The past, present and future of the heavier electroweakinos in the light of LHC and other data

Amitava Datta\textsuperscript{a}, Nabanita Ganguly\textsuperscript{b}

\textsuperscript{a} INSA Senior Scientist
Department of Physics, University of Calcutta, 92 Acharya Prafulla Chandra Road,
Kolkata 700009, India

\textsuperscript{b} Department of Physics, University of Calcutta, 92 Acharya Prafulla Chandra Road,
Kolkata 700009, India

Abstract

As a sequel to our earlier works, we briefly review our old constraints on the full electroweakino sectors of several generic pMSSMs, containing both lighter and heavier sparticles, using the ATLAS trilepton data from LHC Run I. We also obtain stronger constraints on this sector using the ATLAS Run II data and give estimates of the yield of multilepton ($n\ell + \not{E}_T$) signals at the high luminosity LHC. Our focus is on the channels with $n > 3$ which are hallmarks of the heavier electroweakinos. If the spectrum of the lighter electroweakinos are compressed, these signals might very well be the discovery channels of the electroweakinos relevant for the high luminosity LHC. We also discuss the implications of the new LHC constraints for the observed dark matter relic density of the universe, the measured value of the anomalous magnetic moment of the muon and the dark matter direct detection experiments.

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1 Introduction

Supersymmetry (SUSY) is a novel symmetry which predicts that corresponding to every boson (fermion) in the Standard Model (SM) there is a fermionic (bosonic) superpartner which are collectively called sparticles (For reviews and text books on supersymmetry, see, e.g., [1, 2, 3, 4] and [5, 6] respectively). The painstaking searches for the sparticles spanning several years at the LHC Run I and Run II experiments are approaching the next long shutdown. Yet no signal has been seen so far. This leads to stringent lower bounds on many
sparticle masses [7, 8]. As expected the bounds on the masses of the strongly interacting sparticles (the squarks and the gluinos) with large production cross sections turn out to be the most stringent ones. In some models the relevant limits could be as large as 2-3 TeV. Therefore the possibility that the masses of these sparticles could be beyond the kinematic reach of the LHC is gradually gaining ground.

If this indeed is the case then the best bet for SUSY discovery is to search for the sparticles belonging to the electroweak (EW) sector. It should be emphasized that the interest in this sector is not restricted to LHC signatures only. These sparticles can shed light on the origin of the observed Dark Matter (DM) in the Universe [9, 10] improve the agreement between the measured anomalous magnetic moment of the muon \((g-2)_\mu\) [21, 22] and the theoretical prediction in the SM [23, 24]. Moreover, it is well known that the naturalness [25, 26, 27, 28] of any SUSY model favours small values of the EW parameter \(\mu\) known as the higgsino mass parameter. The constraints on these parameters from the LHC searches and other observables can, therefore, potentially test various SUSY models in the light of naturalness arguments.

The LHC collaborations have searched for the sparticles belonging to the EW sector using both Run I [29, 30, 31, 32] and Run II [33, 34] data. They are the electroweakinos (eweakinos) (the superpartners of the gauge and Higgs bosons) and the sleptons (the superpartners of the leptons). As is well-known model independent mass limits are hard to extract from the current LHC data since the signals depends on too many unknown parameters (mostly the soft SUSY breaking terms) present in the most general Minimal Supersymmetric Standard Model (MSSM). Thus the LHC collaborations usually derive the constraints from the search results in the so called simplified models [29, 30, 31, 32, 33, 34]. These models may be obtained after imposing some simplifying assumptions on the general MSSM which reduce the number of free parameters.

The above limits were reexamined [35, 36] in the phenomenological MSSM (pMSSM) [37] with 19 free parameter. It has been shown that in some regions of the parameter space the predictions of the pMSSM resemble that of the simplified models employed by the ATLAS group quite well and the resulting limits are very similar for comparisons using Run I and Run II data respectively (see Fig. 1 of [35], Fig. 7,8 of [38] and Fig. 1 of this paper). In several other regions, however, the limits in the pMSSM models are significantly weaker.

We wish to emphasize that the above experimental and phenomenological works as well as most of the other recent analyses involving the eweakinos [39, 40, 41, 42, 43] imposed the ad hoc assumption that the LHC signals come from only a few relatively light eweakinos while the heavier ones are decoupled. The heavier eweakinos were included in the analyses of [44, 45, 46, 47] using LHC Run I data. In the most detailed analyses in [45, 47] it was pointed out that the non-decoupled heavier eweakinos may have three important implications for the LHC searches.

\(^1\)For reviews and recent phenomenological works see e.g., [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]
• The ATLAS and CMS collaborations have interpreted the null search results in various simplified models with decoupled heavier eweakinos. The main results of their analyses are exclusion contours in the $m_{\tilde{\chi}^0_1} - m_{\tilde{\chi}^\pm_1}$ plane. On the other hand in a pMSSM with non-decoupled heavier eweakinos similar constraints may become significantly stronger due to the additional contributions from the heavier eweakinos to the signal (see Figs. 3,4 and 5 of [47] based on ATLAS Run I data).

• The cascade decays of the heavier eweakinos can lead to novel multilepton (n-lepton ($l$) + $E_T$, n = 3,4,5) signals. It may be recalled that events with $n > 3$ are not very common in the models with decoupled heavier eweakinos.

• If the lighter eweakinos have a compressed mass spectrum the signals can come only from the heavier sector with characteristics different from the decoupled scenario. For example, the conventional trilepton signals ($n = 3$) which dominantly come from the former may be swamped by the SM background while signals with $n > 3$ triggered by the latter, which have highly suppressed backgrounds, may show up at the LHC.

The last two points were illustrated in Section 6 of [47].

In this paper we update and upgrade the constraints in [45, 47] using, for the first time, the LHC Run II data (ATLAS) and other non-LHC constraints, taking into account all eweakinos - the heavier as well as the lighter ones. We then define a set of post LHC Run II benchmark points (BPs) and use them to assess the prospect of observing the multilepton signatures in future high luminosity LHC experiments after next long shut down.

The plan of this paper is as follows. In Section 2 we present a brief discussion of different pMSSMs involving both heavier and lighter eweakinos studied in this work. The methodology adopted to get the main results are described in details in Section 3. In Section 4 we identify the Allowed Parameter Space (APS) of the models discussed in Section 2 in the light of LHC data from Run II, the observed value of DM relic density of the universe and also the experimental constraint from the measured value of the anomalous magnetic moment of muon. The prospect of observing various multilepton signals in different models is assessed using post LHC-II benchmark points (BPs) selected from the corresponding APS. In section 5 we check the status of all models introduced in Section 2 vis-a-vis the spin-independent DM direct detection cross-section limits in section 6. Finally we conclude in Section 6.
2 The pMSSMs to be constrained

In this section we briefly review several pMSSMs with 19 parameters \[37\] which have been constrained using LHC eweakino search at Run II and other data in a later section. We emphasize that these models are generic in the sense that different models are characterized by certain hierarchies among the masses and mass parameters rather than their specific values. The fermionic sparticles in the EW sector are the charginos (\(\tilde{\chi}^\pm_j, j = 1, 2\)) and the neutralinos (\(\tilde{\chi}_i^0, i = 1 - 4\)) - collectively called the eweakinos. The indices i and j are arranged in ascending order of the masses. The masses and the compositions of these sparticles are determined by four parameters: the U(1) gaugino mass parameter \(M_1\), the SU(2) gaugino mass parameter \(M_2\), the higgsino mass parameter \(\mu\) and \(\tan \beta\) - the ratio of the vacuum expectation values of the two neutral Higgs bosons. If no assumption regarding the SUSY breaking mechanism is invoked the soft breaking masses \(M_1, M_2\) and the superpotential parameter \(\mu\) are all independent. Throughout this paper we take \(\tan \beta = 30\) since relatively large values of this parameter give a better agreement with the \(a_\mu\) data, ensure that the SM like Higgs boson has practically the maximum mass at the tree level and improves the prospect of charged Higgs boson search. The stable, neutral lightest neutralino (\(\tilde{\chi}_1^0\)), which is assumed to be the lightest supersymmetric particle (LSP), is a popular DM candidate.

