Explaining muon $g - 2$ data in the $\mu\nu$SSM

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Abstract

We analyze the anomalous magnetic moment of the muon $g - 2$ in the $\mu\nu$SSM. This $R$-parity violating model solves the $\mu$ problem reproducing simultaneously neutrino data, only with the addition of right-handed neutrinos. In the framework of the $\mu\nu$SSM, light muon left sneutrino and wino masses can be naturally obtained driven by neutrino physics. This produces an increase of the dominant chargino-sneutrino loop contribution to muon $g - 2$, solving the gap between the theoretical computation and the experimental data. To analyze the parameter space, we sample the $\mu\nu$SSM using a likelihood data-driven method, paying special attention to reproduce the current experimental data on neutrino and Higgs physics, as well as flavor observables. We then apply the constraints from LHC searches for events with multi-lepton + MET on the viable regions found. They can probe this scenario through chargino/chargino and chargino/neutralino pair production.

Keywords: Supersymmetry Phenomenology; Supersymmetric Standard Model; Muon $g - 2$
1 Introduction

One of the long standing problems of the Standard Model (SM) is the deviation between the SM prediction and the measured value of the muon anomalous magnetic dipole moment, \( a_\mu = (g-2)\mu/2 \). This discrepancy has survived over decades even after improving the theoretical calculations within the SM and performing accurate experimental measurements. The latest value of \( \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \) is given by \[1\]

\[
\Delta a_\mu = (26.8 \pm 6.3 \pm 4.3) \times 10^{-10},
\]

where the errors are from experiment and theory prediction (with all errors combined in quadrature), respectively. This represents a discrepancy of 3.5 \( \sigma \) times the combined 1 \( \sigma \) error, that one could try to explain through effects of new physics beyond the SM. Besides, muon \( g - 2 \) experiments at Fermilab (E989) \[2\] and at J-PARC (E34) \[3\] are planned to reduce the experimental uncertainty of \( a_\mu \) by a factor of four \[4,5\], and this would lead to a deviation between the experimental value and the SM prediction up to about 7 \( \sigma \) \[6\] which would a very strong evidence of new physics.

Weak scale Supersymmetry (SUSY) has been in the forefront among handful candidates for beyond SM theories, and has received a lot of attention from both theoretical and experimental viewpoints. If SUSY is responsible for the deviation of the measurement of
with respect to the SM prediction, then the SUSY particle spectrum is expected to be in the vicinity of the electroweak scale, especially concerning the masses of the muon left sneutrino, smuon and electroweak gauginos. The search for predictions of $R$-parity conserving (RPC) SUSY models at the experiments, such as in the minimal supersymmetric standard model (MSSM) [7,9], puts significant bounds on sparticle masses [1], especially for strongly interacting sparticles whose masses must be above about 1 TeV [10,11]. Although less stringent bounds of about 100 GeV have been obtained for weakly interacting sparticles, and even the bino-like neutralino is basically not constrained, in models with universal soft terms at the GUT scale such as the CMSSM, NUHM1 and NUHM2 it is already not possible to fit the muon $g - 2$ while respecting all the LHC constraints. Nevertheless, this is still possible in the pMSSM11 where universality is not assumed, although at the expense of either chargino or slepton coannihilation to reduce the neutralino dark matter abundance [12]. Thus some tuning in the input parameters is necessary. Simplified SUSY models can also reproduce $g - 2$ data and the correct amount of relic abundance, but direct detection experiments searching for dark matter can give stringent constraints on the parameter space [13,14].

On the other hand, $R$-parity violating (RPV) models [15,16] are free from these tensions with dark matter and LHC constraints. Concerning the former, the problem is avoided since the lightest supersymmetric particle (LSP) is not stable. Concerning the latter, the extrapolation of the usual bounds on sparticle masses in RPC models cannot be applied automatically to the case of RPV. All this offers greater flexibility that can be exploited to explain more naturally the muon $g - 2$ discrepancy. In this work, we will focus on the ‘$\mu$ from $\nu$’ supersymmetric standard model ($\mu\nu$SSM) [16], which solves the $\mu$-problem [17] of the MSSM and simultaneously reproduces neutrino data [18,21] through the presence of three generations of right-handed neutrino superfields. In this framework, gravitino and/or axino can be candidates for dark matter with a lifetime longer than the age of the Universe, and they can be detectable with gamma-ray experiments [22,27]. Also, it was shown in Refs. [28,29] that the LEP lower bound on masses of slepton LSPs of about 90 GeV obtained in the simplified trilinear RPV scenario [30,35] is not applicable in the $\mu\nu$SSM. For the case of the bino LSP, only a small region of the parameter space of the $\mu\nu$SSM was excluded [36] when the left sneutrino is the next-to-LSP (NLSP) and hence a suitable source of binos. In particular, this happens in the region of bino (neutrino) masses of $110 - 150$ (110 – 160) GeV.

A key ingredient in SUSY to solve the discrepancy of the muon $g - 2$ [37], is to enhance the dominant chargino-sneutrino loop contribution decreasing the values of soft wino mass $M_2$ and muon left sneutrino mass $m_{\tilde{\nu}_\mu}$. The $\mu\nu$SSM offers a framework where this can be obtained in a natural way. In particular, left sneutrinos are special in the $\mu\nu$SSM because their masses are directly connected to neutrino physics, and the hierarchy in neutrino Yukawas implies also a hierarchy in sneutrino masses. This was exploited in Ref. [29] to obtain the tau left sneutrino as the LSP, using the hierarchy $Y_{\nu_3} < Y_{\nu_1} < Y_{\nu_2}$. However, as we will show, a different hierarchy $Y_{\nu_2} < Y_{\nu_1} < Y_{\nu_3}$ is also possible to reproduce neutrino physics, giving rise to a light muon left sneutrino. In addition, as also shown in Ref. [29], light electroweak gaugino soft masses, $M_{1,2}$, are viable reproducing correct neutrino physics. With both ingredients, light muon left sneutrino and wino masses, the SUSY contributions to $a_\mu$ in the $\mu\nu$SSM can be sizable solving the discrepancy between theory and experiment.

In this work, we analyze first the regions of the parameter space of the $\mu\nu$SSM that
feature light muon left sneutrino and electroweak gauginos, reproducing simultaneously neutrino/Higgs physics, and flavor observables, and explaining the discrepancy shown in Eq. (1). Second, we study the constraints from LHC searches on the viable regions obtained. The latter correspond to different patterns of muon left sneutrino and neutralino/chargino masses, which can be analysed through multi-lepton + MET searches from the production and subsequent decays of chargino/chargino and chargino/neutralino pairs.

The paper is organized as follows. In Sec. 2 we will briefly review the \(\mu\nu\)SSM and its relevant parameters for our analysis of the neutrino/sneutrino sector, emphasizing the special role of the sneutrino in this scenario since its couplings have to be chosen so that the neutrino oscillation data are reproduced. In Sec. 3 we will discuss the SUSY contributions to \(a_\mu\) in the \(\mu\nu\)SSM, studying in particular the parameters controlling them. Sec. 4 will be devoted to the strategy that we employ to perform the scan searching for points of the parameter space compatible with experimental data on neutrino and Higgs physics, as well as flavor observables, and explaining the discrepancy of the muon \(g - 2\). The results of the scan will be presented in Sec. 5. In Sec. 6 we will apply the constraints from LHC searches on the points found. Finally, our conclusions are left for Sec. 7.

