of which can have three or more leptons and \cancel{E}_T in the final states. The ZZ and ZW^\pm backgrounds are by far dominant over the $t\bar{t}W/Z$ one [61]. Among the reducible backgrounds are included top quarks produced singly or in pairs, WW and W or Z bosons produced in association with jets or photons. Among these the $t\bar{t}$ background is highly dominant. For each BP, the cross section for the signal process was calculated at next-to-leading order (NLO) using PROSPINO-v2.1 [79]. We then first generated the event files corresponding to $\sqrt{s} = 8$ TeV for the signal process and passed these to the public package CHECKMATE-v1.2.0 [80] for testing against the current LHC limits from the trilepton

searches. In CHECKMATE the signal regions given in table 2 have been defined and the corresponding backgrounds from the ATLAS experiment implemented. For testing a model point it therefore calculates the signal efficiency for each region, after ATLAS detector simulation with DELPHES 3 [81].

After confirming that the given BP is not excluded by the available data, we proceeded to the future 3ℓ search at the 14 TeV LHC. We generated the signal event files for $\sqrt{s} = 14$ TeV and passed these to CHECKMATE again. In this way we obtained the signal efficiencies, after multiplying the NLO cross section with an assumed integrated luminosity, \mathcal{L} , of 300 fb^{-1} (i.e., design luminosity of the LHC) to get the number of signal events in each signal region.

As for the backgrounds, we only simulated the three dominant ones, ZZ , ZW^\pm and $t\bar{t}$, for the 14 TeV LHC. We used MADGRAPH5 to generate the background events and passed these to CHECKMATE to get the cut efficiencies for all the backgrounds in each signal region. After multiplying the NLO cross section [82, 83] and the luminosity, we got the number of background events in each signal region.

4.2 Collimated muons from an A_1

Due to the smallness of the A_1 mass of our interest here, the muons it decays into are highly collinear. In order to isolate such muons, we employ the technique of clustering them together into one object, μ_{col} . This method, similar in concept to the construction of a ‘lepton-jet’ [84–89], has recently been shown in [90] to be very effective for probing highly mass-degenerate higgsinos.

For using this method, the signal events generated for BP1 and BP2 were passed to PYTHIA 6.4 for hadronization and subsequently to DELPHES 3 for jet-clustering via the anti- k_T [91] algorithm using FASTJET-v3.0.6 [92]. The object μ_{col} is constructed as follows.

1. Require the transverse momentum, p_T , larger than 10 GeV for each muon in the signal. In addition, impose the cut $m_{\mu\bar{\mu}} < 5$ GeV on the invariant mass of the muon pair.
2. Define I_{sum} as the scalar sum of the transverse momenta of all additional charged tracks, each with $p_T > 0.5$ GeV, within a cone centered along the momentum vector of μ_{col} and satisfying $\Delta R = 0.4$. Impose $I_{\text{sum}} < 3$ GeV.

The main backgrounds, containing two collinear muons along with a third lepton and \cancel{E}_T , include $W(\rightarrow \ell^\pm \nu)\gamma^*$ and $Z(\rightarrow \ell^+ \ell^-)\gamma^*$, wherein the μ_{col} comes from the photon, and $Wb\bar{b}$, when one of the b -jets produces the μ_{col} . The $Z\gamma^*$ background fakes the signal process when one of the two leptons escape undetected. Note that while the $t\bar{t}$ background mentioned above for the 3ℓ search is also relevant for this signal process, it becomes negligible here owing to the requirement of the two final state muons being highly collinear. In order to isolate these backgrounds, we implement the following cuts.

1. Since the A_1 resulting from the higgsino decay is highly boosted, we expect the μ_{col} from its subsequent decay to have a large p_T . We therefore require $p_{T(\mu_{\text{col}})} > 50$ GeV. We also require $p_{T(\ell_3)} > 20$ GeV.