The scalar sparticles are the \(L\) and \(R\) type sleptons which are superpartners of leptons with left and right chirality. The sneutrinos are the superpartners of the neutrinos. We assume \(L\) (\(R\))-type sleptons of all flavours to be mass degenerate with a common mass \(m_{\tilde{l}_L} (m_{\tilde{l}_R})\). Because of the SU(2) symmetry the sneutrinos are mass degenerate with \(L\)-sleptons modulo the D-term contribution. We neglect L-R mixing in the slepton sector. For simplicity we work in the decoupling regime (See, e.g., \[48\]) of the Higgs sector with only one light, SM like Higgs boson, a scenario consistent with all Higgs data collected so far (See, e.g., \[49\])

The signals of the eweakinos at the LHC are also sensitive to their compositions which are governed by the hierarchy among the parameters \(M_1, M_2\) and \(\mu\). Most of the existing analyses revolve around the broad scenarios listed in the next few subsections.

Following our earlier works \[35, 36, 45, 47\] we introduce a convenient nomenclature with four letters for denoting the pMSSMs belonging to three broad scenarios. The first two letters represent the composition of the lighter eweakinos which lead to the signals when the heavier ones are decoupled. We have considered three generic cases: the LW (Light Wino) model (\(M_2 \ll \mu\)), the LH (Light Higgsino) model (\(M_2 \gg \mu\)) and the LM (Light Mixed) model (\(M_2 \approx \mu\)). These models will be described in subsections 2.1, 2.2 and 2.3 respectively. In subsection 2.4 we shall consider a few LH models where the lighter weakino spectrum is compressed in different ways and the observable signals are mainly due to the heavier eweakinos.
2.1 The LW models ($M_2 << \mu$)

In this class of models the two relatively light eweakinos ($\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$) are wino like and their masses are controlled by the parameter $M_2$. They are the main sources of the signal/signals. The production cross section of the higgsino like heavier eweakinos ($\tilde{\chi}^0_3$ and $\tilde{\chi}^0_4$), with masses controlled by the parameter $\mu$, are suppressed both due to their composition and larger masses. Thus their contributions to the signal are negligible. The assumption that the heavier eweakinos are decoupled is therefore realistic in this case. Here the LSP is either a pure bino ($M_1 << M_2$) or a wino/bino admixture ($M_1 \approx M_2$). The trilepton signal ($3l + E_T$) in this model also depend sensitively on the hierarchy among the sleptons and the eweakino masses. This leads to the following subclasses:

- LWLS (Light Wino Light Left Slepton) model (1.1 a).
- LWHS (Light Wino Heavy Slepton) model (1.1 b).

The simplified models considered by the LHC collaborations [29, 30, 31, 32, 33, 34] with wino dominated $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$, bino dominated $\tilde{\chi}^0_1$ and decoupled heavier eweakinons are special cases of this generic pMSSM model in the limit of very large $\mu$.

In the LWLS model (1.1 a) only the left sleptons ($\tilde{\ell}_L$) are lighter than $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ while the right sleptons ($\tilde{\ell}_R$) are assumed to be decoupled. These eweakinos directly decay into sleptons and sneutrinos via two body modes with large BRs which enhances the leptonic signals. Slepton belonging to all generations are assumed to be degenerate and their common mass lies between $m_{\tilde{\chi}^0_1}$ and $m_{\tilde{\chi}^\pm_1}$. The choice $m_{\tilde{\ell}_L} = (m_{\tilde{\chi}^\pm_1} + m_{\tilde{\chi}^0_1})/2$ by the LHC collaborations optimizes the leptonic signals and yields the strongest bounds on eweakino masses. We shall mostly use this choice of $m_{\tilde{\ell}_L}$. However, one can also think of various tilted scenarios where $m_{\tilde{\ell}_L}$ is either shifted towards $m_{\tilde{\chi}^0_1}$ or $m_{\tilde{\chi}^\pm_1}$ so that the eweakino spectrum is somewhat compressed leading to weaker but not drastically different mass limits if the compression is not drastic. Several tilted models were examined in the light of LHC Run I data and other constraints [35].

In the LWHS (1.1 b) model all sleptons ($\tilde{\ell}_L$ and $\tilde{\ell}_R$) are heavier than $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$. These eweakinos decay into leptonic final states only via (on shell or off shell) $W$ and $Z$ bosons respectively. Since the BRs of leptonic $W$ and $Z$ decays are small, the leptonic signals in this case are suppressed compared to the LWLS model leading to weaker bounds on $m_{\tilde{\chi}^\pm_1}$. The LHC collaborations have published mass limits in a simplified model related to this scenario assuming decoupled heavier eweakinos [33, 34]. Multilepton signals are not favoured in this LW type models. However we will briefly discuss in a later section that it is one of the few models which are consistent with the current DM direct detection data [50, 51, 52] taken at its face value.
2.2 The LH models \((M_2 \gg \mu)\)

In this class of models the relatively light Higgsino like eweakinos are \(\tilde{\chi}^\pm_1, \tilde{\chi}^0_2\) and \(\tilde{\chi}^0_3\) with masses controlled by the parameter \(\mu\). They are the main sources of the signal/signals if the heavier eweakinos are decoupled. The pair production cross section of these higgsino like eweakinos are small compared to that in the LW models for comparable masses of the lighter eweakinos. Thus weaker mass bounds are obtained from the LHC data. In all cases the LSP is either a pure bino \((M_1 << \mu)\) or a bino-higgsino admixture \((M_1 \approx \mu)\). The constraints on this model using Run I data were obtained in [36].

It should be stressed that the wino dominated heavier eweakinos \((\tilde{\chi}^\pm_2, \tilde{\chi}^0_4)\) are phenomenologically important. Their masses are determined by the free parameter \(M_2\). As expected the pair production cross section of these eweakinos are suppressed due to their larger masses. However, their favourable couplings to the gauge bosons compensates this suppression to some extent. As a result their contributions to the signal turn out to be appreciable or even dominant when the lighter eweakino spectrum is compressed. This point was emphasized in [45, 47] and the importance of the heavier eweakinos was illustrated using LHC RUN I data. We have constrained the following models using the Run II and other data:

- The LHLS (Light Higgsino Light Left Slepton) model (2.2 a).
- The LHHS (Light Higgsino Heavy Slepton) model (2.2 b).

In the former model the L-slepton - eweakino mass hierarchies are similar to that in the LWLS model (see subsection 2.1). In the LHHS model it is assumed that all sleptons are heavier than the lighter eweakinos \((\tilde{\chi}^\pm_1, \tilde{\chi}^0_2\) and \(\tilde{\chi}^0_3)\) but are lighter than the heavier eweakinos. In the numerical computations the common slepton mass is chosen to be \(m_{\tilde{\chi}_L} = m_{\tilde{\chi}_R} = (m_{\tilde{\chi}^\pm_1} + m_{\tilde{\chi}^0_2})/2\) and we set \(M_2 = 1.5\mu\). An additional attraction of the LHHS model is that it is consistent with the direct DM detection data [50, 51, 52] as will be shown in a later section.

2.3 The LM models \((M_2 \approx \mu)\)

Here all eweakinos except for the LSP are wino-higgsino admixtures. The LSP is dominantly a pure bino but in some zones of the parameter space all eweakinos are admixtures of all the weak eigenstates. In [47] the LMLS model was constrained using LHC Run I data. In this paper we have updated these constraints using LHC Run II data.
2.4 The Compressed LHHS models

In this section we consider a few LHHS models (2.1 b) where the lighter eweakinos have a compressed spectrum. As a result observable multilepton signals come mainly from the heavier eweakinos. We consider the following models:

- The CLHHS \( \tilde{W} \) (Compressed Light Higgsino Heavy Slepton) model with wino \( \tilde{W} \) like heavier eweakinos \[45, 47\] (2.4 a).

- The MCLHHS \( \tilde{W} \) : Same as 3.1 a) except that the light higgsinos are moderately compressed \[47\] (2.4 b).

- The CLHHS \( \tilde{B} - \tilde{W} \) model with one bino \( \tilde{B} \) like and one wino \( \tilde{W} \) like heavier eweakino (2.4 c).

In the CLHHS \( \tilde{W} \) model we set \( M_1 \approx \mu \) with \( M_2 > \mu \). This choice leads to a compressed lighter eweakino spectrum where \( \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3 \) and \( \tilde{\chi}^\pm_1 \) are approximately mass degenerate and each has significant bino and higgsino components. The masses of the wino dominated heavier eweakinos are determined by the free parameter \( M_2 \). As in all LHHS models we set \( m_{\tilde{l}_L} = m_{\tilde{l}_R} = (m_{\tilde{\chi}^\pm_1} + m_{\tilde{\chi}^\pm_2})/2 \) so that the sleptons are always heavier than lighter eweakinos. For future use we define a compression parameter \( x = \mu/M_1 \) which represents the degree of compression. For numerical results in the CLHHS \( \tilde{W} \) model we have chosen \( x = 1.05 \).