2 The \(\mu\nu\)SSM

2.1 Neutrino/sneutrino mass spectrum

The \(\mu\nu\)SSM is a natural extension of the MSSM where the \(\mu\) problem is solved and, simultaneously, the neutrino data can be reproduced. This is obtained through the presence of trilinear terms in the superpotential involving right-handed neutrino superfields \(\tilde{\nu}_i^c\), which relate the origin of the \(\mu\)-term to the origin of neutrino masses and mixing angles. The simplest superpotential of the \(\mu\nu\)SSM with three right-handed neutrinos is the following:

\[
W = \epsilon_{ab} \left( Y_{\nu_{ij}} \hat{H}_d^a \hat{L}_i^b \hat{\nu}_j^c + Y_{\tilde{\nu}_{ij}} \hat{H}_d^a \hat{\nu}_i^c \hat{\nu}_j^a + Y_{\nu_{ij}} \hat{H}_u^b \hat{Q}_a^j \hat{\nu}_i^c \right) + \epsilon_{ab} \left( Y_{\nu_{ij}} \hat{H}_u^a \hat{L}_i^b \hat{\nu}_j^c - \lambda_i \hat{\nu}_i^c \hat{H}_u^a \hat{H}_d^b \right) + \frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c, \tag{2}
\]

where the summation convention is implied on repeated indices, with \(a, b = 1, 2\) \(SU(2)_L\) indices and \(i, j, k = 1, 2, 3\) the usual family indices of the SM.

The simultaneous presence of the last three terms in Eq. (2) makes it impossible to assign \(R\)-parity charges consistently to the right-handed neutrinos \((\nu_{iR})\), thus producing explicit RPV (harmless for proton decay). Note nevertheless, that in the limit \(Y_{\nu_{ij}} \to 0\), \(\hat{\nu}^c\) can be identified in the superpotential as a pure singlet superfield without lepton number, similar to the next-to-MSSM (NMSSM), and therefore \(R\) parity is restored. Thus, the neutrino Yukawa couplings \(Y_{\nu_{ij}}\) are the parameters which control the amount of RPV in the \(\mu\nu\)SSM, and as a consequence this violation is small. After the electroweak symmetry breaking induced by the soft SUSY-breaking terms of the order of the TeV, and with the choice of CP conservation, the neutral Higgses \((H_u,d)\) and right \((\tilde{\nu}_{iR})\) and left \((\tilde{\nu}_i)\) sneutrinos
develop the following vacuum expectation values (VEVs):

\[
\langle H_d \rangle = \frac{v_d}{\sqrt{2}}, \quad \langle H_u \rangle = \frac{v_u}{\sqrt{2}}, \quad \langle \tilde{\nu}_R \rangle = \frac{v_{iR}}{\sqrt{2}}, \quad \langle \tilde{\nu}_i \rangle = \frac{v_i}{\sqrt{2}},
\]

where \( v_{iR} \sim \text{TeV} \), whereas \( v_i \sim 10^{-4} \text{ GeV} \) because of the small contributions \( Y_\nu \ll 10^{-6} \) whose size is determined by the electroweak-scale seesaw of the \( \mu \nu \text{SSM} \). Note in this sense that the last term in Eq. (2) generates dynamically Majorana masses, \( M_{ij} = 2\kappa_{ijk} v_k R \sqrt{2} \sim \text{TeV} \). On the other hand, the fifth term in the superpotential generates the \( \mu \)-term, \( \mu = \lambda_i v_i R \sqrt{2} \sim \text{TeV} \).

The new couplings and sneutrino VEVs in the \( \mu \nu \text{SSM} \) induce new mixing of states. The associated mass matrices were studied in detail in Refs. [40,42,45]. Summarizing, there are eight neutral scalars and seven neutral pseudoscalars (Higgses-sneutrinos), eight charged scalars (charged Higgses-sleptons), five charged fermions (charged leptons-charginos), and ten neutral fermions (neutrinos-neutralinos). In the following, we will concentrate in briefly reviewing the neutrino and neutral Higgs sectors, which are the relevant ones for our analysis.

The neutral fermions have the flavor composition \((\nu_i, \tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u, \nu_{iR})\). Thus, with the low-energy bino and wino soft masses, \( M_1 \) and \( M_2 \), of the order of the TeV, and similar values for \( \mu \) and \( M \) as discussed above, this generalized seesaw produces three light neutral fermions dominated by the left-handed neutrino \( (\nu_i) \) flavor composition. In fact, data on neutrino physics\([18–21]\) can easily be reproduced at tree level\([16,40–44]\), even with diagonal Yukawa couplings\([41,43]\), i.e. \( Y_{\nu ii} = Y_{\nu i} \) and vanishing otherwise. A simplified formula for the effective mixing mass matrix of the light neutrinos is\([43]\):

\[
(m_\nu)_{ij} \sim \frac{Y_{\nu i} Y_{\nu j} v_u^2}{6\sqrt{2} \kappa v_R} (1 - 3\delta_{ij}) - \frac{v_i v_j}{4M_{\text{eff}}} \left[ v_d \left( Y_{\nu i} v_j + Y_{\nu j} v_i \right) / 3\lambda + \frac{Y_{\nu i} Y_{\nu j} v_d^2}{9\lambda^2} \right],
\]

with

\[
M_{\text{eff}} \equiv M - \frac{v^2}{2\sqrt{2}(\kappa v_R^2 + \lambda v_a v_d)} \left( 2\kappa v_R^2 v_d^2 v_a / v^2 + \frac{v^2}{2} \right),
\]

and

\[
\frac{1}{M} = \frac{g'^2}{M_1} + \frac{g^2}{M_2},
\]

where \( v^2 = v_d^2 + v_u^2 + \sum_i v_i^2 = 4m_Z^2 / (g^2 + g'^2) \approx (246 \text{ GeV})^2 \). For simplicity, we are also assuming in these formulas, and in what follows, \( \lambda_i = \lambda, v_{iR} = v_R, \) and \( \kappa_{iii} \equiv \kappa_i = \kappa \) and vanishing otherwise. We are then left with the following set of variables as independent parameters in the neutrino sector:

\[
\lambda, \kappa, Y_{\nu i}, \tan \beta, v_i, v_R, M,
\]

and the \( \mu \)-term is given by

\[
\mu = 3\lambda v_R / \sqrt{2}.
\]
In Eq. (7), we have defined $\tan \beta \equiv v_u/v_d$ and since $v_i \ll v_d, v_u$, we have $v_d \approx v/\sqrt{\tan^2 \beta + 1}$. For the discussion, hereafter we will use indistinctly the subindices $(1,2,3) \equiv (e, \mu, \tau)$. In the numerical analyses of the next sections, it will be enough for our purposes to consider the sign convention where all these parameters are positive. Of the five terms in Eq. (4), the first two are generated through the mixing of $\nu_i$ with $\nu_i -$Higgsinos, and the rest of them also include the mixing with the gauginos. These are the so-called $\nu_i$-Higgsino seesaw and gaugino seesaw, respectively [43].

As we can understand from these equations, neutrino physics in the $\mu\nu$ SSM is closely related to the parameters and VEVs of the model, since the values chosen for them must reproduce current data on neutrino masses and mixing angles.