2. In order to reduce the background a large \cancel{E}_T is required, so we add the cut $\cancel{E}_T > 50 \text{ GeV}$.
3. In the $W\gamma^*$ background the M_T distribution has an end point around the W boson mass, which leads us to impose $M_T > 80 \text{ GeV}$.
4. Our signal would appear as a narrow peak in the $m_{\mu_{\text{col}}}$ distribution. Hence, we impose a narrow cut width, $5 \times \sigma_{A_1}$, where $\sigma_{A_1} = 0.26 + 0.0013m_{A_1}$, around m_{A_1} . This parametrization of σ_{A_1} follows the mass resolution study of the J/Ψ resonance in [93]. We also remove the J/Ψ resonance region ($3.0 \text{ GeV} < m_{\mu_{\text{col}}} < 3.2 \text{ GeV}$).

To get a sufficient number of Monte Carlo events in the kinematic regime of our interest, we require $m_{\mu\bar{\mu}} > 1.5 \text{ GeV}$ and $p_{T(\ell_3)} > 10 \text{ GeV}$ at the parton level for the $W\gamma^*$ and $Z\gamma^*$ backgrounds. For the $Wb\bar{b}$ background, we additionally require the p_T of the b -jet to be larger than 30 GeV .

5 Results and discussion

In table 3 are recorded some specifics of the two BPs used for the signal-to-background analyses. The consistency of each of the H_2 signal rates given in the last three rows of the table is to be checked against the experimental quantity $\mu^X \equiv \frac{\sigma(pp \rightarrow H_{\text{obs}} \rightarrow X)}{\sigma(pp \rightarrow h_{\text{SM}} \rightarrow X)}$ for each corresponding channel X . Note that this comparison assumes that the inclusive pp cross section for H_2 production can be approximated by the dominant gluon-fusion production cross section. Note also that, since the WW and ZZ decays of H_2 are proportional to the same coupling, NMSMTOOLS provides a unique value of the signal rates for these two channels, which we denote by R^{VV} in the table. The most recent measurements of μ^X by the CMS (ATLAS) collaboration(s) read [94–97]

$$\begin{aligned}
 \mu^{\gamma\gamma} &= 1.13 \pm 0.24 (1.17 \pm 0.27), \\
 \mu^{ZZ(WW)} &= 1.0 \pm 0.29 (1.09_{-0.21}^{+0.23}), \\
 \mu^{\tau\tau} &= 0.91 \pm 0.28 (1.4_{-0.4}^{+0.5}).
 \end{aligned}
 \tag{5.1}$$

Using each of the two analysis methods described in the previous section we calculated the number of signal events, S , and that of background events, B , for each BP at the LHC with $\sqrt{s} = 14 \text{ TeV}$ and $\mathcal{L} = 300 \text{ fb}^{-1}$. In table 4 we provide the S and B corresponding to each of the six signal regions in the ATLAS 3ℓ search. The total signal cross sections obtained are 24.3 fb and 3.93 fb for BP1 and BP2, respectively. In the Z -enriched region, ZW^\pm production dominates the total background. In the Z -depleted region, a comparable contribution is obtained from the $t\bar{t}$ background. One can notice in the table that for both the BPs, the highest sensitivity is obtained in the signal region SRZc.

In the μ_{col} channel, the cross sections for the signal and background processes are given in table 5 for the BP1, along with the efficiency of the cuts and the effective cross sections and numbers of events after implementing these cuts. One notices that the $Wb\bar{b}$ is by far the largest background. It, however, gets greatly reduced by the cuts, after which $W\gamma^*$

	BP1	BP2
<i>Model parameters</i>		
M_0 (GeV)	1951.1	1826.0
$M_{1/2}$ (GeV)	892.24	929.2
A_0 (GeV)	2462.2	2626.2
μ_{eff} (GeV)	191.34	164.52
$\tan \beta$	14.056	19.785
λ	0.0814	0.3102
κ	0.0002	0.0008
A_λ (GeV)	4080.2	3596.7
A_κ (GeV)	-3.6681	-6.8466
<i>Masses</i>		
$m_{\tilde{\chi}_1^0}$ (GeV)	1.0025	1.4081
$m_{\tilde{\chi}_2^0}$ (GeV)	189.09	170.13
$m_{\tilde{\chi}_3^0}$ (GeV)	-201.67	-182.27
$m_{\tilde{\chi}_1^\pm}$ (GeV)	194.97	167.72
m_{A_1} (GeV)	2.1776	2.9856
m_{H_2} (GeV)	124.12	125.79
<i>Branching ratios</i>		
$BR(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0)$	0.634	0.603
$BR(\tilde{\chi}_2^0 \rightarrow A_1\tilde{\chi}_1^0)$	0.004	0.089
$BR(\tilde{\chi}_3^0 \rightarrow Z\tilde{\chi}_1^0)$	0.736	0.704
$BR(\tilde{\chi}_3^0 \rightarrow A_1\tilde{\chi}_1^0)$	0.004	0.081
$BR(A_1 \rightarrow \mu^+\mu^-)$	0.039	0.087
<i>H_2 signal rates</i>		
$R^{\gamma\gamma}$	0.998	0.901
R^{VV}	0.996	0.885
$R^{\tau\tau}$	1.003	0.847

