Impact of LHC data on muon $g - 2$ solutions in vector-like extension of the Constrained MSSM

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Abstract: The long–standing discrepancy between the experimental determination by the Muon $g - 2$ Collaboration at Brookhaven and the Standard Model predictions for the anomalous magnetic moment of the muon cannot be explained within simple unified framework like the Constrained Minimal Supersymmetric Standard Model, but it can within its extension with vector-like fermions. In this paper we consider a model with an additional vector-like 5 + ¯5 pair of SU(5). Within this model we first identify its parameter space that is consistent with the current discrepancy and show that this implies the lighter chargino mass in the range of 700 − 1200 GeV. We examine how it is affected by constraints from electroweak sparticle search at the LHC based on 13 TeV search with 36.1 fb$^{-1}$ integrated luminosity. We show that null trilepton signal searches coming from chargino–neutralino pair production significantly constrains the allowed parameter space except when the chargino–neutralino mass difference is relatively small, below about 10 GeV. Next we consider the expected impact of the New Muon $g - 2$ experiment at Fermilab with its projected sensitivity reach of 7σ and, assuming it confirms the current discrepancy, show that the remaining parameter space of the considered model will be in strong tension with the current LHC limits.
1 Introduction

Despite the absence of a signal for supersymmetry (SUSY) at the LHC, it still remains one of the most appealing frameworks for physics beyond the Standard Model (BSM). Besides providing a natural candidate for dark matter (DM), it also gives possible explanation for the discrepancy that exists in the Standard Model (SM) value of the anomalous magnetic moment of muon, \((g-2)_\mu\), and the experimentally measured quantity. The SM value for \((g-2)_\mu\) differs by more than 3\(\sigma\) from the measured value \([1, 2]\). Future measurement at Fermilab \([3, 4]\) is expected to improve the sensitivity of the previous measurement by a factor of four and hence potentially confirm or falsify the persistent disagreement. In SUSY, the explanation for the difference arises from contributions due to smuon-neutralino and sneutrino-chargino loops. To fit the \((g-2)_\mu\) anomaly within the framework of the minimal supersymmetric Standard Model (MSSM), one requires the slepton and the lighter chargino masses in a range of a few hundreds of GeV \([5–11]\). However, the stringent bounds on the strong sector (squarks and gluinos) from the LHC and the Higgs mass measurements rule out the possibility of explaining \((g-2)_\mu\) in GUT-constrained models like the Constrained MSSM (CMSSM) and the Non-Universal Higgs Mass (NUHM) model \([12–14]\). The way out has usually been to assume non-universal gaugino masses \([15–22]\) which can provide a viable parameter space to explain \((g-2)_\mu\) while at the same time not conflicting with constraints from LEP and LHC.

There have also been alternative solutions as for example, adding vector-like (VL) matter to MSSM which has been studied in Refs. \([23–32]\). The presence of new VL sector
gives extra contribution to \((g - 2)_\mu\) by introducing new sources of smuon mixing and new Yukawa couplings \([32]\). Apart from \((g - 2)_\mu\), it has been shown that VL colored sparticles provide extra contributions to Higgs mass \([33-38]\) and several phenomenological analyses have addressed the extra VL matter in the context of various long-standing theoretical issues related to beyond SM physics \([23-32]\).

In particular, Ref. \([32]\) studied two simple extensions of the CMSSM by adding a pair of multiplets, firstly in the \(5 + \bar{5}\) and secondly in the \(10 + \bar{10}\) representations of \(SU(5)\). It was shown that the model could satisfy various constraints from flavor physics and LHC direct searches, as well as include a viable dark matter candidate that was in agreement with relic density and direct detection constraints, for a considerable region of the parameter space \([32]\). In particular, through the additional mixing of VL fields with second generation leptons, the model proved particularly useful in explaining the \((g - 2)_\mu\) discrepancy. In this work we extend the analysis considered in Ref. \([32]\), using the models with additional \(5 + \bar{5}\). Motivated by the solution to the \((g - 2)_\mu\) discrepancy, we examine the impact of collider constraints on the viable parameter space.