As discussed in detail in sections 5.1 and 6.5 of \[47\], the compatibility of CLHHS \( \tilde{W} \) model with the observed DM relic density is obtained for \( m_{\tilde{\chi}^\pm_2} > 600 \) GeV. On the other hand in the MCLHHS \( \tilde{W} \) model with slightly larger value of \( x (= 1.3) \) this compatibility is obtained for lower values of \( m_{\tilde{\chi}^\pm_2} \) which ensures better signals. In \[47\] this issue was illustrated with some benchmark points (BPs). Here we make a detailed study of the phenomenology of this model by making a parameter space scan using the constraints from LHC Run II and other data.

The CLHHS \( \tilde{B} - \tilde{W} \) model with decoupled heavier eweakinos have higgsino like and nearly degenerate \( \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3 \) and \( \tilde{\chi}^\pm_1 \). As a result the signals from the lighter eweakinos are expected to consist of only soft visible particles. For a long time there was no LHC constraint on this model. More recently both ATLAS \[63\] and CMS \[54\] collaborations have obtained some interesting constraints on simplified models closely related to this model using improved techniques for detecting soft leptons. The excluded parameter space corresponds to \( m_{\tilde{\chi}^0_2} \approx m_{\tilde{\chi}^\pm_1} = 100-140 \) GeV. A comparison with Fig. 5 of \[63\] shows that in a closely related pMSSM such masses may be theoretically forbidden. In this paper we focus on scenarios with non decoupled heavier eweakinos. Here \( \tilde{\chi}^\pm_2 \) and \( \tilde{\chi}^0_4 \) are chosen to be wino and bino dominated respectively or admixtures.
of these sparticles. Then multilepton signals can directly come from the production and decay of these sparticles.

3 Methodology

The work in this paper is based on the following methodology.

3.1 The constraints

We first constrain the pMMSMs discussed in the previous section using the model independent ATLAS Run II data in the $3l + E_T$ channel collected with $36.1 \text{ fb}^{-1}$ of integrated luminosity [34]. We have also used the ATLAS Run II constraints from slepton search data [34] when the model under consideration contains a light slepton. The constraint on the CLHHS($\tilde{B} - \tilde{W}$) also takes into account the ATLAS Higgsino search data using the soft lepton detection technique [33]. However we have not simulated the last two signals. Instead we have simply rejected the points lying within the ATLAS exclusion contours.

We have also used the WMAP-Planck constraints [10] and that from the measured value of the anomalous magnetic moment of the muon [21, 22] following the discussions of [47]. We believe that the theoretical and experimental uncertainties in the above three constraints are relatively small. To clarify this statement further we note the constraints from flavour physics can be applied to the MSSM only after imposing yet another assumption known as the minimal flavour violation. In a nutshell this implies that the mixing angles in the squark and quark sectors are the same. For a discussion on non-minimal flavour violation, see for example, ref [55].

We have also taken into consideration the constraints from different experiments on direct detection of DM [50, 51, 52]. As is well known this data disfavour many SUSY models. However, there are many assumptions, both theoretical and experimental, in the derivation of the spin independent LSP-nucleon scattering cross section $\sigma_{SI}$ (for a brief discussion see, e.g, Section 4 of [47]). Relaxing these assumptions may significantly lower the computed value of $\sigma_{SI}$. This makes the comparison of the theoretical prediction and the experimental upper bound on $\sigma_{SI}$ somewhat ambiguous. We have, therefore, not displayed the impact of these constraints in our main figures. They are discussed in a separate section.

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2See model 3.1 c) of subsection 2.4
3.2 The Simulation

Using Pythia we simulate the $3l + \not{E}_T$ events in the pMSSM models studied by us. We closely follow the ATLAS [34] group for selection and isolation of signal objects. Jets are reconstructed using the anti-$k_T$ algorithm with radius parameter $R = 0.4$ and they have $p_T > 20$ GeV, $|\eta| < 2.8$. Signal $e$ and $\mu$ are required to have $p_T > 10$ GeV and $|\eta| < 2.47 (2.5)$ for $e$ ($\mu$). ATLAS has defined 11 signal regions (SRs) each characterized by a set of cuts. Some of these regions target slepton mediated decays of $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ while the others target $W$ and $Z$-mediated decays. The results are presented in terms of number of observed events in the $3l + \not{E}_T$ channel in each SR and the corresponding number of SM backgrounds (see Table 13 and 14 of [34]) are extracted from the data. With these two numbers one can obtain the model independent upper bound on $N_{BSM}$ for each SR [57]. We have used this information to constrain the pMSSMs discussed in the last section. In Fig.1 we compare the exclusion contours obtained by us and the one by the ATLAS collaboration from the Run II trilepton search data [34]. They had obtained the contour for a simplified model with wino like $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ and a bino like LSP with light sleptons (the black exclusion contour). The pMSSM model closest to the above simplified model is the LWLS model (see subsection 2.1, model 1.1a))

Figure 1: The black line represents the exclusion contour in the $m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1}$ plane at 95% CL in a simplified model (see text) obtained by the ATLAS collaboration from trilepton searches at 13 TeV LHC [34]. The blue line shows the exclusion obtained by our simulations in the closely related LWLS model. The area enclosed by the blue curve is excluded by the ATLAS $\tilde{l}_L$ search at Run II (see text). The brown, green and yellow regions are consistent with the $a_\mu$ data at 3$\sigma$, 2$\sigma$ and 1$\sigma$ levels respectively. The red points satisfy WMAP/PLANCK data of DM relic density. The grey region at the lower left corner is disfavoured theoretically.
with decoupled heavier eweakinos. The blue exclusion contour in Fig.1 is the result of our simulation in this model. It may be noted that for $m_{\tilde{\chi}_1^\pm} >> m_{\tilde{\chi}_1^0}$, $\tilde{\chi}_1^\pm (\tilde{\chi}_1^0)$ is almost a pure wino (bino) and the results of the two simulations agree quite well. As $m_{\tilde{\chi}_1^0}$ increases $\tilde{\chi}_2^0$ acquire significant bino component. As a result the $\tilde{\chi}_1^+\tilde{\chi}_2^0$ production cross section decreases leading to weaker exclusions. Each point in the parameter space corresponds to a L-slepton mass due to the choice $m_{\tilde{l}_L} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^+})/2$. The magenta curve is the exclusion contour from the ATLAS L-slepton search data at Run II.

The impact of the other two constraints - namely the measurements of $a_\mu$ and the DM relic density as discussed in section 3.1 are also shown by different colour bands. The colour convention is explained in the figure caption. It may be noted that the APS consistent with all constraints is rather tiny. As we shall show in the next section the APS in some of the LH models are considerably larger.

We next turn our attention to the prospect of observing the multilepton signals ($nl + E_T$ with $n = 3,4,5$) for an integrated luminosity of 3000 fb$^{-1}$. From the allowed parameter space of each pMSSM with non-decoupled heavier eweakinos we select a few benchmark points (BPs). We then simulate the signals corresponding to each BP for different $n$. We closely follow different selection criteria introduced in the ATLAS Run II analysis [34]. The estimation of the SM background for each $n$ is common to all the pMSSMs studied here. They will be presented in the next section.

All signals in this work are generated using PYTHIA [58]. The relevant background processes in case of $nl + E_T$ with $n > 3$ are generated using ALPGEN [59] with MLM matching [60, 61] and then passed through PYTHIA for showering and hadronization. Jets are reconstructed using FASTJET [62] with anti-$k_T$ algorithm. For parton distribution function (PDF), CTEQ6L [63] has been used in all our simulations.

### 3.3 Scanning of the Parameter Spaces

In the CLHHS ($\tilde{W}$) model we set $M_1 \approx \mu$ with $M_2 > \mu$. This choice of parameters leads to a compressed lighter eweakino spectrum where $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ are approximately mass degenerate and each has significant bino and higgsino components. The masses of the wino dominated heavier eweakinos are determined by the free parameter $M_2$. As in the LHHS model we set $m_{\tilde{l}_L} = m_{\tilde{l}_R} = (m_{\tilde{\chi}_1^+} + m_{\tilde{\chi}_1^-})/2$ so that the sleptons are always heavier than lighter eweakinos. We extend this analysis of [34] for our models with non-decoupled heavier eweakinos to find out the allowed parameter space (APS) in each case (See section 2 and [17] for a detailed description of such models).