Concerning the neutral scalars and pseudoscalars in the $\mu\nu$ SSM, although they have the flavor composition $(H_d, H_u, \tilde{\nu}_i R, \tilde{\nu}_i)$, the off-diagonal terms of the mass matrix mixing the left sneutrinos with Higgses and right sneutrinos are suppressed by $Y_{\nu}i$ and $v_i L$, implying that scalar and pseudoscalar left sneutrino states will be almost pure. In addition scalars have degenerate masses with pseudoscalars $m_{\tilde{\nu}^i} \approx m_{\tilde{\nu}^i} \equiv m_{\tilde{\nu}_i}$. From the minimization equations for $v_i$, we can write their approximate tree-level values as

$$m_{\tilde{\nu}_i}^2 \approx \frac{Y_{\nu}i v_u v_R}{v_i} \left[ -T_{\nu_i} \frac{v_R}{\sqrt{2}} \left( -\kappa + \frac{3\lambda}{\tan \beta} \right) \right],$$

where $T_{\nu_i}$ are the trilinear parameters in the soft Lagrangian, $-\epsilon_{ab} T_{\nu_i} H_u H_d \tilde{L}_a \tilde{L}_b$, taking for simplicity $T_{\nu_i} = T_{\nu}i$ and vanishing otherwise. Therefore, left sneutrino masses introduce in addition to the parameters of Eq. (7), the

$$T_{\nu},$$

as other relevant parameters for our analysis. In the numerical analyses of Sections 4 and 5, we will use negative values for them in order to avoid tachyonic left sneutrinos.

Let us point out that if we follow the usual assumption based on the breaking of supergravity, that all the trilinear parameters are proportional to their corresponding Yukawa couplings, defining $T_{\nu} = A_{\nu} Y_{\nu}$ we can write Eq. (9) as:

$$m_{\tilde{\nu}_i}^2 \approx \frac{Y_{\nu}i v_u v_R}{v_i} \left[ -A_{\nu_i} + \frac{v_R}{\sqrt{2}} \left( -\kappa + \frac{3\lambda}{\tan \beta} \right) \right],$$

and the parameters $A_{\nu_i}$ substitute the $T_{\nu_i}$ as the most representative. We will use both type of parameters throughout this work.

Since we have assumed diagonal sfermion mass matrices, and from the minimization conditions we have eliminated the soft masses $m_{H_d}^2$, $m_{H_u}^2$, $m_{\tilde{\nu}_i R}^2$ and $m_{\tilde{\nu}_i L}^2$ in favor of the VEVs, the parameters in Eqs. (7) and (10), together with the rest of soft trilinear parameters, soft scalar masses, and soft gluino masses

$$T_\lambda, T_\kappa, T_u, T_d, T_e, m_{\tilde{Q}_i L}, m_{\tilde{u}_i R}, m_{\tilde{d}_i R}, m_{\tilde{e}_i R}, M_3,$$

constitute our whole set of free parameters, and are specified at low scale. Given that we will focus on a light $\tilde{\nu}_\mu$, we will use negative values for $T_{u_3}$ in order to avoid cases with too light left sneutrinos due to loop corrections.
The neutral Higgses and the three right sneutrinos, which can be substantially mixed in the \( \mu \nu \) SSM, were discussed in detail recently in Ref. [47]. The tree-level mass of the SM-like Higgs can be written in a elucidate form for our discussion below as

\[
m_{0h}^2 = m_Z^2 \left\{ \left( \frac{1 - \tan^2 \beta}{1 + \tan^2 \beta} \right)^2 + \left( \frac{v/\sqrt{2}}{m_Z} \right)^2 \left( \frac{2 \tan \beta}{1 + \tan^2 \beta} \right)^2 \right\},
\]

(13)

where the factor \((v/\sqrt{2}m_Z)^2 \approx 3.63\), and we have neglected for simplicity the mixing of the SM-like Higgs with the other states in the mass squared matrix. We see straightforwardly that the second term grows with small \( \tan \beta \) and large \( \lambda \). As in the case of the MSSM, if \( \lambda \) is not large enough a contribution from loops is essential to reach the target of a SM-like Higgs in the mass region around 125 GeV. This contribution is basically determined by the soft parameters \( T_3u, m_{\tilde{u}_3R} \) and \( m_{\tilde{Q}_3L} \). Clearly, these parameters together with \( \lambda \) and \( \tan \beta \) are crucial for Higgs physics. In addition, the parameters \( \kappa, v_R \) and \( T_{\kappa} \) are the key ingredients to determine the mass scale of the right sneutrino states [40,41]. For example, for \( \lambda \lesssim 0.01 \) they are basically free from any doublet contamination, and the masses can be approximated by [48,45]:

\[
m_{\nu_{iR}}^2 \approx \frac{v_R}{\sqrt{2}} \left( T_{\kappa} + \frac{v_R}{\sqrt{2}} \frac{4\kappa^2}{v^2} \right), \quad m_{\nu_{iL}}^2 \approx -\frac{v_R}{\sqrt{2}} 3T_{\kappa}.
\]

(14)

Given this result, we will use negative values for \( T_{\kappa} \) in order to avoid tachyonic pseudoscalar right sneutrinos. Finally, the parameters \( \lambda_i \) and \( T_{\lambda_i} \) (assuming the supergravity relation \( T_{\lambda_i} = \lambda_i A_{\lambda_i} \)) also control the mixing between the singlet and the doublet states and hence, contribute in determining the mass scale. We conclude that the relevant independent low-energy parameters in the Higgs-right sneutrino sector are the following subset of the parameters in Eqs. (7), (10), and (12):

\[
\lambda, \kappa, \tan \beta, v_R, T_{\kappa}, T_{\lambda}, T_{u_3}, m_{\tilde{Q}_3L}, m_{\tilde{u}_3R}.
\]

(15)

### 2.2 Neutrino/sneutrino physics

Since reproducing neutrino data is an important asset of the \( \mu \nu \) SSM, as explained above, we will try to establish here qualitatively what regions of the parameter space are the best in order to be able to obtain correct neutrino masses and mixing angles. Although the parameters in Eq. (7), \( \lambda, \kappa, v_R, \tan \beta, Y_{\nu}, v_i \) and \( M \), are important for neutrino physics, the most crucial of them are \( Y_{\nu}, v_i \) and \( M \). Thus, we will first determine natural hierarchies among neutrino Yukawas, and among left sneutrino VEVs.

Considering the normal ordering for the neutrino mass spectrum, which is nowadays favored by the analyses of neutrino data [18–21], representative solutions for neutrino physics using diagonal neutrino Yukawas in this scenario were obtained in Ref. [29], taking advantage of the dominance of the gaugino seesaw for some of the three neutrino families. In particular, the type 3) solutions with the following structure:

- \( M > 0 \), with \( Y_{\nu_2} < Y_{\nu_1} < Y_{\nu_3} \), and \( v_1 < v_2 \sim v_3 \),

are especially interesting for us, since, as we will argue below, they are able to produce the muon left sneutrino as the lightest of all sneutrinos. In this case of type 3), it is
easy to find solutions with the gaugino seesaw as the dominant one for the second family. Then, \( v_2 \) determines the corresponding neutrino mass and \( Y_{\nu_2} \) can be small. On the other hand, the normal ordering for neutrinos determines that the first family dominates the lightest mass eigenstate implying that \( Y_{\nu_1} < Y_{\nu_3} \) and \( v_1 < v_2, v_3 \), with both \( \nu_R \)-Higgsino and gaugino seesaws contributing significantly to the masses of the first and third family. Taking also into account that the composition of the second and third families in the third mass eigenstate is similar, we expect \( v_3 \sim v_2 \).