As mentioned earlier, the allowed parameter spaces satisfying \((g - 2)_\mu\) constraints are characterised by light electroweak (EW) sparticles, i.e., light EW gauginos or electroweakinos (the charginos and the neutralinos) and charged sleptons. Hence to probe the relevant parameter space at the LHC, the most sensitive search is chargino and neutralino pair production (via \(pp \rightarrow \chi^\pm_1 \chi^0_2\)) leading to the trilepton + transverse missing energy (\(E_T^\text{miss}\)) signal. Both CMS and ATLAS Collaborations have looked for electroweakinos, or EWinos, with different leptonic final states \([39-47]\), among which the trilepton data gives the most stringent bound. From the very recent LHC analysis of Run-II data with \(\mathcal{L} = 36.1\ \text{fb}^{-1}\), ATLAS has excluded chargino masses upto 1150 GeV for relatively light LSP \([46]\). However, ATLAS and CMS have presented these limits for a few particular type of simplified models with specific assumptions on the compositions and branching ratios of EWinos. The electroweakinos searches and related topics in the context of the LHC have been analysed by various phenomenology group in Ref. \([7, 9, 48-66]\). Due to the presence of VL particles and their mixing with SM, the electroweakinos (mainly \(\chi^\pm_1, \chi^0_2\)) can have non standard branching ratios compared to the CMSSM or usual phenomenological MSSM (pMSSM) scenarios. Hence the limits interpreted by ATLAS or CMS for various simplified models are not directly applicable to such models and a reinterpretation of the bounds from trilepton searches at the LHC is necessary.

The paper is organized as follows. We first give a brief overview of the model which is obtained by adding a VL \(5 + \bar{5}\) of \(SU(5)\) pair to CMSSM in Section 2. We briefly mention the constraints applied to obtain the relevant allowed parameter space in Section 3 and then discuss different scenarios for chargino (\(\chi^+_1\)) and neutralino (\(\chi^0_2\)) decays in the context of VL extension of CMSSM in Section 4. In Section 5, we show results for LHC trilepton searches from chargino-neutralino pair production using the latest LHC Run-II 36.1\(\text{fb}^{-1}\) data. Finally, we give our conclusions in Section 6.
2 Vector like extension of the CMSSM

We follow the model studied and analysed in [32], particularly in the context of \((g - 2)_\mu\) where the MSSM is extended through the addition of a pair \(5 + \bar{5}\) or a pair \(10 + \bar{10}\). However, it was shown in [32] that the \(10 + \bar{10}\) extension was more fine tuned in order to provide a viable parameter space for a significant contribution to \((g - 2)_\mu\) and therefore the analysis was restricted to \(5 + \bar{5}\). Here we shall focus only on the \(5 + \bar{5}\) extension, which we shall from now on refer to as the LD model following the previous convention. We summarize the main features of the LD model below (for more details see Ref. [32]).

The LD model consists of extending the MSSM spectrum with the addition of the following fields:

\[
\begin{align*}
D &= (3, 1, 1/3) \\
D' &= (3, 1, -1/3) \\
L &= (1, 2, -1/2) \\
L' &= (1, 2, 1/2).
\end{align*}
\]

This implies the addition of a quark with charge \(-1/3\) and a charged lepton along with their antiparticles, and two massive neutrinos to the MSSM spectrum. Correspondingly the sparticle content sees the addition of squarks, sleptons and sneutrinos.

In comparison to the MSSM, there are now additional trilinear and bilinear terms in the superpotential,

\[
W \supset -\lambda_D qH_d D - \lambda_L LH_d e + M_D DD' + M_L LL' + \tilde{M}_L LL' + \tilde{M}_D dD',
\]

(2.1)

Finally the soft SUSY-breaking Lagrangian also has extra terms involving \(\tilde{L}^{(i)}\) and \(\tilde{D}^{(i)}\) as follows

\[
-\mathcal{L}_{\text{soft}} \supset \left[ m_L^2 |\tilde{L}|^2 + m_{L'}^2 |\tilde{L}'|^2 + m_D^2 |\tilde{D}|^2 + m_{D'}^2 |\tilde{D}'|^2 + \left( \tilde{m}_L^2 \tilde{L} \tilde{L} + \tilde{m}_D^2 \tilde{D} \tilde{D} + \text{h.c.} \right) \right]
+ \left( B_{M_L} \tilde{L} \tilde{L}' + B_{M_{L'}} \tilde{L}' \tilde{L}' + B_{M_D} \tilde{D} \tilde{D}' + B_{M_{D'}} \tilde{D}' \tilde{D}' + \text{h.c.} \right)
- \left( T_D \tilde{q} H_d \tilde{D} + T_L \tilde{L} H_d \tilde{e} + \text{h.c.} \right),
\]

(2.2)

where \(\tilde{m}_L^2, \tilde{m}_D^2, T_L, T_D, B_{M_L},\) and \(B_{M_D}\) are 3-dimensional matrices that govern mixing between MSSM and VL matter. This mixing plays an important role for \((g - 2)_\mu\) phenomenology.