The squark mass parameters, $M_A, M_3$ which do not play any role in our present simulation are set at a large value of 2 TeV. The trilinear coupling $A_t$ is fixed at -2 TeV so that Higgs mass $m_h$ falls within the experimentally allowed window $122 \text{ GeV} < m_h < 128 \text{ GeV}$ around a central value of 125 GeV [64, 65]. All
other trilinear couplings are set at zero. The heavier Higgs like bosons are assumed to be decoupled. For all our simulations, we have fixed $\tan \beta$ at 30 which gives better agreement with $a_\mu$ data and the parameters $M_1, M_2, \mu$ are varied. The masses of sleptons are fixed by the definition of each model as discussed in section 2. The SM Parameters are taken as follows: $m_{t_{\text{pole}}} = 175$ GeV, $m_Z = 91.18$ GeV, $m_{\mu} = 4.2$ GeV and $m_{\tau} = 1.77$ GeV. The complete SUSY spectrum and $a_\mu$ are generated using SUSPECT [66]. The decay modes of sparticles are calculated using SUSYHIT [67]. We compute DM relic density and $\sigma_{SI}$ using MICROMEGA [68].

4 Results

In this section, we perform detailed scanning of parameter space of each of the generic model described in section 2 subjected to three constraints - ATLAS eweakino search data in the $3l + E_T$ channel at LHC Run II, observed DM relic density of universe and experimentally measured anomalous magnetic moment of muon and identify the APS for each of them. We then discuss the prospects of discovery for these models through various multilepton channels for an integrated luminosity of 3000 fb$^{-1}$. We specifically emphasize on the $nl + E_T$ channel with $n > 3$ that arises predominantly from the non-decoupled heavier eweakino sector.

We begin by estimating the SM backgrounds to all multilepton signals in subsection 4.1. Since the three compressed models introduced in section 2 nicely highlights the importance of the heavier eweakinos, we first discuss the phenomenology of these models (see subsections 4.2, 4.3 and 4.4). The following subsections deal with the remaining models.

4.1 Estimation of the backgrounds to the multilepton signals

In this subsection we obtain rough estimates of the backgrounds to the multilepton signals. For the $3l + E_T$ signal, we take background obtained by the ATLAS Run II experiment in this channel [34] and scale the number of events for the higher luminosity (3000 fb$^{-1}$). For simulating the $3l + E_T$ signal, we also follow the procedure of [34]. For the other signals, namely $4l$, $ss3os1l$ (three same sign and one opposite sign l) and $5l$, suitable cuts are devised to control the SM background in each case (see Table 1). The dominant SM processes contributing to the multilepton final states are $t\bar{t}Z$, $ZZ$ and $VVV$ with $V = W^\pm, Z$. 

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| Channel          | Cuts                                                                 |
|------------------|----------------------------------------------------------------------|
| $4l + \mathcal{E}_T$ | $N_l = 4$, $m_{\text{SFOS}} \not\in (81.2,101.2)$ GeV, $\mathcal{E}_T > 80$ GeV, $n_{b-jet} = 0$ |
| $ss3os1l + \mathcal{E}_T$ | $N_l = 4$ with $Q_l \neq 0$, $\mathcal{E}_T > 80$ GeV |
| $5l + \mathcal{E}_T$ | $N_l = 5$, $\mathcal{E}_T > 80$ GeV |

Table 1: The different choices of cuts for each type of multilepton signal.

In Table 1, $N_l, Q_l$ are total number of isolated leptons in the final state and their total electric charge respectively and $m_{\text{SFOS}}$ is the invariant mass of a pair of same flavour opposite sign (SFOS) lepton pair. The main background in case of $4l + \mathcal{E}_T$ channel comes from pair productions of $Z$ boson and hence the invariant mass cut around the $Z$-window turns out to be very useful for reducing the background events. As the lepton multiplicity in the final state increases, the backgrounds become weaker and can be adequately suppressed by fewer cuts. For example, for the $5l + \mathcal{E}_T$ signal a moderate cut of 80 GeV on $\mathcal{E}_T$ is sufficient to make the background negligible.

The total effective cross-section (i.e. the cross-section after all cuts) of the SM backgrounds in the $3l + \mathcal{E}_T$ channel after the cuts listed in Table 2 is 0.261 fb. For the $nl + \mathcal{E}_T$ channels with $n > 3$, the total SM backgrounds are negligible. The strength of each multilepton signal is illustrated by two observables $\sigma_{\text{eff}}$ and $N_{\text{BSM}}$ where $\sigma_{\text{eff}}$ is the effective cross-section in the respective channels after passing all cuts and $N_{\text{BSM}}$ is the corresponding number of surviving signal events. As a rough guideline we take $N_{\text{BSM}} = 5$ as the discovery if the background is negligible. For the $3l + \mathcal{E}_T$ channel, however, we quote the signal significance $S/\sqrt{B}$ where $S$ is the number of signal events and $B$ is the number of corresponding background which is nonzero.

### 4.2 Compressed Light Higgsino Heavy Slepton (CLHHS ($\tilde{W}$)) Model

We first present the result of scanning the parameter space of the compressed model (section 2.4, model 2.4 a) by varying two gaugino masses in Fig. 2. Along the $x$-axis $m_{\tilde{\chi}_2^\pm}$ is varied while along the $y$-axis the variable is $m_{\tilde{\chi}_1^0}$ which is nearly degenerate with other lighter eweakino masses. The blue (black) contour represents the exclusion coming from $3l + \mathcal{E}_T$ data at 13 (8) TeV [30, 34]. The Run II data rules out a larger part of the parameter space as compared to Run I data. For a LSP of mass around 80 GeV, the bound on $m_{\tilde{\chi}_2^\pm}$ is now extended upto $\approx 800$ GeV (previously it was nearly 600 GeV). Since we have illustrated the effect of compression by the choice $\mu = 1.05M_1$, $m_{\tilde{\chi}_1^0} < 80$ GeV is not allowed by the LEP lower bound on
On the other hand, above $m_{\tilde{\chi}^0_1} \approx 350$ GeV (which was around 200 GeV for Run I), there is no bound on $m_{\tilde{\chi}^\pm_2}$. The eweakino search in the $3l + E_T$ channel at Run II disfavours bulk of the bands allowed by the $a_\mu$ constraints at 1σ and 2σ levels for low $m_{\tilde{\chi}^\pm_2}$. But almost the entire 2σ band in the high $m_{\tilde{\chi}^\pm_2}$ region survives. Although the red parabolic region allowed by the measured DM relic density remains unaffected by the Run II data, a large part of lower branch is excluded by the same data.
Table 2: The masses and production cross-sections of all possible e weakino pairs for different BPs in the CLHHS (\(\tilde{W}\)) model are given. For the trilepton signal in each case we display the significance (\(S/\sqrt{B}\)). The corresponding \(\sigma_{eff}\) and total number of signal events (with negligible backgrounds) for each type of multilepton signal with \(n > 3\) are also shown. Masses and cross-sections are in GeV and fb respectively.