In addition, left sneutrinos are special in the \( \mu \nu \) SSM with respect to other SUSY models. This is because, as discussed in Eq. (9), their masses are determined by the minimization equations with respect to \( v_i \). Thus, they depend not only on left sneutrino VEVs but also on neutrino Yukawas, and as a consequence neutrino physics is very relevant. For example, if we work with Eq. (11) assuming the simplest situation that all the \( A_{\nu_i} \) are naturally of the order of the TeV, neutrino physics determines sneutrino masses through the prefactor \( Y_{\nu_i} v_u / v_i \). Thus, values of \( Y_{\nu_i} v_u / v_i \) in the range of about \( 0.01-1 \), i.e. \( Y_{\nu_1} \sim 10^{-8} - 10^{-6} \), will give rise to left sneutrino masses in the range of about \( 100 - 1000 \) GeV. This implies that with the hierarchy of neutrino Yukawas \( Y_{\nu_2} \sim 10^{-8} - 10^{-7} < Y_{\nu_1,3} \sim 10^{-6} \), we can obtain a \( \tilde{\nu}_\mu \) with a mass around 100 GeV whereas the masses of \( \tilde{\nu}_{e,\tau} \) are of the order of the TeV, i.e. we have \( m_{\tilde{\nu}_2} \) as the smallest of all the sneutrino masses. Clearly, we are in the case of solutions for neutrino physics of type 3) discussed above.

Let us finally point out that the crucial parameters for neutrino physics, \( Y_{\nu_i}, v_{iL} \) and \( M \), are essentially decoupled from the parameters in Eq. (15) controlling Higgs physics. Thus, for a suitable choice of \( Y_{\nu_i}, v_{iL} \) and \( M \) reproducing neutrino physics, there is still enough freedom to reproduce in addition Higgs data by playing with \( \lambda, \kappa, v_R, \tan \beta \), etc., as shown in Ref. [47]. As a consequence, in Sect. 5 we will not need to scan over most of the latter parameters, relaxing our demanding computing task. We will discuss this issue in more detail in Subsect. 4.3.

### 3 SUSY contribution to \( a_\mu \) in the \( \mu \nu \) SSM

The contributions to \( a_\mu \) in SUSY models, \( a_\mu^{\text{SUSY}} \), are known to essentially come from the chargino-sneutrino and neutralino-smuon loops. In the case of the MSSM, one- and two-loop contributions have been intensively studied in the literature. See for example Refs. [49, 52] and [53, 58], respectively. In the singlet(s) extension(s) of the MSSM, the contributions to \( a_\mu^{\text{SUSY}} \) have the same expressions provided that the mixing matrices are appropriately taken into account. Nevertheless, as pointed out in Refs. [59, 60] the numerical results in these models can differ from the ones in the MSSM. Depending on the parameters of the concerned model, very light neutral scalars (few GeV) can appear at the bottom of the spectrum and the presence of such very light eigenstates can have an impact on the value of \( a_\mu^{\text{SUSY}} \). This scenario has been also addressed in [61, 63] in the context of two-Higgs-doublet-models. Note also that light neutralinos with leading singlino composition are possible, but their contributions are small owing to their small mixing to the MSSM sector.

Concerning the \( \mu \nu \) SSM, which is an extension of the MSSM with three singlet superfields, i.e. the three generations of right sneutrinos, RPV induces on the one hand, a mixing of the MSSM neutralinos and charginos with left- and right-handed neutrinos and charged
leptons, respectively, and on the other hand a mixing of the Higgs doublets with the left and right sneutrinos. However, assuming that singlets scalars and pseudoscalars as well as singlino-like states are heavy, as naturally expected, their contributions are very small, and therefore the expressions of $a^\mu_{\text{SUSY}}$ in the $\mu\nu$SSM can be straightforwardly obtained from the MSSM. In particular, it follows that the dominant one-loop contributions to $a^\mu_{\text{SUSY}}$, displayed in Fig. 1, can be approximated for charginos when $\tan\beta$ is not too small, as

$$a^C_\mu \approx \frac{\alpha_2 m^2_\mu}{4\pi} \frac{\mu M_2 \tan\beta}{m^2_\nu} \left\{ \frac{F_C(M^2_2/m^2_\nu)}{M^2_2 - \mu^2} \right\},$$

(16)

and for neutralinos when there is a light bino-like neutralino, as

$$a^N_\mu \approx \frac{\alpha_1 m^2_\mu}{4\pi} \frac{M_1 (\mu \tan\beta - A_\mu)}{(m^2_{\tilde{\mu}} - m^2_{\tilde{\mu}_1})} \left\{ \frac{F_N(M^2_1/m^2_{\tilde{\mu}_1})}{m^2_{\tilde{\mu}_1}} - \frac{F_N(M^2_1/m^2_{\tilde{\mu}_2})}{m^2_{\tilde{\mu}_2}} \right\},$$

(17)

where the loop functions are given by

$$F_C(k) = \frac{3 - 4k + k^2 + 2\ln k}{(1 - k)^3}, \quad F_N(k) = \frac{1 - k^2 + 2k \ln k}{(1 - k)^3},$$

(18)

$m_\mu$ and $m_{\tilde{\mu}_1}$ ($m_{\tilde{\mu}_2}$) are muon and lightest (heaviest) smuon masses, respectively, and $\alpha_i = g^2_i/(4\pi)$.

It is well known that the chargino contribution $a^C_\mu$ is typically larger than the neutralino contribution $a^N_\mu$ [49,51]. Thus, in the following we concentrate our discussions on Eq. (16) in order to draw some important conclusions about the SUSY contributions to $a_\mu$, that we will check with our numerical results using the full one-loop formulas. In the light of Eq. (1), decreasing the values of $M_2$, $\mu$ or $m_{\tilde{\nu}_\mu}$ leads to an enhancement in $a^C_\mu$. Also, the sign of $a^C_\mu$ is given by the sign of the product $\mu M_2$ since the factor in brackets of Eq. (16) is positive in general [51]. As discussed in Sect. 2, we are working with positive $M_2$ and $\mu$ and therefore we have a positive contribution to $a_\mu$. One the other hand, $a^C_\mu$ increases with increasing $\tan\beta$. Thus, the parameters controlling the SUSY contributions to $a_\mu$ in
the scenario that we are considering are

\[ M_2, \mu, m_{\tilde{\nu}_\mu}, \tan \beta, \]  

and they have to be appropriately chosen to satisfy in addition the constraints that we impose on Higgs/neutrino physics and flavor observables.

To qualitatively understand the behaviour of the dominant contribution to \( a_\mu^{\text{SUSY}} \), we show as an example in Fig. 2 \( a_\mu^C \) versus \( m_{\tilde{\nu}_\mu} \) for several values of the other relevant parameters. As we can see, for the examples studied with \( \tan \beta = 14 \) and \( \mu = 380 \) GeV, \( a_\mu^C \) is compatible at to 2\( \sigma \) with \( \Delta a_\mu \) in Eq. (1) for \( m_{\tilde{\nu}_\mu} \lesssim 600 \) (100) GeV corresponding to \( M_2 = 150 \) (900) GeV. In these regions, for larger sneutrino masses the contribution to \( a_\mu^C \) is too small. On the contrary, this contribution turns out to be too large for small masses \( m_{\tilde{\nu}_\mu} \lesssim 200 \) GeV in the case of \( M_2 = 150 \) GeV. We will check these features with the numerical results presented in Section 5.