In addition to the above, we also make the choice of GUT scale parameters such that the boundary conditions for the extra Yukawa couplings demanded by UV completion at the GUT scale are given by

\[
\lambda_L = \begin{pmatrix}
0 \\
\lambda_5 \\
\epsilon \lambda_5
\end{pmatrix},
\]

(2.3)

where \(\epsilon < 1\). This in turn means that the soft mass matrices which also satisfy the same flavor constraints as the Yukawa couplings, will have their off-diagonal mixing terms parametrized similar to Eqn. 2.3 as follows

\footnote{The MSSM fields are \(q = (3, 2, 1/6), u = (3, 1, -2/3), d = (3, 1, 1/3), l = (1, 2, -1/2), e = (1, 2, -1/2), H_u = (1, 2, 1/2), H_d = (1, 2, -1/2)\) with \(SU(3) \times SU(2) \times U(1)\) quantum numbers in parentheses.}
\[
\tilde{m}_L^2 = \tilde{m}_D^2 = \begin{pmatrix} 0 & \tilde{m}^2 \\ \alpha \tilde{m}^2 & 0 \end{pmatrix},
\]

(2.4)

where once again \( \alpha < 1 \).

Thus the first generation mixing is almost absent compared to second and third generation mixing. Eqns. 2.3 and 2.4 not only impact the \((g - 2)_\mu\) contribution but also have a significant effect on the trilepton signal from chargino and neutralino decays as we shall see in Section 4.

3 Constraints from flavor physics, \((g - 2)_\mu\) and direct detection of DM

In this section we mention the GUT scale input parameters used as well as the constraints applied in order to obtain the parameter space shown in Fig. 1. The parameter space was scanned using MultiNest [67] and the SARAH [68–71] package was used to generate the spectrum, while the relevant flavor constraints were calculated using the SARAH package FlavorKit [72]. In addition, dark matter constraints on relic density and direct detection were obtained using micrOMEGAs v.3.5.5 [73]. Bounds on the Higgs sector from LHC searches for Higgs production channels, branching ratios as well as Higgs decay were applied using the codes HiggsSignals [74] and HiggsBounds [75–77]. The following ranges of values for the GUT scale input parameters were used, which are also listed in [32]:

- VL Yukawa coupling, \( \lambda_5 \in [-0.5, 0.5] \),
- Yukawa hierarchy factor, \( \epsilon \in [-0.5, 0.5] \),
- superpotential mass VL fields, \( M_V \in [50, 1500] \) GeV,
- superpotential mass mixing, \( \tilde{M} \in [-20, 20] \) GeV,
- mass mixing hierarchy factor, \( \alpha \in [0.01, 1] \),
  - scalar mass, \( m_0 \in [100, 4000] \) GeV,
  - gaugino mass, \( m_{1/2} \in [300, 4000] \) GeV,
  - soft mass mixing, \( \tilde{m}^2 \in [-5 \times 10^6, 5 \times 10^6] \) GeV^2,
  - trilinear coupling, \( A_0 \in [-4000, 4000] \) GeV,
  - soft bilinear term VL fields, \( B_0 \in [-1500, 1500] \) GeV,
- ratio of the Higgs vevs, \( \tan \beta \in [1, 60] \),
- and the sign of the Higgs mass parameter, \( \text{sgn} \mu = +1 \).