| Mass | Cross-section | \(3l + E_T\) | \(4l + E_T\) | \(ss3os1l + E_T\) | \(5l + E_T\) |
|------|---------------|---------------|---------------|----------------|---------------|
| \(m_{\tilde{\chi}^0_1}\) | \(m_{\tilde{\chi}^\pm_2}\) | \(m_{\tilde{\chi}^\pm_3}\) | \(\sigma_{eff}\) | \(S/\sqrt{B}\) | \(\sigma_{eff}\) | \(N_{4l}\) | \(\sigma_{eff}\) | \(N_{ss3os1l}\) | \(\sigma_{eff}\) | \(N_{5l}\) |
| 249.7 | 290.2 | 649.9 | 156.7 | 0.0423 | 13.1 | 0.0752 | 225.6 | 0.0282 | 84.6 | 0.0157 | 47.0 |
| 399.9 | 440.7 | 650.2 | 40.14 | 0.0064 | 1.9 | 0.0313 | 93.9 | 0.0144 | 43.3 | 0.0068 | 20.5 |
| 499.8 | 527.9 | 650.3 | 23.64 | 0.0054 | 1.2 | 0.0147 | 43.9 | 0.0083 | 24.8 | 0.0033 | 9.9 |
| 199.9 | 239.8 | 749.8 | 298.0 | 0.0805 | 24.9 | 0.0387 | 116.2 | 0.0059 | 17.9 | 0.0057 | 17.1 |
| 400.7 | 445.4 | 750.3 | 33.42 | 0.0144 | 4.4 | 0.0214 | 64.2 | 0.0070 | 21.1 | 0.0053 | 16.1 |
| 550.8 | 591.0 | 750.3 | 13.59 | 0.0031 | 0.69 | 0.0098 | 29.4 | 0.0043 | 13.0 | 0.0024 | 7.3 |
| 300.6 | 344.4 | 850.2 | 80.86 | 0.0307 | 9.5 | 0.0145 | 43.7 | 0.004 | 12.1 | 0.0032 | 9.7 |
| 400.6 | 447.1 | 849.9 | 30.68 | 0.0129 | 3.9 | 0.0117 | 34.9 | 0.0043 | 12.9 | 0.0012 | 3.7 |
| 500.2 | 548.3 | 850.0 | 14.40 | 0.0056 | 1.7 | 0.0095 | 28.5 | 0.0029 | 8.6 | 0.0017 | 5.2 |
| 350.7 | 376.2 | 500.3 | 88.62 | 0.0195 | 3.8 | 0.0691 | 207.4 | 0.031 | 93.1 | 0.0071 | 21.3 |
| 350.9 | 393.9 | 700.4 | 53.56 | 0.0198 | 6.1 | 0.0348 | 104.4 | 0.0134 | 40.2 | 0.0075 | 22.5 |
| 350.4 | 396.0 | 899.9 | 47.59 | 0.0186 | 5.7 | 0.0081 | 24.3 | 0.0038 | 11.4 | 0.0019 | 5.7 |

In Table 2 we showcase the results of our simulations of multilepton signals at \(\sqrt{s} = 13\) TeV for an integrated luminosity of 3000 fb\(^{-1}\) using BPs chosen from the APS. For clarity we have studied four groups of BPs all belonging to the APS shown in Fig. 2. For the first three groups, \(m_{\tilde{\chi}^\pm_2}\) is fixed at 650, 750 and 850 GeV respectively while \(m_{\tilde{\chi}^0_1}\) is varied. It is important to note that for \(m_{\tilde{\chi}^0_1} > 350\) GeV, the trilepton signal is below the observable level (\(S/\sqrt{B} < 5\)) irrespective of \(m_{\tilde{\chi}^\pm_2}\). In most of such cases one of the multilepton signals with \(n > 3\) is likely to be the discovery channel (\(N_{BSM} > 5\)). On the other hand the last group of BPs illustrates that the \(3l + E_T\) signal improves for \(m_{\tilde{\chi}^0_1} = 350\) GeV even for \(m_{\tilde{\chi}^\pm_2}\) as high as 900 GeV. Similar features have been observed for the moderately compressed model (see the next subsection).
4.3 Moderately Compressed Light Higgsino Heavy Slepton (MCLHHS ($\tilde{W}$)) Model

Fig. 3 represents the result of scanning in the $m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0_1}$ plane in the model with moderate compression (model 2.4 b) illustrated by the choice $\mu = 1.3M_1$. The blue line is the exclusion contour coming from ATLAS $3l + E_T$ data from Run II. For a LSP with mass around 60 GeV, $m_{\tilde{\chi}^\pm_2}$ below 850 GeV is disfavoured by the LHC search. LSP mass cannot be lowered further due to the lower bound on $m_{\tilde{\chi}^\pm_1}$ coming from LEP [69]. On the other hand, above $m_{\tilde{\chi}^0_1} \approx 230$ GeV, all $m_{\tilde{\chi}^\pm_2}$ masses are allowed.

![Figure 3: Exclusion contours in the $m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0_1}$ plane in the Moderately Compressed Light Higgsino Heavy Slepton (MCLHHS ($\tilde{W}$)) model. The blue line represents the exclusion obtained by us using ATLAS $3l + E_T$ search data from Run II (Run I). Colors and conventions are the same as in Fig. 1.](image)

We pointed out in [47] that by relaxing the compression between $\mu$ and $M_1$, it is possible to get DM relic density satisfying parameter space for lower values of $m_{\tilde{\chi}^\pm_2}$ which looks interesting from the perspective of sparticle searches. The red points in Fig. 3 is consistent with observed DM relic density of the universe. A significant fraction of the upper red patches lying in the low $m_{\tilde{\chi}^\pm_2}$ region is indeed allowed by Run II data. However for the lower red band only the part with $m_{\tilde{\chi}^\pm_2} \gtrsim 850$ GeV is consistent with present LHC limits. For $m_{\tilde{\chi}^\pm_2}$ lying between approximately 500 - 600 GeV a significant part of the APS is consistent with both DM relic density and $a_\mu$ data (at 1$\sigma$ level). Also the 2$\sigma$ band of $a_\mu$ corresponding to larger values of $m_{\tilde{\chi}^\pm_2}$ is compatible with $3l + E_T$ data.
Table 3: The masses and production cross-sections of all possible e weakino pairs for different BPs in the MCLHHS ($\tilde{W}$) model are given. For the trilepton signal in each case we display the significance ($S/\sqrt{B}$). The corresponding $\sigma_{\text{eff}}$ and total number of signal events (with negligible backgrounds) for each type of multilepton signal with $n > 3$ are also shown. Masses and cross-sections are in GeV and fb respectively.

Table 3 shows the status of multilepton signals for different representative BPs. The BPs are bunched into three groups for reasons discussed in the last subsection. For a $\tilde{\chi}_{\pm}^2$ with masses 600 and 800 GeV, the entire range of LSP masses considered gives potential $nl + E_T$ signals for $n > 3$ for 3000 fb$^{-1}$ of integrated luminosity. But in most of the cases the trilepton signal is weaker compared to the other multilepton channels. On the other hand, keeping LSP mass fixed around 300 GeV, we have also varied $m_{\tilde{\chi}_{\pm}^2}$ and found that it is possible to get significantly large $3l + E_T$ signal even for 900 GeV. Although for $m_{\tilde{\chi}_{\pm}^2} = 900$ GeV, the ss3os1l and 5l are already rather weak.

4.4 CLHHS ($\tilde{B} - \tilde{W}$) Model

The result of scanning the parameter space for this model (model 2.4 c) is displayed in Fig. 5. The blue line is the exclusion contour obtained using ATLAS 3l + $E_T$ search at Run II. The mass of $\tilde{\chi}_{\pm}^2$ all the way upto $\sim$ 900 GeV is ruled out by the LHC data for a LSP with mass around 105 GeV. Note that, here LSP mass has a lower bound at around 105 GeV coming from LEP data. This is because in this model the entire
lighter eweakino spectrum is degenerate with mass controlled by higgsino parameter \( \mu \) and hence the LEP bound on \( m_{\tilde{\chi}_1^\pm} \) is tantamount to a bound on \( m_{\tilde{\chi}_0^1} \) (see subsection 2.4 model 2.4c c)). On the other hand, above \( m_{\tilde{\chi}_0^1} \approx 290 \text{ GeV} \), there is no bound on \( m_{\tilde{\chi}_2^\pm} \).

![Exclusion contour in the \( m_{\tilde{\chi}_2^\pm} - m_{\tilde{\chi}_0^1} \) plane in the CLHHS (\( \tilde{B} - \tilde{W} \)) model.](image)

Figure 4: Exclusion contour in the \( m_{\tilde{\chi}_2^\pm} - m_{\tilde{\chi}_0^1} \) plane in the CLHHS (\( \tilde{B} - \tilde{W} \)) model. The blue line represents exclusion obtained by us using ATLAS 3l + \( E_T \) search data from Run II. Colors and conventions are the same as in Fig. 1.