4 Strategy for the scanning

In this section, we describe the methodology that we have employed to search for points of our parameter space that are compatible with the current experimental data on neutrino and Higgs physics as well as with the measurement of \( \Delta a_\mu \). In addition, we have demanded the compatibility with some flavor observables. To this end, we have performed a scan on the parameter space of the model, with the input parameters optimally chosen.
4.1 Sampling the $\mu\nu$SSM

For the sampling of the $\mu\nu$SSM, we used a likelihood data-driven method employing the Multinest \[65\] algorithm as optimizer. The goal is to find regions of the parameter space of the $\mu\nu$SSM that are compatible with a given experimental data.

For it we have constructed the joint likelihood function:

$$L_{\text{tot}} = L_{a_{\mu}} \times L_{\text{neutrino}} \times L_{\text{Higgs}} \times L_{\text{B physics}} \times L_{\mu \text{ decay}} \times L_{m_{\tilde{\chi}^{\pm}}},$$

where $L_{a_{\mu}}$ is the constraint from the muon anomalous magnetic moment, $L_{\text{neutrino}}$ represents measurements of neutrino observables, $L_{\text{Higgs}}$ Higgs observables, $L_{\text{B physics}}$ B-physics constraints, $L_{\mu \text{ decay}}$ $\mu$ decays constraints and $L_{m_{\tilde{\chi}^{\pm}}}$ LEP II constraints on the chargino mass.

To compute the spectrum and the observables we used SARAH \[66\] to generate a SPheno \[67,68\] version for the model. We condition that each point is required not to have tachyonic eigenstates. For the points that pass this constraint, we compute the likelihood associated to each experimental data set and for each sample all the likelihoods are collected in the joint likelihood $L_{\text{tot}}$ (see Eq. (20) above).

4.2 Likelihoods

We used three types of likelihood functions in our analysis. For observables in which a measure is available we use a Gaussian likelihood function defined as follows

$$L(x) = \exp \left[ -\frac{(x - x_0)^2}{2\sigma_T^2} \right],$$

where $x_0$ is the experimental best fit set on the parameter $x$, $\sigma_T^2 = \sigma^2 + \tau^2$ with $\sigma$ and $\tau$ being respectively the experimental and theoretical uncertainties on the observable $x$.

On the other hand, for any observable for which the constraint is set as lower or upper limit, an example is the chargino mass lower bound, the likelihood function is defined as

$$L(x) = \frac{\sigma}{\sigma_T} [1 - K(D(x))] \exp \left[ -\frac{(x - x_0)^2 p}{2\sigma_T^2} \right] + \frac{1}{\tau} K \left( (x - x_0)p \right),$$

where

$$D(x) = \frac{\sigma}{\tau} \left( \frac{(x_0 - x)p}{\sigma_T} \right), \quad K(a) = \frac{1}{2} \text{erfc} \left( \frac{a}{\sqrt{2}} \right).$$

The variable $p$ takes +1 when $x_0$ represents the lower limit and -1 in the case of upper limit, while erfc is the complementary error function.

The last class of likelihood function we used is a step function in such a way that the likelihood is one/zero if the constraint is satisfied/non-satisfied.

It is important to mention that in this work unless explicitly mentioned, the theoretical uncertainties $\tau$ are unknown and therefore are taken to be zero. Subsequently, we present each constraint used in this work together with the corresponding type of likelihood function.

Parameters & $\sin^2 \theta_{12}$ & $\sin^2 \theta_{13}$ & $\sin^2 \theta_{23}$ & $\Delta m_{21}^2 / 10^{-5}$ (eV$^2$) & $\Delta m_{31}^2 / 10^{-3}$ (eV$^2$) \\
$\mu_{\text{exp}}$ & 0.310 & 0.02241 & 0.580 & 7.39 & 2.525 \\
$\sigma_{\text{exp}}$ & 0.012 & 0.00065 & 0.017 & 0.20 & 0.032 \\

Table 1: Neutrino data used in the sampling of the $\mu\nu$SSM for the anomalous magnetic moment of the muon.

Muon anomalous magnetic moment

The main goal of this work is to explain the current $3.5 \sigma$ discrepancy between the measurement of the anomalous magnetic moment of the muon and the SM prediction $\Delta a_{\mu}$ in Eq. (1), therefore we impose $a_{\mu}^{\text{SUSY}} = \Delta a_{\mu}$. The corresponding likelihood is $L_{a_{\mu}}$.

Neutrino observables

We used the results for normal ordering from Ref. [21] summarized in Table 1, where $\Delta m_{ij}^2 = m_i^2 - m_j^2$. For each of the observables listed in the neutrino sector, the likelihood function is a Gaussian (see Eq. (21)) centered at the mean value $\mu_{\text{exp}}$ and with width $\sigma_{\text{exp}}$. Concerning the cosmological upper bound on the sum of the masses of the light active neutrinos given by $\sum m_{\nu_i} < 0.12$ eV [69], even though we did not include it directly in the total likelihood, we imposed it on the viable points obtained.

Higgs observables

Before the discovery of the SM-like Higgs boson, the negative searches of Higgs signals at the Tevatron, LEP and LHC, were transformed into exclusions limits that must be used to constrain any model. Its discovery at the LHC added crucial constraints that must be taking into account in those exclusion limits. We have considered all these constraints in the analysis of the $\mu\nu$SSM, where the Higgs sector is extended with respect to the MSSM as discussed in Section 2. For constraining the predictions in that sector of the model, we interfaced HiggsBounds v5.3.2 [70,71] with MultiNest. First, several theoretical predictions in the Higgs sector (using a $\pm 3$ GeV theoretical uncertainty on the SM-like Higgs boson) are provided to determine which process has the highest exclusion power, according to the list of expected limits from LEP and Tevatron. Once the process with the highest statistical sensitivity is identified, the predicted production cross section of scalars and pseudoscalars multiplied by the BRs are compared with the limits set by these experiments. Then, whether the corresponding point of the parameter under consideration is allowed or not at 95% confidence level is indicated. In constructing the likelihood from HiggsBounds constraints, the likelihood function is taken to be a step function. Namely, it is set to one for points for which Higgs physics is realized, and zero otherwise. Finally, in order to address whether a given Higgs scalar of the $\mu\nu$SSM is in agreement with the signal observed by ATLAS and CMS, we interfaced HiggsSignals v2.2.3 [72,73] with MultiNest. A $\chi^2$ measure is used to quantitatively determine the compatibility of the $\mu\nu$SSM prediction with the measured signal strength and mass. The experimental data used are those of the LHC with some complements from Tevatron. The details of the likelihood evaluation can be found in Refs. [72,73].
We also included in the joint likelihood the constraint from BR $\mu \rightarrow e\gamma$ (see Eq. (21)). Similarly to the previous process, $b \rightarrow s\gamma$ and $B_d \rightarrow \mu^+\mu^-$ are also forbidden at tree level in the SM but occur radiatively. In the likelihood for these observables (21), we used the combined results of LHCb and CMS [75]. BR($B_s \rightarrow \mu^+\mu^-$) = $(2.9 \pm 0.7) \times 10^{-9}$ and BR($B_d \rightarrow \mu^+\mu^-$) = $(3.6 \pm 1.6) \times 10^{-10}$. Concerning the theoretical uncertainties for each of these observables we take $\tau = 10\%$ of the corresponding best fit value. We denote by $\mathcal{L}_{B \text{physics}}$ the likelihood from $b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$ and $B_d \rightarrow \mu^+\mu^-$.