The experimental constraints used to derive the parameter space in addition to the Higgs bounds are flavor physics constraints such as \( \text{BR} (B \to X_s \gamma) \) [78], \( \text{BR} (B_u \to \tau \nu) \) [79], \( \Delta M_{B_s} \) [80], \( \Delta \rho \) [80], \( \text{BR} (B_s \to \mu^+ \mu^-) \) [81, 82] and \( \text{BR} (\tau^\pm \to \mu^\pm \gamma) \) [83], while in DM sector

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\[\text{The result shown in Fig. 1 is obtained using the same numerical tools and priors used in Ref. [32].} \]
the constraint on relic abundance \([84]\), \(\Omega \chi h^2\), and the current LUX limit \([85]\) on the spin-independent DM-nucleon scattering cross section, \(\sigma_{SI}^p\), are taken into account. For more details on ranges and theoretical and experimental errors see Table 1 of ref. \([32]\).

4 Allowed parameter space and decay properties of EWinos

In this section we study decay properties of \(\chi_{\pm 1}^\pm\) and \(\chi_0^2\) in the parameter space which satisfies the constraints mentioned in the previous section as well as \(\delta (g - 2)\mu\) bounds \((2 \sigma)\) as shown in Fig. 1. The \(2\sigma\) allowed region for \(\delta (g - 2)\mu\) according to the latest data \([1, 2]\) is indicated by the blue solid lines, while the dashed lines indicate future measurement \([3, 4]\) with four times greater sensitivity, assuming that the central value remains the same. We consider the red points that are allowed by current \(\delta (g - 2)\mu\) bounds for further analysis. The trilepton final states from direct chargino-neutralino pair production will be the most effective channel to probe all these points. Due to the choice of input parameters and mixing in our model, it is expected that the decay modes of EWinos could be different from the MSSM cases or usual choices made by ATLAS/CMS with simplified scenarios.

**Figure 1:** Allowed parameter space for \(\delta (g - 2)\mu\) in the LD model as a function of chargino mass. The \(2\sigma\) allowed region for \(\delta (g - 2)\mu\) according to the latest data \([1, 2]\) is indicated by the blue solid lines, while the dashed lines indicate future measurement \([3, 4]\) with four times greater sensitivity, assuming that the central value remains the same.
Figure 2: Branching ratio of $\chi_2^0 \to l \tilde{e}$ (left panel) and $\chi_1^\pm \to l \tilde{\nu}$ (right panel) plotted against $\chi_2^0$ and $\chi_1^\pm$ masses, respectively, for the parameter space satisfying the constraints described in the text as well as giving a $(g-2)_\mu$ contribution that is within the current $2\sigma$ limit.

4.1 Decay modes for $\chi_2^0$:

In general for light slepton scenarios (lighter than $m_{\chi_1^\pm}$), the second lightest neutralino $\chi_2^0$ decays into 2 body final state – $l \tilde{l}$ and $\nu \tilde{\nu}$ where $l$ denotes for $e, \mu$ and $\tau$. For our model, the first slepton mass eigenstate is mostly mixed smuon/VL and the second slepton eigenstate is usually right-handed stau. Hence we sometimes obtain large mass splitting between the first two slepton mass eigenstates. For a significant portion of the parameter space $\chi_2^0$ decays to a muon and a slepton at 50% branching ratio, or one sees the $\tau$ lepton channel but no electrons, with 50% branching ratio for invisible modes. Thus the flavour democratic simplified model scenarios are mostly absent in our model. As a result, apart from the invisible modes which have a 50% branching ratio, $\chi_2^0$ can dominantly decay either into $\mu \tilde{\mu}$ or $\tau \tilde{\tau}$ with 50% branching ratios. For the first case the usual LHC limit will then put more stringent bounds.

In the left panel of Fig. 2, the branching ratios for different leptonic decay modes are plotted against the $\chi_2^0$ mass. The muon channel is always at 50% branching ratio but the $\tau$ channel has a branching ratio which is mostly less than 20% with some points having branching ratio in the range between 20 – 100% while no electrons are seen.

In Fig. 3, we present the branching ratios of $\chi_2^0$ which decays into a muon and a slepton ($\tilde{e}_1/\tilde{e}_2$ ), where the slepton further decays into a muon and an LSP with 100% branching ratio. The points are color coded according to the mass differences $m_{\tilde{e}} - m_{\chi_2^0}$ (left panel) and $m_{\chi_2^0} - m_{\tilde{e}}$ (right panel). These BRs($\chi_2^0 \to \mu \tilde{e}_{1/2} \to \mu \mu \chi_1^0$) vary within 40 – 50% with the rest being invisible, where the slepton could be degenerate with either $\chi_1^0$ or $\chi_2^0$. 
Figure 3: Branching ratio of $\chi^0_2 \rightarrow \mu \tilde{e}$ plotted against $\chi^0_2$ mass for parameter space satisfying the constraints described in the text as well as giving a $(g - 2)_\mu$ contribution that is within the current $2\sigma$ limit. The left panel shows the points color coded with slepton-LSP mass difference while the right panel shows them color coded according to the $\chi^0_2$-slepton mass difference.