We also show the 1\( \sigma \) (yellow) and 2\( \sigma \) (green) allowed bands in the same plot. A fairly large part of these \( a_\mu \) bands in the APS covering a wide range of \( m_{\tilde{\chi}_2^\pm} \) is consistent with the present LHC Limit. Another point worth noting is that the APS as shown in Fig. 5 does not contain any region consistent with the DM relic density data. This, however, is not surprising. It is well known that for a higgsino dominated LSP, DM relic density in the right ballpark value can be obtained only for high values of \( m_{\tilde{\chi}_0^1} \) e.g. \( m_{\tilde{\chi}_0^1} \) around 1 TeV assuming single component DM. Our result agrees with this. In ref. 20, authors have shown that this upper limit for higgsino DM mass can be relaxed if a small amount of slepton co-annihilation is present. Note that in our model such a co-annihilation cannot occur as sleptons are much heavier than the LSP.
Table 4: The masses and production cross-sections of all possible e weakino pairs for different BPs in the CLHHS (\(\tilde{B}\rightarrow\tilde{W}\)) model are given. For the trilepton signal in each case we display the significance (\(S/\sqrt{B}\)). The corresponding \(\sigma_{eff}\) and total number of signal events with negligible backgrounds for each type of multilepton signal with \(n > 3\) are also shown. Masses and cross-sections are in GeV and fb respectively.

| Mass  | Cross-section | \(3l + E_T\) | \(4l + E_T\) | \(ss3os1l + E_T\) | \(5l + E_T\) |
|-------|---------------|---------------|---------------|----------------|---------------|
| \(m_{\tilde{\chi}^0_1}\) | \(m_{\tilde{\chi}^\pm_1}\) | \(m_{\tilde{\chi}^\pm_2}\) | \(\sigma_{eff}\) | \(\sigma_{eff} (S/\sqrt{B})_{3l}\) | \(\sigma_{eff}^{ss3os1l}\) | \(N_{ss3os1l}\) | \(\sigma_{eff}^{5l}\) | \(N_{5l}\) |
| 310.1 | 316.9 | 600.5 | 140.31 | 0.0449 | 13.8 | 0.0463 | 138.9 | 0.0014 | 4.2 | 0.0014 | 4.2 |
| 370.0 | 377.4 | 600.1 | 80.21 | 0.0104 | 3.2 | 0.0216 | 64.9 | 0.0016 | 4.8 | - | - |
| 330.2 | 335.6 | 700.6 | 104.88 | 0.0367 | 11.3 | 0.0231 | 69.2 | - | - | - | - |
| 380.2 | 386.3 | 700.1 | 63.55 | 0.0229 | 7.1 | 0.0178 | 53.4 | 0.0013 | 3.8 | - | - |
| 430.5 | 437.2 | 700.3 | 41.55 | 0.0108 | 3.3 | 0.0095 | 28.6 | 0.0017 | 4.9 | - | - |
| 280.8 | 289.3 | 500.1 | 222.58 | 0.0356 | 10.9 | 0.0935 | 280.4 | 0.0044 | 13.4 | - | - |
| 280.1 | 285.4 | 700.5 | 190.24 | 0.0609 | 18.7 | 0.0418 | 125.6 | 0.0019 | 5.7 | - | - |
| 280.2 | 284.8 | 800.5 | 186.62 | 0.0504 | 15.5 | 0.0186 | 55.9 | - | - | - | - |

In Table 5 we present the results of multilepton searches for an integrated luminosity of 3000 fb\(^{-1}\). Our investigation reveals that for \(m_{\tilde{\chi}^\pm_2} \approx 700\) GeV, the entire range of \(m_{\tilde{\chi}^0_1}\) in the APS can be probed via \(3l + E_T\) and \(4l + E_T\) channel. Again, for a LSP of mass around 280 GeV, \(\tilde{\chi}^\pm_2\) as heavy as 800 GeV can lead to observable \(3l/4l + E_T\) signal. However, note that, \(ss3os1l + E_T\) and \(5l + E_T\) channels produce weaker signals in most of the cases.

4.5 Light Higgsino and Heavy Slepton (LHHS) Model

We delineate the APS of LHHS model (subsection 2.2, model 2.2b) in the \(m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1}\) plane in Fig. 5. Run II data puts stronger constraint (the blue curve) on the APS compared to Run I data (the black contour). For massless LSP, \(\tilde{\chi}^\pm_1\) with mass above \(\simeq 370\) GeV (the corresponding value of \(m_{\tilde{\chi}^\pm_2}\) is \(\geq 600\) GeV) is allowed whereas above \(m_{\tilde{\chi}^0_1} \approx 200\) GeV there is no bound on \(m_{\tilde{\chi}^\pm_1}\). Run II data eliminates a larger part of the lower DM band originating from \(h\) and \(Z\) resonances as compared to Run I data. However almost the entire upper DM band survives except a tiny part. For \(m_{\tilde{\chi}^\pm_1}\) lying in the range 250 - 450 GeV, a large part of the APS is in agreement with both DM relic density and \(a_\mu\) data (both at 1\(\sigma\) and 2\(\sigma\) level).

We exhibit the results of multilepton searches for LHHS model in Table 5. The mode of presentation is the same as in earlier tables. For a \(\tilde{\chi}^\pm_1\) with mass e.g. say 500 GeV, the entire range of LSP mass 50 - 450 GeV (see Fig. 5) allowed by the \(3l + E_T\) data can be probed at the LHC with \(L = 3000\) fb\(^{-1}\). On the other
hand, for a LSP of mass 300 GeV, good signal strength can be expected for almost each type of multilepton signal for $m_{\tilde{\chi}_1^\pm}$ nearly up to 550 GeV (which corresponds to $m_{\tilde{\chi}_2^\pm}\approx 900$ GeV). In some cases $3l + E_T$ signal again turns out to be weaker as compared to channels with higher lepton multiplicities. For higher values of $m_{\tilde{\chi}_1^\pm}$, multilepton signal especially $ss3os1l$ and $5l$ signals get weaken rapidly. This can be understood easily as follows. In LHHS model, as sleptons masses are put between $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_2^\pm}$ (see subsection 2.2 model 2.2 b), only $\tilde{\chi}_2^\pm(\tilde{\chi}_2^0)$ has direct decays into sleptons while the leptons can come from $\tilde{\chi}_1^\pm (\tilde{\chi}_2^0, \tilde{\chi}_3^0)$ decays via SM gauge bosons with low BR. Therefore, the heavy EW sector is the main source of multileptons in the case. It was shown in [47] explicitly. Now, $m_{\tilde{\chi}_2^\pm}$ increases with increasing value of $m_{\tilde{\chi}_1^\pm}$ and that in turn decreases the cross-section of heavy sector. As a result, one starts getting poor signals.
Table 5: The masses and production cross-sections of all possible e weakino pairs for different BPs in the LHHS model are given. For the trilepton signal in each case we display the significance \((S/\sqrt{B})\). The corresponding \(\sigma_{eff}\) and total number of signal events with negligible backgrounds for each type of multilepton signal with \(n > 3\) are also shown. Masses and cross-sections are in GeV and fb respectively.

| Mass | Cross-section | 3l + \(E_T\) | 4l + \(E_T\) | ss3os1l + \(E_T\) | 5l + \(E_T\) |
|------|--------------|--------------|--------------|----------------|--------------|
| \(m_{\tilde{\chi}_1^0}\) | \(m_{\tilde{\chi}_2^+}\) | \(m_{\tilde{\chi}_1^0}\) | \(\sigma_{eff}\) | \(N_{4l}\) | \(\sigma_{eff}\) | \(N_{ss3os1l}\) | \(\sigma_{eff}\) | \(N_{5l}\) |
| 40.7 | 380.7 | 620.3 | 86.86 | 0.0669 | 20.6 | 0.0269 | 80.8 | 0.0165 | 49.5 | 0.0043 | 13.0 |
| 159.7 | 380.7 | 620.3 | 86.16 | 0.0534 | 16.4 | 0.0293 | 87.8 | 0.012 | 36.2 | 0.0103 | 31.0 |
| 321.3 | 380.7 | 620.3 | 74.43 | 0.0231 | 7.1 | 0.0372 | 111.6 | 0.0067 | 20.1 | 0.0082 | 24.6 |
| 49.98 | 500.8 | 795.9 | 26.57 | 0.0268 | 8.3 | 0.0074 | 22.3 | 0.0039 | 11.9 | 0.0027 | 7.9 |
| 199.7 | 500.8 | 795.9 | 26.48 | 0.0244 | 7.5 | 0.0087 | 26.2 | 0.0045 | 13.5 | 0.0026 | 7.8 |
| 400.3 | 500.8 | 795.9 | 25.64 | 0.0128 | 3.8 | 0.0053 | 15.8 | 0.0015 | 4.5 | 0.0035 | 10.5 |
| 300.4 | 350.7 | 576.9 | 99.23 | 0.0288 | 7.9 | 0.0635 | 190.5 | 0.0228 | 68.5 | 0.0039 | 11.9 |
| 300.3 | 449.6 | 720.8 | 41.73 | 0.0196 | 6.1 | 0.0108 | 32.5 | 0.0033 | 10.0 | 0.0037 | 11.3 |
| 300.4 | 550.7 | 869.6 | 17.07 | 0.0145 | 4.4 | 0.0051 | 15.4 | 0.0027 | 8.2 | 0.0005 | 1.5 |