$\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$

We also included in the joint likelihood the constraint from BR($\mu \rightarrow e\gamma$) < $5.7 \times 10^{-13}$ and BR($\mu \rightarrow eee$) < $1.0 \times 10^{-12}$. For each of these observables we defined the likelihood as a step function. As explained before, if a point is in agreement with the data, the likelihood $\mathcal{L}_{\mu \text{ decay}}$ is set to 1 otherwise to 0.

Chargino mass bound

In RPC SUSY, the lower bound on the lightest chargino mass of about 94 GeV depends on the spectrum of the model [1][76]. Although in the $\mu\nu$SSM there is RPV and therefore this constraint does not apply automatically, to compute $\mathcal{L}_{m_{\tilde{\chi}^\pm}}$ we have chosen a conservative limit of $m_{\tilde{\chi}^\pm} > 92$ GeV with the theoretical uncertainty $\tau = 5\%$ of the chargino mass.

4.3 Input parameters

In order to efficiently scan for $a^{\text{SUSY}}_{\mu}$ in the $\mu\nu$SSM to reproduce $\Delta a_{\mu}$, it is important to identify the parameters to be used, and optimize their number and their ranges of values. As discussed in Subsec. 2.2, the most relevant parameters in the neutrino sector of the $\mu\nu$SSM are $v_i$, $Y_{\nu_i}$ and $M$. Concerning $M$, which is a kind of average of bino and wino soft masses (see Eq. (6)), inspired by GUTs we will assume $M_2 = 2M_1$, and scan over $M_2$. On the other hand, sneutrino masses introduce in addition the parameters $T_{\nu_i}$ (see Eq. (9)). In particular, $T_{\nu_2}$ is the most relevant one for our discussion of a light $\tilde{\nu}_\mu$, and we will scan it in an appropriate range of small values. Since the left sneutrinos of the other two generations can be heavier, we will fix $T_{\nu_{1,3}}$ to a larger value. The parameter $\tan \beta$ is important for Higgs physics, thus we will consider a narrow range of possible values to ensure good Higgs physics.

Summarizing, we will perform scans over the 9 parameters $Y_{\nu_i}, v_i, T_{\nu_2}, \tan \beta, M_2$, as shown in Table 2, using log priors (in logarithmic scale) for all of them, except for $\tan \beta$ which is taken to be a flat prior (in linear scale). The ranges of $v_i$ and $Y_{\nu_i}$ are natural in the context of the electroweak-scale seesaw of the $\mu\nu$SSM, as discussed in Sec. 2. The range of $T_{\nu_2}$ is chosen to have light $\tilde{\nu}_\mu$ below about 600 GeV. This is a reasonable upper bound to be able to have sizable SUSY contributions to $a_{\mu}$. If we follow the usual assumption based on the supergravity framework discussed in Eq. (11) that the trilinear parameters are proportional to the corresponding Yukawa couplings, i.e. in this case $T_{\nu_2} = A_{\nu_2} Y_{\nu_2}$,
| Parameter | Scan |
|-----------|------|
| tan $\beta$ | $(10, 16)$ |
| $Y_{\nu_i}$ | $(10^{-8}, 10^{-6})$ |
| $v_i$ | $(10^{-6}, 10^{-3})$ |
| $-T_{\nu_2}$ | $(10^{-6}, 4 \times 10^{-4})$ |
| $M_2$ | $(150, 1000)$ |

Table 2: Range of low-energy values of the input parameters that are varied in the scan, where $Y_{\nu_i}, v_i, T_{\nu_2}$ and $M_2$ are log priors while $\tan \beta$ is a flat prior. The VEVs $v_i$, and the soft parameters $T_{\nu_2}$ and $M_2$, are given in GeV. The GUT-inspired relation $M_2 = 2M_1$ is assumed.

| Parameter | Scan |
|-----------|------|
| $\lambda$ | 0.102 |
| $\kappa$ | 0.4 |
| $v_R$ | 1750 |
| $T_\lambda$ | 340 |
| $-T_\kappa$ | 390 |
| $-T_{u_3}$ | 4140 |
| $m_{\tilde{Q}_{3L}}$ | 2950 |
| $m_{\tilde{u}_{3R}}$ | 1140 |
| $M_3$ | 2700 |
| $m_{\tilde{Q}_{1,2L}}, m_{\tilde{u}_{1,2R}}, m_{\tilde{d}_{1,2,3R}}, m_{\tilde{e}_{1,2,3R}}$ | 1000 |
| $T_{u_{1,2}}$ | 0 |
| $T_{d_{1,2}}, T_{d_3}$ | 0, 100 |
| $T_{e_{1,2}}, T_{e_3}$ | 0, 40 |
| $-T_{\nu_{1,3}}$ | $10^{-3}$ |

Table 3: Low-energy values of the input parameters that are fixed in the scan. The VEV $v_R$ and the soft trilinear parameters, soft gluino masses and soft scalar masses are given in GeV.
then \(-A_{\nu_2} \in (1.4 \times 10^4)\) GeV.

Other benchmark parameters relevant for Higgs physics are fixed to appropriate values, and are shown in Table 3. As one can see, we choose a small/moderate value for \(\lambda \approx 0.1\). Thus, we are in a similar situation as in the MSSM, and moderate/large values of \(\tan \beta\), \(|T_{u_3}|\), and soft stop masses, are necessary to obtain through loop effects the correct SM-like Higgs mass, as discussed in Eq. (13). In addition, if we want to avoid the chargino mass bound of RPC SUSY, the value of \(\lambda\) also forces us to choose a moderate/large value of \(v_R\) to obtain a large enough value of \(\mu = 3\lambda \frac{v_R}{\sqrt{2}}\). In particular, we choose \(v_R = 1750\) GeV giving rise to \(\mu \approx 379\) GeV. As explained in Eq. (14), the parameters \(\kappa, T\) are also crucial to determine the mass scale of the right sneutrinos. Since we choose \(T_\kappa = -390\) GeV to have heavy pseudoscalar right sneutrinos (of about 1190 GeV), the value of \(\kappa\) has to be large enough in order to avoid too light (even tachyonic) scalar right sneutrinos. Choosing \(\kappa = 0.4\), we get masses for the latter of about 700 – 755 GeV. The parameter \(T_\lambda\) is relevant to obtain the correct values of the off-diagonal terms of the mass matrix mixing the right sneutrinos with Higgses, and we choose for its value 340 GeV.