Figure 4: Same as Fig. 3 but for $\chi^\pm_1 \rightarrow \nu \tilde{e}$ with the points in the left panel color coded according to the mass difference $m_{\tilde{e}} - m_{\chi^0_1}$ while those in the right panel according to $m_{\chi^\pm_1} - m_{\tilde{e}}$.

4.2 Decay modes for $\chi^\pm_1$:
The charginos decay into $l \tilde{\nu}$ and $\nu \tilde{l}$ with equal branching ratios for three generation in “flavor-democratic” simplified model. As we discussed in the previous subsection, due to
the different smuon mixing as compared to MSSM, the charginos largely decay into $\nu \tilde{\mu}$ and $\mu \tilde{\nu}$ with a branching ratio of 50% each or the corresponding $\tau$ lepton channel.

In the right panel of Fig. 2, we show the branching ratios into different leptonic channels for $\chi_1^\pm$ as a function of $m_{\chi_1^0}$. We can see that the chargino dominantly decays to muons with a very small fraction going to $\tau$ and none to electrons. Thus a three muon signal is the most likely and also the most constraining signature to look for in the trilepton searches.

In Fig. 4, we present the branching ratios of $\chi_1^\pm$ where it decays into a neutrino and a slepton ($\tilde{e}_1/\tilde{e}_2$), where the slepton further decays into a muon and an LSP. The points are color coded according to the mass differences $m_\tilde{\nu} - m_{\chi_1^0}$ (left panel) and $m_{\chi_1^\pm} - m_\tilde{e}$ (right panel). These BRs($\chi_1^\pm \rightarrow \nu \tilde{e}_{1/2} \rightarrow \nu \mu \chi_0^0$) varies within 40 - 50 % with the rest being $\chi_1^\pm \rightarrow \mu \tilde{\nu}$, where the slepton could be degenerate with either $\chi_1^0$ or $\chi_2^0$.

### 4.3 Benchmark points and models

From the results of the previous section on the decay modes of $\chi_1^\pm$ and $\chi_2^0$, we can see that the collider constraint that is best suited to probe the chargino-neutralino pair production are the trilepton searches. In Table 1, we show three benchmark points chosen from Figs. 2-4. The decay properties of these points are strikingly different from the usual simplified models considered by LHC collaboration to interpret the trilepton limits. Also the mass hierarchies between sleptons and the electroweakinos are different in our model. Motivated by these benchmark points we choose the following three scenarios, or benchmark models.

- **Benchmark Model 1 (BM1)**: This model is motivated by benchmark point 1 (BP1) where the electroweakinos dominantly decay into muons. Here sleptons are NLSP and nearly degenerate with the LSP and we assume $m_{\tilde{\nu}_1} = m_{\tilde{e}_1} = m_{\chi_1^0} + 10$ GeV. For the branching ratios of the electroweakinos we assume BR($\chi_1^\pm \rightarrow \nu \tilde{e}_{1/2}$) = 0.50, and BR($\chi_2^0 \rightarrow \mu \tilde{\nu}_1, \nu \tilde{e}_1$) = 0.50; where BR($\tilde{e}_1 \rightarrow \mu \chi_1^0$) = 1.0. These assumptions apply to each point in the parameter space.

- **Benchmark Model 2 (BM2)**: BM2 is motivated by BP2 and the decay patterns of BM2 are same as BM1 but with the choice $m_{\tilde{\nu}_1} = m_{\tilde{e}_1} = m_{\chi_1^0} + 50$ GeV. This choice of mass dependence can significantly change the limits on chargino masses.

- **Benchmark Model 3 (BM3)**: BM3 is motivated by BP3 and the decay patterns of chargino and neutralino are similar to previous benchmark models. We choose the slepton mass as: $m_{\tilde{\nu}_1} = m_{\tilde{e}_1} = (m_{\chi_2^0} + m_{\chi_1^0})/2$. This choice of mass basically is similar to the simplified models considered by ATLAS, but BM3 is different in terms of branching ratios.