Table 3. Properties of the two benchmark points used for the signal-to-background analyses.

Background or signal	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
ZZ events	410	59	10	280	39	12
ZW^\pm events	1391	595	71	6850	661	189
$t\bar{t}$ events	1715	401	62	272	178	19
All background events	3516	1055	143	7402	878	220
BP1 signal events	12	37	19	191	134	130
BP2 signal events	20	46	18	270	144	96

Table 4. The number of background and signal events at the 14 TeV LHC for $\mathcal{L} = 300 \text{ fb}^{-1}$ in each of the signal regions of the ATLAS 3ℓ search.

	BP1	$W\gamma^*$	$Z\gamma^*$	$Wb\bar{b}$
Cross section (fb)	0.178	246.9	10.0	3770.0
Cut efficiency	0.123	2.15×10^{-4}	6×10^{-5}	1×10^{-6}
Effective cross section (fb)	0.022	0.053	0.0006	0.003
No. of events	6.6	15.9	0.18	0.9

Table 5. The backgrounds and the signal for the BP1 in the μ_{col} search channel at the 14 TeV LHC for $\mathcal{L} = 300 \text{ fb}^{-1}$.

takes over as the most dominant background. The corresponding quantities for the BP2 are listed in table 6. Due to the different masses of the A_1 and $\tilde{\chi}_1^0$ obtained for the two BPs, different sets of cuts need to be implemented for each of them.

We quantify the strengths of the two analyses in terms of S/B for comparing them against each other. This quantity is listed in table 7 for the two BPs in each of the search channel. The 3ℓ analysis gives a slightly higher S/B for the BP1 compared to that for the BP2. On the other hand, S/B for the BP2 in the μ_{col} analysis is considerably larger than the S/B obtained for the BP1 in each of the two analyses. This is due, evidently, to the sizable $\text{BR}(\tilde{\chi}_2^0 \rightarrow A_1 \tilde{\chi}_1^0)$ and $\text{BR}(A_1 \rightarrow \mu^+ \mu^-)$, as noted in table 3. In addition, the cut efficiency for the signal is much higher while that for the $W\gamma^*$ background is much lower in the case of the BP1.

For a more realistic analysis of the prospects of a signal process though, the statistical and systematic uncertainties in it also need to be taken into account. Hence, for each BP we have also provided in table 7 the statistical significance, given by the approximate formula,

$$\mathcal{Z} \equiv \frac{S}{\sqrt{B + (\varepsilon B)^2}}, \tag{5.2}$$

where the systematic uncertainty is given by the fraction ε of the background. From the ATLAS 3ℓ search [61], we note that the systematic uncertainty is 21% for the SRZc signal region, where the highest sensitivity is achieved, as seen above. We expect this number not to vary considerably at the 14 TeV LHC and hence use $\varepsilon = 0.21$ in our estimation

	BP2	$W\gamma^*$	$Z\gamma^*$	$Wb\bar{b}$
Cross section (fb)	3.93	246.9	10.0	3770.0
Cut efficiency	0.050	5.3×10^{-5}	3×10^{-5}	1×10^{-6}
Effective cross section (fb)	0.197	0.013	0.0003	0.003
No. of events	59.1	3.9	0.09	0.9

Table 6. The backgrounds and the signal for the BP2 in the μ_{col} search channel at the 14 TeV LHC for $\mathcal{L} = 300 \text{ fb}^{-1}$.