The values of the other parameters, shown below \(m_{\tilde{\nu}_\mu}\), concern gluino, squark and slepton masses, and quark and lepton trilinear parameters, and are not specially relevant for our scenario of muon \(g-2\). Finally, compared to the values of \(T_{\nu_2}\), the values chosen for \(T_{\nu_1,3}\) are natural within our framework \(T_{\nu_1,3} = A_{\nu_1,3} Y_{\nu_1,3}\), since larger values of the Yukawa couplings are required for similar values of \(A_{\nu_i}\). In the same way, the values of \(T_{d_3}\) and \(T_{e_3}\) have been chosen taking into account the corresponding Yukawa couplings.

5 Results of the scan

Following the methods described in the previous sections, to find regions consistent with experimental observations we have performed about 36 million of spectrum evaluations in total and the total amount of computer required for this was approximately 190 CPU years.

To carry this analysis out, we select points from the scan that lie within \(\pm 3\sigma\) of all neutrino physics observables [21] summarized in Table 1. Second, we put \(\pm 3\sigma\) cuts from \(b \to s\gamma, B_s \to \mu^+\mu^-\) and \(B_d \to \mu^+\mu^-\) and require the points to satisfy also the upper limits of \(\mu \to e\gamma\) and \(\mu \to eee\). In the third step, we impose that Higgs physics is realized. In particular, we require that the p-value reported by HiggsSignals be larger than 5%. We also check with Vevacious [77] that the electroweak symmetry-breaking vacua corresponding to the previous allowed points are stable. The points found will be discussed in Subsec. 5.1. Finally, since we want to explain the current experimental versus theoretical discrepancy in the muon anomalous magnetic moment, of the allowed points we select those within \(\pm 2\sigma\) of \(\Delta a_\mu\). The resulting points will be presented in Sec. 5.2.

5.1 Constraints from neutrino and light \(\tilde{\nu}_\mu\) physics.

Imposing all the cuts discussed above, we show in Fig. 3 the values of the parameter \(A_{\nu_2}\) versus the prefactor in Eq. (11), \(Y_{\nu_2} v_u / v_2\), giving rise to different values for the mass of the \(\tilde{\nu}_\mu\). The colours indicate different values of this mass. Let us remark that the plot has been obtained using the full numerical computation including loop corrections, although the tree-level mass in Eq. (11) gives a good qualitative idea of the results. We found
Figure 3: \(-A_{\nu_2} \) versus \( Y_{\nu_2} \frac{v_u}{v_2} \). The colours indicate different values of the muon left sneutrino mass.

Figure 4: \( v_2 \) versus \( Y_{\nu_2} \) for the scan. The colours indicate different values of the gaugino mass parameter \( M \) defined in Eq. (6).
solutions with \( A_{\nu_2} \) in the range \(-A_{\nu_2} \in (861, 25.5 \times 10^4) \text{ GeV}, \) corresponding to \(-T_{\nu_2} \in (8.8 \times 10^{-6}, 3.8 \times 10^{-4}) \text{ GeV}, \) but for the sake of naturalness we prefer to discuss only those solutions with the upper bound for \(-A_{\nu_2} \) in 5 TeV. These are the ones shown in Fig. 3. In any case, larger values of \(-A_{\nu_2} \) increase the sneutrino mass, being disfavoured by the value of the muon \( g - 2. \) Thus, our solutions correspond to \(-A_{\nu_2} \in (861, 5 \times 10^3) \text{ GeV} \) with \(-T_{\nu_2} \in (10^{-5}, 3 \times 10^{-4}) \text{ GeV}. \) We can see, as can be deduced from Eq. (11), that for a fixed value of \(-A_{\nu_2} (Y_{\nu_2} v_u/v_2) \) the greater \( Y_{\nu_2} v_u/v_2 (=-A_{\nu_2}) \) is, the greater \( m_{\tilde{\nu}_\mu} \) becomes. Let us finally note that \( m_{\tilde{\nu}_\mu} \) is always larger than 64 GeV, which corresponds to about half of the mass of the SM-like Higgs (remember that we allow a \( \pm 3 \text{ GeV} \) theoretical uncertainty on its mass). For smaller masses, the latter would dominantly decay into sneutrino pairs, leading to an inconsistency with Higgs data \[29\].

In any case, larger values of \(-A_{\nu_2} \) increase the sneutrino mass, being disfavoured by the value of the muon \( g - 2. \) Thus, our solutions correspond to \(-A_{\nu_2} \in (861, 25.5 \times 10^4) \text{ GeV}, \) corresponding to \(-T_{\nu_2} \in (8.8 \times 10^{-6}, 3.8 \times 10^{-4}) \text{ GeV}, \) but for the sake of naturalness we prefer to discuss only those solutions with the upper bound for \(-A_{\nu_2} \) in 5 TeV. These are the ones shown in Fig. 3.

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5.2 Constraints from muon $g - 2$

Once neutrino (and sneutrino) physics has determined the relevant regions of the parameter space of the $\mu\nu$SSM with light muon left sneutrino mass consistent with Higgs physics, we are ready to analyze the subset of regions that can explain the deviation between the SM prediction and the experimental value of the muon anomalous magnetic moment.

As discussed in Sec. 4.3, we have chosen $\mu \approx 379$ GeV, thus, from Eq. (19) the relevant parameters to determine the chargino-sneutrino contribution to $a_{\mu}^{\text{SUSY}}$ are $M_2$, $m_{\tilde{\nu}_\mu}$ and $\tan \beta$. In the following we will discuss the $\Delta a_\mu$ constraint on these parameters.

First, we expect $\tan \beta$ not to have notable effects on the $a_{\mu}^{\text{SUSY}}$ considering the narrow range, between 10–16, that we have chosen for it. This is shown in Fig. 6 where all the points found in the previous subsection are plotted. As we can see, although not all of them (red points) are within the 2$\sigma$ cut on $\Delta a_\mu$, there are many not only in the 2$\sigma$ (blue) but also in the 1$\sigma$ region (green). Obviously, the green points are also included in the 2$\sigma$ region of the blue points. As expected, $a_{\mu}^{\text{SUSY}}$ is quite independent of the variation of $\tan \beta$ in the range 10–16.

On the other hand, the effects are expected to be significant with the variations of $M_2$ and $m_{\tilde{\nu}_\mu}$, for the ranges analyzed in our scan. In Figs. 7 and 8 we show $a_{\mu}^{\text{SUSY}}$ versus $M_2$ and $m_{\tilde{\nu}_\mu}$, respectively. As we can see, now the smaller $M_2$ ($m_{\tilde{\nu}_\mu}$) is, the greater $a_{\mu}^{\text{SUSY}}$ becomes. For example, for $M_2$ from $\sim 800$ to 200 GeV, the SUSY contribution to $a_{\mu}$ increases from about 13 to 40 in units of $10^{-10}$. The same increase in $a_{\mu}^{\text{SUSY}}$ occurs when $m_{\tilde{\nu}_\mu}$ decreases.

Figure 6: $a_{\mu}^{\text{SUSY}}$ versus $\tan \beta$. The green and blue colors represent points in the 1$\sigma$ and 2$\sigma$ regions of $\Delta a_\mu$ in Eq. (1), respectively. The red points are not within the 2$\sigma$ cut on $\Delta a_\mu$.

tested in future CMB experiments such as CMB-S4 [78].
Figure 7: $a_{\mu}^{\text{SUSY}}$ versus $M_2$. The color code is the same as in Fig. 6.