### 5 Collider analysis for trilepton searches

Both CMS and ATLAS Collaborations have searched for the EWinos with different final states (2l, 3l, with/without taus, lbb, l$\gamma\gamma$ etc.) from direct pair production of $\chi_1^\pm \chi_2^0$ or $\chi_1^\mp \chi_1^\pm$ [39–47]. The results are mainly interpreted for Slepton mediated simplified model, WZ mediated simplified model and Wh mediated simplified model. In the first case, the
| Parameter          | BP1  | BP2  | BP3  |
|-------------------|------|------|------|
| $m_0$             | 1023 | 1162 | 970  |
| $m_{1/2}$         | 1398 | 1544 | 1358 |
| $A_0$             | 36   | 1317 | 606  |
| $M_V$             | 329  | 324  | 746  |
| $B_0$             | 692  | -410 | 278  |
| $\lambda_5$      | -0.16| -0.14| -0.16|
| $\tilde{m}^2 (\times 10^6)$ | 1.6  | 1.9  | 1.6  |
| $\tilde{M}$       | 4.3  | 4    | -10.9|
| $\tan \beta$     | 44.7 | 48.5 | 48.8 |
| $\lambda_{D,2}$  | -0.39| -0.34| -0.38|
| $\lambda_{L,2}$  | -0.2 | -0.17| -0.19|
| $m_h$             | 124  | 123  | 123  |
| $m_{\chi_1^0}$   | 474  | 526  | 463  |
| $m_{\chi_1^\pm}$ | 898  | 993  | 875  |
| $m_{\tilde{e}_1}$| 484  | 576  | 669  |
| $m_{\tilde{e}_2}$| 858  | 866  | 752  |
| $m_{\tilde{\tau}_1}$ | 475  | 569  | 663  |
| $m_{\tilde{\nu}_R}$ | 2021 | 2297 | 1986 |
| $\chi_1^\pm \rightarrow \mu \tilde{\nu}$ | 0.5  | 0.5  | 0.5  |
| $\chi_1^\pm \rightarrow \nu \tilde{e}_1$ | 0.49 | 0.48 | 0.47 |
| $\chi_2^0 \rightarrow \mu \tilde{\tau}_1$ | 0.49 | 0.49 | 0.48 |
| $\chi_2^0 \rightarrow \nu \tilde{\nu}$ | 0.5  | 0.5  | 0.49 |
| $\tilde{\chi}_1^0 \rightarrow \mu \chi_1^0$ | 1.0  | 1.0  | 1.0  |
| $\delta (g - 2)_\mu (\times 10^{-9})$ | 2.54 | 2.23 | 2.09 |
| $\Delta m = m_{\tilde{e}_1} - m_{\chi_1^0}$ | 10   | 50   | $(m_{\chi_2^0} - m_{\chi_1^0}) / 2$ |

**Table 1:** Benchmark points chosen such that they satisfy the constraints as described in the text as well as giving a contribution to $(g - 2)_\mu$ that is consistent with the current $2\sigma$ limit. All masses are in GeV.

Sleptons are assumed to be lighter than $\chi_1^\pm$ and $\chi_2^0$ and this channel gives the most stringent bounds as the EWinos decay via slepton to lepton enriched final states \cite{46}. For rest of the two cases, sleptons are assumed to be much heavier than $\chi_1^\pm$ or $\chi_2^0$ and the electroweakinos decay via real or virtual $W$, $Z$ and Higgs boson. In our own model, the LHC limits on gluinos from 13 TeV data put stringent bounds on $m_{\chi_1^\pm} \gtrsim 700$ GeV (due to high scale input) and only the trilepton analysis targeting $\chi_1^\pm \chi_2^0$ production is sensitive to $m_{\chi_1^\pm} > 700$ GeV region. Hence in this analysis we only focus on the trilepton channels (dedicated signal regions for Slepton mediated simplified model). First we will briefly discuss about the 13 TeV trilepton search analysis considered by ATLAS \cite{46} and present our results.
Table 2: Selection requirements for slepton mediated \((3l)\) channel considered by ATLAS for 13 TeV 36.1 fb\(^{-1}\) data \cite{46}.