4.6 Light Higgsino and Light Left Slepton (LHLS) Model

We show the exclusion contour (the blue curve) in the \(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}\) plane obtained by scanning the parameter space of the LHLS Model (see section 2.2, model 2.2 a) in Fig. 6. The choice of the L-slepton masses are as in section 2.2. The constraints are significantly stronger than the ones obtained from Run I data (the black contour) \[67\. For example, the lower bound on \(m_{\tilde{\chi}_1^\pm}\) for a LSP with negligible mass is now extended from 450 GeV (Run I) to 650 GeV. The corresponding lower bound on \(m_{\tilde{\chi}_2^\pm}\) is \(\approx 1.01\) TeV. Above \(m_{\tilde{\chi}_1^0} \approx 300\) GeV, there is no bound on \(m_{\tilde{\chi}_1^\pm}\). In addition one can also put correlated bounds on \(m_{\tilde{\chi}_1^\pm}\) and \(m_{\tilde{\chi}_1^0}\) coming from ATLAS slepton search \[34\) at Run II \[34\) of the LHC (see the magenta curve in Fig. 6). It is interesting to note that the bound on \(m_{\tilde{\chi}_1^\pm}\) for a massless LSP as obtained from slepton search is around 1 TeV which is much stronger than that coming from direct eweakino searches at Run II.

The exclusion using Run II data depletes the bands allowed by the \(a_\mu\) data severely leaving only a small fraction of the green 2\(\sigma\) band within the APS. The lower branch of the red region allowed by the DM relic density constraint, a part of which was allowed by the LHC Run I eweakino searches, are now excluded by

\[\text{Slepton mass in LHLS model is related to } m_{\tilde{\chi}_1^\pm} \text{ and } m_{\tilde{\chi}_1^0} \text{ through the assumption } m_{\tilde{l}_L} = \frac{m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0}}{2}.\]
the Run II data. This has implications for the compatibility of this model and the direct detection of DM data taken at its face value (see below). A significant portion of the upper red branch is still allowed.
Table 6: The masses and production cross-sections of all possible e weakino pairs for different BPs in the LHLS model are given. For the trilepton signal in each case we display the significance \((S/\sqrt{B})_{3l}\). The corresponding \(\sigma_{eff}\) and total number of signal events with negligible backgrounds for each type of multilepton signal with \(n > 3\) are also shown. Masses and cross-sections are in GeV and fb respectively.

Various multilepton signals in this model for an integrated luminosity of 3000 fb\(^{-1}\) are displayed in Table 6. The 3\(l + \slashed{E_T}\) signal is observable for almost the full set of BPs considered here. It also follows that \(N_{BSM}\) exceeds 5 for all signals with \(n \geq 3\) for a relatively low \(m_{\tilde{\chi}^\pm_1} = 480\) GeV for several choices of the LSP mass. However, as \(m_{\tilde{\chi}^\pm_1}\) increases to 600 GeV, the cross-section of heavy eweakino pair production decreases rapidly (for this \(m_{\tilde{\chi}^\pm_1}\), we have \(m_{\tilde{\chi}^\pm_2} (\tilde{\chi}^0_4) \approx 940\) GeV). The ssosos\(l + \slashed{E_T}\) and 5\(l + \slashed{E_T}\) signals that mainly come from heavy eweakino production become weaker. The same features are seen when we vary \(m_{\tilde{\chi}^\pm_1}\) keeping \(m_{\tilde{\chi}^0_1}\) fixed at 400 GeV. For the entire range considered by us the 4\(l + \slashed{E_T}\) signal, which is not very common is the corresponding model with decoupled heavier eweakinos, is observable.

4.7 Light Mixed and Light Left Slepton (LMLS) Model

The APS of the LMLS model in the \(m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1}\) plane consistent with all constraints is shown in Fig 7. The parameter space is tightly constrained in this case. The bound on \(m_{\tilde{\chi}^\pm_1}\) for a massless LSP coming from Run II data (the blue line) is \(\approx 960\) GeV. This limit on \(m_{\tilde{\chi}^\pm_1}\) differs from that in case of Run I (the black line) by atleast 300 GeV. On the other hand above \(m_{\tilde{\chi}^0_1} = 450\) GeV, LHC puts no constraint on the mass of \(\tilde{\chi}^\pm_2\). The magenta line represents the exclusion limit on \(m_{\tilde{\chi}^\pm_1}\) as a function of LSP mass coming from the LHC slepton search. The present LHC limits affects severely the APS which is now consistent with the...
DM relic density and $a_\mu$ data over a small region. A small part of 1$\sigma$ and 2$\sigma$ allowed $a_\mu$ bands lies beyond the Run II exclusion contour. The APS with $m_{\tilde{\chi}_1^\pm}$ in the range $\approx 350 - 600$ GeV is phenomenologically very interesting as it is allowed by both DM relic density and $a_\mu$ data. Although the upper DM band extends up to $m_{\tilde{\chi}_1^\pm} \approx 900$ GeV, the region with high $m_{\tilde{\chi}_1^\pm}$ is likely to give poor multilepton signal at the high luminosity LHC (see below). Note that, the lower DM band was already ruled out by Run I search.

![Figure 7](image_url) Exclusion contours in the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane in the Light Mixed and Light Left Slepton (LMLS) model. The blue (black) line represents exclusion obtained by us using ATLAS $3l + E_T$ search data from Run II (Run I). The exclusion from direct slepton search (the magenta curve) is also shown. Colors and conventions are the same as in Fig. 1.

Table 7 represents the result of multilepton signals in the LMLS model with the help of several BPs. For $m_{\tilde{\chi}_1^\pm} = 550$ GeV, the entire allowed range of LSP masses (see Fig. 7) may be probed through multilepton channels with an integrated luminosity of 3000 fb$^{-1}$. In fact, even the channels like $ss3os1l + E_T, 5l + E_T$ which are unique features of non-decoupled heavy eweakinos yield large signals. For higher values of $m_{\tilde{\chi}_1^\pm}$ (e.g. say 750 GeV), however, $ss3os1l$ and $5l$ signals are poor even with $L = 3000$ fb$^{-1}$. This again mainly happens due to the large masses of the heavier EW sector that result into low cross-section. We get the same result when we vary $m_{\tilde{\chi}_1^\pm}$ keeping LSP mass fixed at a particular value (say 500 GeV). The $4l + E_T$ channel turns out to be the most promising for the rest of the BPs.
Constraints from dark matter direct detection experiments

In this section we study the models constrained in section 4 in the light of the measured spin independent dark matter nucleon scattering cross section ($\sigma_{SI}$) by the XENON 1T [50], LUX [51] and Panda [52] experiments. However, in view of the large uncertainties in the computation of $\sigma_{SI}$ due to theoretical as well as experimental inputs (see section 3), the relatively small differences among them is not very significant. From our scanning we take the points in the APS of each model, compute $\sigma_{SI}$ for them and compare the results with the upper bounds on $\sigma_{SI}$. Our results are shown in Figs 8, 9 and 10. In all figures the black curves represent the upper bound on $\sigma_{SI}$ as a function of the DM mass as obtained by the XENON 1T experiment. The green and yellow regions represent the 1σ and 2σ sensitivity bands respectively. The widths of these bands reflect the statistical fluctuations in a typical low count experiment. The lowest curve show the projected sensitivity of the PandaX-4T experiment [72], which will be operational after the ongoing PandaX-II experiment.

It follows from Fig 8 that both the compressed (CLHHS ($\tilde{W}$)) and the moderately compressed (MCLHHS ($\tilde{W}$)) models predict $\sigma_{SI}$ far above the experimental upper bounds. Thus these models can only survive provided the computed values of $\sigma_{SI}$ are overestimated by a large factor - a possibility that cannot be ruled out.