Point	S/B in analysis		\mathcal{Z} (σ) in analysis	
	3ℓ (SRZc region)	μ_{col}	3ℓ (SRZc region)	μ_{col}
BP1	0.591	0.42	2.7	1.2
BP2	0.436	15	2.0	27

Table 7. Results in the two analyses methods for the benchmark points.

of \mathcal{Z} for the 3ℓ channel. For the $W + \mu_{\text{col}} + \cancel{E}_T$ channel, since there is no experimental analysis available, the systematic uncertainty has to be estimated roughly. There are two major sources of this uncertainty: the reconstruction of the μ_{col} , in which case it is around 5% [51], and that of the ℓ_3 , where it is less than 2% [98]. As a conservative estimate, which also allows a direct comparison between the 3ℓ channel and this channel, we set $\varepsilon = 0.21$ here also. This results in $\mathcal{Z} = 27\sigma$ in this channel for the BP2, as seen in table 7, which is much higher than the estimated \mathcal{Z} for the same point in the 3ℓ channel.

There is, however, a caveat here. As noted from table 6, B for the BP2 is much smaller than S , resulting in a large S/B . In such a case, the approximate expression for \mathcal{Z} , which assumes $S \ll B$, is in principle not valid [99]. While, for a consistent treatment of the systematic uncertainties between the two search channels, we retain this approximate expression for the μ_{col} channel also, we emphasize that the given S/B values be considered a much more accurate estimate of the strength of each channel at the 14 TeV LHC.

6 Conclusions

In this article we have discussed an $\mathcal{O}(1)$ GeV neutralino DM in the NMSSM and its detectability at the LHC. Despite being very light, such a singlino-like DM can generate thermal relic abundance of the universe consistent with the PLANCK measurement, owing to the existence also of a singlet-like pseudoscalar, A_1 , with a mass around twice the DM mass. A very light DM giving the correct relic abundance is impossible to obtain in the MSSM, and thus its detection will provide a clear indication of physics beyond minimal SUSY. We have noted that the current direct and indirect detection facilities have very poor detection prospects for such a light DM with and hence its dedicated searches at the LHC can prove very crucial. We have therefore studied in depth the prospects for its observation at the 14 TeV LHC.

By performing a through scan of the NMSSM parameter space, chosen taking into account the analytical structure of the neutralino mass matrix, we found a variety of its configurations where an $\mathcal{O}(1)$ GeV DM can be obtained. We then carried out detector-level analyses of two of the main production modes of such a DM. In both these modes, the DM is produced in the decays of a higgsino-like heavier neutralino, $\tilde{\chi}_{2/3}^0$, which itself is produced in a pair with the lightest chargino. The $\tilde{\chi}_{2/3}^0$ then decays into either $Z + \text{DM}$ or $A_1 + \text{DM}$. The former channel, combined with the chargino decay, results in a trilepton + \cancel{E}_T final state, for which dedicated searches are already being performed by the CMS and ATLAS collaborations. In the latter channel the final state comprises of a pair of muons and a third lepton along with the DM.

In the $\tilde{\chi}_{2,3}^0 \rightarrow \text{DM} + A_1$ channel, the two muons that the very light A_1 decays into are highly collinear. Therefore, this channel can not be probed using the usual muon identification criteria. For this reason, we have adopted the technique of grouping the two muons together into a single jet-like object by applying certain unconventional rigorous cuts. By implementing this method on two benchmark points from our scan, we have found that this channel can have a signal strength comparable to that of the trilepton channel at the 14 TeV LHC with $\mathcal{L} = 300 \text{ fb}^{-1}$. In fact, for one of the two points, wherein the $\text{BR}(\tilde{\chi}_{2,3}^0 \rightarrow \text{DM} + A_1)$ is significant and the $\text{BR}(A_1 \rightarrow \mu^+ \mu^-)$ is maximal, the obtained S/B for this channel is much larger than that for the trilepton channel. We thus emphasize that dedicated searches in this channel may prove very crucial for the discovery of a very light SUSY DM within a few years of the current LHC run.

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