![Diagram](image)

**Figure 5**: Validation of the ATLAS trilepton analysis for Run-II 36.1 fb\(^{-1}\) data \cite{46}. The exclusion limit in the \(m_{\chi_0} - m_{\chi_\pm}\) plane obtained by the ATLAS Collaboration (red line) in their trilepton analysis is reproduced using similar mass relations and branching ratios of the relevant gauginos and sleptons (black line).

alongside ATLAS for validation and direct comparison.

### 5.1 Validation for trilepton analysis

In *slepton* \((\tilde{\ell}_L)\)-mediated models, it is assumed that the left handed sleptons and sneutrinos lie exactly midway between \(\chi^0_1\) and \(\chi^0_2\), \(m_{\tilde{\ell}_L} = (m_{\chi^0_1} + m_{\chi^0_2})/2\), and the EWinos decay either to left handed sleptons or sneutrinos universally. Events are considered with exactly three tagged leptons (electron or muon) \cite{46}. Event reconstruction details like electron, muon, tau and jet identification, isolation, overlap removal etc. are followed according to the ATLAS analysis as mentioned in Sec. 5 and Sec. 6 of \cite{46}. In this trilepton analysis, a
veto on $b$-jet is applied to all signal channels. For $b$-jets, we use the $p_T$ dependent $b$-tagging efficiencies obtained by ATLAS collaboration in Ref. [86].

Depending upon the requirement of $m_{SFOS}$ (invariant mass of same-flavour opposite-sign (SFOS) lepton) and $p_T^3$ ($p_T$ of third leading lepton), ATLAS has optimised five signal regions (SR), namely, SR3l-a to SR3l-e for *Slepton mediated simplified model*. The basic selection requirements for these channels, number of observed events and total SM background are listed in Table 2. In the absence of any BSM signal in all these channels, limits are set on the number of SUSY signal events at 95% confidence level (CL). For these five signal regions (SR3l-a to SR3l-e) $N_{BSM}$ at 95% CL are 7.2, 5.5, 10.6, 3.0 and 3.0, respectively. The ATLAS Collaboration has translated these obtained upper limits on $N_{BSM}$ into exclusion limits in the $m_{\chi_1^0} - m_{\chi_1^\pm}$ plane. In a similar way, we have also reproduced the exclusion contours obtained by ATLAS assuming similar mass relations and branching ratios of the relevant gauginos and sleptons. In order to validate our results we reproduce the exclusion contours using PYTHIA (v6.428) [88] 3. We use the next-to-leading order (NLO) + next-to-leading logarithmic (NLL) chargino-neutralino pair production cross-sections given in Ref. [89], which have been calculated for 13 TeV using the resummino code [90, 91]. For *slepton mediated models*, SR3l-e is the most sensitive channel for the parameter space with

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3These same set-up of codes were also used in Ref. [59]
large mass splitting between $\chi^\pm_1$ and $\chi^0_1$ ($\delta m = m_{\chi^\pm_1} - m_{\chi^0_1}$). For smallest $\delta m$, low-valued $m_{SFOS}$ SR3l-a is more effective to probe the relevant parameter space.

In Fig. 5, we present the validated results for slepton mediated simplified models. The red line corresponds to 95 % CL exclusion limits obtained by ATLAS and the black line corresponds to our validated results adopting the ATLAS analysis. From Fig. 5, it is evident that our validated results are in good agreement with that of ATLAS.

5.2 New limits for benchmark models

First we present our results for Benchmark Model 1 (BM1), where the scenarios represent slepton co-annihilation regions and due to the extreme mass degeneracy ($\delta m = m_{\chi^\pm_1} - m_{\chi^0_1} = 10$ GeV) the leptons coming from slepton decay are very soft (below the trigger cuts). The soft leptons cause the reduction on limits on chargino masses. The orange regions in Fig. 6 are excluded from 13 TeV data where the red dotted line represents the usual limits from simplified scenarios with the sleptons being midway between LSP and charginos. The vertical and horizontal magenta lines present the indirect limit on $m_{\chi^\pm_1}$ and $m_{\chi^0_1}$ from the gluino limits coming from 13 TeV data [87]. The blue points (circle) are allowed by the New Muon $g - 2$ result in a future measurement at Fermilab [3, 4] while the red points (star) are ruled out, assuming that the central value of the measurement remains the same. It is clear from Fig. 6 that for co-annihilation scenarios trilepton limits are even weaker than the indirect bounds from direct gluino searches due to the mass correlations in GUT models. It may be noted that with non-universal gaugino mass models the indirect limits from gluino searches are not valid and the models have a wide range of parameter space which are still allowed (except for the magenta regions).