Table 7: The masses and production cross-sections of all possible eweakino pairs for different BPs in the LMLS model are given. For the trilepton signal in each case we display the significance ($S/\sqrt{B}$). The corresponding $\sigma_{eff}$ and total number of signal events with negligible backgrounds for each type of multilepton signal with $n > 3$ are also shown. Masses and cross-sections are in GeV and fb respectively.

| Mass     | Cross-section | $3l + E_T$ | $4l + E_T$ | $ss3os1l + E_T$ | $5l + E_T$ |
|----------|---------------|-----------|-----------|----------------|-----------|
| $m_{\tilde{\chi}_1^0}$ | $m_{\tilde{\chi}_1^\pm}$ | $m_{\tilde{\chi}_2^\pm}$ | in fb | $\sigma_{eff}^{3l}$ | $\sigma_{eff}^{4l}$ | $N_{4l}$ | $\sigma_{eff}^{ss3os1l}$ | $N_{ss3os1l}$ | $\sigma_{eff}^{5l}$ | $N_{5l}$ |
| 400.0    | 550.1         | 664.3     | 26.18     | 0.0688         | 19.1      | 0.0259   | 77.7   | 0.0034   | 10.2    | 0.006   | 18.1    |
| 459.8    | 550.4         | 664.5     | 25.76     | 0.0551         | 10.9      | 0.0227   | 68.0   | 0.0059   | 17.8    | 0.049   | 14.7    |
| 520.5    | 550.7         | 664.8     | 22.32     | 0.0112         | 2.5       | 0.0134   | 40.2   | 0.0024   | 7.4       | 0.0033  | 10.0    |
| 100.6    | 750.9         | 866.1     | 5.761     | 0.2898         | 89.4      | 0.0074   | 22.1   | 0.0005   | 1.72     | 0.0006  | 1.9     |
| 300.5    | 750.3         | 865.3     | 5.809     | 0.1922         | 59.2      | 0.0084   | 25.1   | 0.0006   | 1.74     | 0.0009  | 2.6     |
| 499.9    | 750.0         | 864.8     | 5.813     | 0.0532         | 16.4      | 0.007    | 21.1   | 0.0006   | 1.92     | 0.0011  | 3.3     |
| 699.8    | 750.9         | 865.5     | 5.464     | 0.0102         | 2.2       | 0.0074   | 22.3   | 0.0012   | 3.6      | 0.0015  | 4.6     |
| 500.0    | 530.1         | 644.5     | 26.44     | 0.0148         | 3.3       | 0.0148   | 44.4   | 0.0042   | 12.7     | 0.0032  | 9.5     |
| 499.9    | 629.8         | 744.2     | 13.92     | 0.0339         | 6.7       | 0.0128   | 38.4   | 0.0019   | 5.8       | 0.004   | 12.1    |
| 500.1    | 829.9         | 945.1     | 3.342     | 0.0177         | 2.5       | 0.0049   | 14.8   | 0.0005   | 1.4       | 0.0004  | 1.3     |
Figure 8: Plot of spin independent scattering cross-section $\sigma^{SI}$ for scattering of proton with $\tilde{\chi}_1^0$ as a function of the mass of the LSP for the compressed models (2.4a, 2.4b and 2.4c). Only the points which satisfy WMAP/PLANCK, $a_\mu$ up to the level of $2\sigma$ and LHC Run II constraints are used in the calculation. The exclusion contours for XENON 1T, LUX, PandaX-II and PandaX-4T experiments are shown as black, red, magenta and green lines respectively. In green and yellow are shown the $1\sigma$ and $2\sigma$ sensitivity bands respectively of XENON 1T data.

out apriori. This can happen if, e.g., the DM density in the neighbourhood of the earth, which has not been directly measured, turns out to be unexpectedly small. It may be recalled that only the average value of this density over a astronomically large volume with the sun at the centre has been measured experimentally. Other uncertainties as discussed in section 3.1 leave open the possibility that $\sigma_{SI}$ could be even further suppressed. Thus conclusions based on Fig. 8 should not to be taken at their face values.

From Fig 9 it can be seen that the LHLS and LMLS models are also disfavoured. However they cannot be ruled out with confidence thanks to the uncertainties in the computation of $\sigma_{SI}$ as discussed in the last paragraph. It is interesting to note that the LHHS model is still consistent with the direct DM detection data even if Fig. 9 is taken at its face value. This happens in a part of the APS where the DM relic density is produced by the LSP pair annihilation into the Higgs boson. Similar parameter spaces in other models are now ruled out by the LHC Run II data.

We also note in passing that several LW models are also consistent with the direct detection data (see Fig 10).
In this paper we first constrain the full eweakino sectors of several generic pMSSM models, described in section 2, using the ATLAS model independent upper bounds on the number of any BSM events from trilrpton searches at LHC Run II \cite{34}. We do not employ the often used ad hoc assumption that the heavier eweakinos are decoupled. As explained in section 2 the phenomenology of the heavier eweakinos, which are dominantly winos, are particularly important in the light higgsino(LH) models (see section 2.2) where the lighter eweakinos $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ are higgsino dominated while the LSP is either a higgsino or bino-higgsino admixture. The exclusion contour obtained also depends on the hierarchy among the slepton and the lighter eweakinos masses. Accordingly we have worked in two scenarios i) LHLS (model 2.2a) and ii) LHLS models(model 2.2b). In addition we have also considered the LMLS model (section 2.3) where the lighter and heavier eweakinos - other than the LSP - are admixtures of wino and higgsino eigenstates. For negligible LSP mass the lower bounds on $m_{\tilde{\chi}^\pm_1}$ are 650 GeV (Fig 6), 370 GeV (Fig 5) and 960 GeV (Fig 7).

All of them are significantly weaker than the ATLAS Run II limit of 1150 GeV obtained in a simplified model similar to the LWLS model (model 2.1a, section 2.1) with decoupled heavier eweakinos. This indicates once more that the prospect of observing interesting physics involving relatively low mass sparticles in the LH models looks brighter. The corresponding Limits on $m_{\tilde{\chi}^\pm_2}$ are 1.01 TeV, 600 GeV and 1.07 TeV respectively (see Figs 6, 5 and 7 ). It also follows that the weakest exclusion from LHC Run II data occurs in the LHHS model. As a result the APS, consistent with all constraints, discussed in section 3.1, is quite large in this model. We also note in passing that the prediction of this model for $\sigma_{SI}$ is consistent with all direct DM detection data.
It was emphasized in refs. [45, 47] based on ATLAS Run I data that the heavier eweakinos attain special significance if the lighter eweakino spectrum is compressed so that only weak signals involving mostly soft particles can emanate from them. Keeping this in view we have studied three compressed models i) CLHHS($\tilde{W}$) model (model 2.3a, section 2.3), ii) MCLHHS($\tilde{W}$)(model 2.3b, section 2.3) and iii) CLHHS($\tilde{W} - \tilde{B}$)(model 2.3c, section 2.3). The exclusion contours and the APS for each model using ATLAS Run II data are shown in Figs 2, 3 and 4 respectively. For the lowest LSP mass allowed by the LEP data the lower bounds on $m_{\tilde{\chi}^\pm}$ are 775 GeV, 850 GeV and 900 GeV respectively. On the other hand there is no constraints from Run II data for LSP masses above 200-300 GeV in any of the three compressed models.

The prospects of observing the multilepton ($nl + \not{E}_T, n = 3, 4, 5$) signatures at the high luminosity LHC (3000 fb$^{-1}$) in different models are shown in tables 2 - 7 using benchmark points. These points belong to the APS of the respective models. As already noted, in the compressed models (see Tables 2 - 4) the signals for $n=3$ turn out to be rather poor especially for relatively high LSP masses ($> 350 - 400$ GeV). In such cases one of the search channels with $n > 3$ could be the discovery channel even for higher LSP masses. In particular the signal with $n=4$ appears to be rather promising. Depending on the LSP mass, $m_{\tilde{\chi}^\pm}$ upto 1 TeV can be probed. For the non-compressed model all multilepton channels appear to be relevant provided the LSP mass is around 400 - 450 GeV or smaller( see tables 5 - 7).

As discussed in section 5 the LHHS model deserves special attention since it’s prediction for $\sigma_{SI}$, taken at its face value, is consistent with the upper bound on this cross section measured by DM direct detection experiments [50, 51, 52] (Fig 9). The predictions of all other LH type models violates the above bound by large factors ( see Figs 8, 9). We note in passing that the LW type models look better in this respect (see...
Whether the computed $\sigma_{SI}$ should be taken at its face value is, however, not at all clear. This is because of several inputs in the calculation which involve large uncertainties (see section 3.1 and references there in). We, therefore, refrain from spelling the final verdict based on the above observations.

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