The situation changes drastically if the mass difference is somewhat larger. We present the implication of trilepton data in Fig. 7 for BM2 where the mass splitting between $\chi^\pm_1$
and $\chi^0_1$, $\delta m = m_{\chi^+_1} - m_{\chi^0_1}$, is 50 GeV. The orange regions in Fig. 7 are excluded for BM2. In some region of the parameter space the limits are stronger than usual simplified models (denoted by red line). This is simply due to the enhancement of branching ratios in our model. It may be noted that for the simplified models considered by ATLAS, the electroweakinos decay to leptonic final state universally (but for BM2, electroweakinos decay mainly to $\mu$ final states). In Fig. 7, roughly half the points outside the orange shaded region are ruled out by Future Muon $g - 2$ experiment [3, 4] as indicated by the red points.

In Fig. 8 we analyse the model BM3 where the sleptons are exactly midway of $\chi^+_1$ and $\chi^0_2$ (same choice as simplified models). Similar to BM1 and BM2, EWinos decay also mainly to $\mu$ final states in BM3. For this model, the limits are even stronger than BM2. For light $\chi^0_1$, the limit on chargino mass extends up to 1250 GeV. Hence the current LHC data exclude all the $(g - 2)_\mu$ allowed points which have the same characteristic like BM3.

6 Conclusions

In this work we have studied the VL extension of MSSM – by the addition of a pair $5 + \bar{5}$ of $SU(5)$ which leads to an additional quark, lepton and a pair of neutrinos with corresponding squarks, sleptons and sneutrinos – in the context of $(g - 2)_\mu$, various flavor physics constraints, DM constraints and LHC limits on squarks and gluinos. We identify that the allowed parameter space in Fig. 1 leads to chargino mass in the range of $700 - 1200$ GeV. The mixing of the second and third generation leptons with the extended spectrum of VL particles leads not only to an enhanced contribution to $(g - 2)_\mu$ but also gives a very different kind of signature for electroweakino decay modes.
To probe the allowed parameter space at the LHC, the most sensitive search will be
the trilepton signal coming from chargino-neutralino pair production. For this reason we
do a detailed study of relevant decay properties and the mass hierarchies in Section 4.1
and 4.2. In particular we observe that the VL extension of MSSM along with the specific
choice of GUT scale parameters made here leads to a 3 muon or 3 tau final state instead of
lepton universality assumed in the LHC trilepton analysis. We therefore recast the ATLAS
trilepton searches in chargino-neutralino pair production using the recent Run-II data.
We identify three benchmark points from the scanned dataset. To interpret the trilepton
search we construct three simplified benchmark models based on these benchmark points.
We observe that the slepton coannihilation scenario, i.e. BM1, is not at all sensitive to the
current LHC data due to the soft nature of the lepton signal (see Fig. 6). However, the
points with a relatively larger mass difference, as for example BM2, can exclude chargino
mass up to 1 TeV (see Fig. 7). The strongest constraint comes from BM3 where the
slepton mass lies midway between the chargino and second lightest neutralino. For such
a choice any parameter range allowed by $(g - 2)_{\mu}$ data is already excluded (see Fig. 8).
There still exists more than half of the parameter space that is not covered by the three
benchmark models considered here, which were chosen such that they are most sensitive
to the trilepton searches. For this parameter space, the allowed 2$\sigma$ range of $\delta (g - 2)_{\mu}$
from the New Muon $g - 2$ experiment at Fermilab [3, 4] can potentially rule out more
than two thirds of the region, assuming that the central value of the $(g - 2)_{\mu}$ measurement
remains the same. Much of this parameter space consists of tau lepton final states in
chargino-neutralino pair production, which is not sensitive to the current Run-II data with
$L = 36.1 fb^{-1}$ [92]. Future searches with higher luminosity for 2$\tau$/3$\tau$ signal at the LHC
could potentially probe this region of the parameter space.

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