Figure 8: $a_{\mu}^{\text{SUSY}}$ versus $m_{\tilde{\nu}_\mu}$. The color code is the same as in Fig. 6.

from $\sim 440$ to 100 GeV. Also, one can explain the 1 $\sigma$ (2 $\sigma$) region of $\Delta a_{\mu}$ with values of $M_2$ smaller than about 510 (920) GeV, and with values of $m_{\tilde{\nu}_\mu}$ smaller than 302 (422) GeV.
Figure 9: $m_{\tilde{\nu}_\mu}$ versus $M_2$. The color code is the same as in Fig. 6. The viable points (green and blue) are classified in three categories: The dot symbol corresponds to points with muon left sneutrino mass smaller than bino mass, the plus corresponds to sneutrino mass between bino and wino masses, and the triangle is for points with sneutrino mass heavier than wino mass. Note that we are assuming in our scan $M_2 = 2M_1$, and therefore always $m_{\tilde{\nu}_0} < m_{\tilde{W}}$.

In sum, this result agrees with the features of Fig. 2 and confirms as expected that in our scenario Eq. (16) can be qualitatively used to describe the SUSY contribution to $a_\mu$.

Fig. 9 can be regarded as the summary of our results. There we show $m_{\tilde{\nu}_\mu}$ versus $M_2$. We find (green) points in the $1\sigma$ region of $\Delta a_\mu$ in the mass ranges $72 \lesssim m_{\tilde{\nu}_\mu} \lesssim 302$ GeV and $152 \lesssim M_2 \lesssim 510$ GeV. The (blue) points in the $2\sigma$ region are in the wider ranges $64 \lesssim m_{\tilde{\nu}_\mu} \lesssim 422$ GeV and $152 \lesssim M_2 \lesssim 920$ GeV. Concerning the physical gaugino masses, these ranges of $M_2$ correspond to bino masses in the range about $73 - 465$ GeV and wino masses between $152 - 945$ GeV. We conclude that significant regions of the parameter space of the $\mu$-SSM can solve the discrepancy between theory and experiment in the muon $g - 2$, reproducing simultaneously neutrino and Higgs physics, as well as flavour observables.

Let us finally mention that the viable points (green and blue) are classified in Fig. 9 in three different categories as explained in the caption. This categorization will be important in the next section where the constraints from LHC searches are taken into account. For example, the presence of light muon left sneutrinos and winos, or light long-lived binos, could be excluded by LHC searches of particles decaying into lepton pairs.
Figure 10: Production of chargino pair decaying to muon left sneutrino, which in turn decays to neutrinos giving rise to the signal $2\mu + \text{MET}$.

6 Constraints from LHC searches

Depending on the different masses and orderings of the lightest SUSY particles of the spectrum found in our scan, we expect different signal at colliders. As shown in Fig. 9, the possible situations can be classified in three cases: i) the muon left sneutrino is the LSP, ii) the bino-like neutralino is the LSP and the muon left sneutrino is the NSLP, and iii) the bino-like neutralino is the LSP and the wino-like neutralino/chargino are co-NSLPs. In addition, depending of the value of the parameters, the decay of the LSP can be prompt or displaced. Altogether, there is a variety of possible signals arising from the regions of the parameter space analyzed in the previous sections, that could be constrained using LHC searches. In the following, we will use indistinctly the notation $\tilde{\chi}_i^0$, $\tilde{\chi}_j^0$, $\tilde{\chi}_k^\pm$, or $\tilde{B}_0^0$, $\tilde{W}_0^0$, and $\tilde{W}_\pm^\pm$, respectively.

6.1 Case i) $m_\tilde{\nu}_\mu < m_{\tilde{B}_0^0} < m_{\tilde{W}_0^0}$

Let us consider first the case with a muon left sneutrino as the LSP. As analyzed in Refs. [45, 28, 29], the main decay channel of the LSP corresponds to neutrinos, which constitute an invisible signal. Limits on sneutrino LSP from mono-jet and mono-photon searches have been discussed in the context of the $\mu\nu$SSM in Ref. [28, 29], and they turn out to be ineffective to constrain it. However, the presence of charginos and neutralinos in the spectrum with masses not far above from that of the LSP is relevant to multi-lepton+MET searches. In particular, the production of wino-like chargino pair at the LHC can produce the signal of $2\mu + 4\nu$, as shown in Fig. 10. This process produces a signal similar to the one expected from a directly produced pair of smuons decaying as $\tilde{\mu} \rightarrow \mu + \tilde{\chi}_i^0$ in RPC models. Therefore, the process shown in Fig. 10 can be compared with the limits obtained by the ATLAS collaboration in the search for sleptons in events with two leptons + MET [38]. Other decay modes are possible for the wino-like charginos, in particular chains involving higgsinos when $M_2 > \mu$. However, the search is designed to require exactly two opposite-sign leptons plus MET and the presence of additional leptons, b-jets, or multiple non b-jets, will make the candidate events to be discarded. An exception is the decay of wino-like charginos to lighter higgsino-like charginos plus $Z$ bosons. The produced signal will be similar to the one shown in Fig. 10 with the addition of two $Z$ bosons that would not spoil the signal as long as they decay to neutrinos. This process will have therefore a similar effective cross section than the one in Fig. 10, but the additional suppression from the
branching fraction of both Z bosons to neutrinos makes the channel subdominant. For the points where \( M_2 > \mu \) the same constraint is applied to the process initiated by higgsino-like chargino pair.

Thus, we will compare the limits on the signal cross section available in the auxiliary material of Ref. [38] with the production cross section of the lightest chargino pair times the branching ratio \( \text{BR}(\tilde{\chi}^{\pm} \rightarrow \mu \tilde{\nu}_{\mu}) \), where the former is calculated using RESUMMINO-2.0.1 [79–82] at NLO.

### 6.2 Case ii) \( m_{\tilde{B}_0} < m_{\tilde{\nu}_{\mu}} < m_{\tilde{W}_0} \)

The bino-like neutralino can also be the LSP, with the muon left sneutrino lighter than the wino-like chargino/neutralino. Then, the production of a chargino/neutralino will produce sneutrinos/smuons in the decay. When the mass of the bino is \( m_{\tilde{B}_0} \lesssim m_W \) its decay is suppressed in comparison with the one of the left sneutrino LSP. This is because of the kinematical suppression associated with the three-body nature of the bino decay. For this reason, it is natural that the bino proper decay length is an order of magnitude larger than the one of the left sneutrino, being therefore of the order of ten centimeters. The points of the parameter space where the LSP decays with a proper decay distance larger than 1 mm can be constrained applying the limits on long-lived particles (LLPs) obtained by the ATLAS collaboration [39], as explained in the following.

The proton-proton collisions produce a pair chargino-chargino or chargino-neutralino of dominant wino composition as shown in Fig. 11. The charginos and neutralinos will rapidly decay to sneutrinos/smuons and muons/neutrinos, with the former subsequently decay to muons/neutrinos plus long-lived binos. The possible decays form the following combinations:

1) \( pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^+_1 \rightarrow 3\mu \nu \ 2[\tilde{\chi}^0_1]_{\text{displaced}} \)
2) \( pp \rightarrow \tilde{\chi}^+_1 \tilde{\chi}^+_1 \rightarrow 2\mu 2\nu \ 2[\tilde{\chi}^0_1]_{\text{displaced}} \)
3) \( pp \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^+_1 \rightarrow \mu 3\nu \ 2[\tilde{\chi}^0_1]_{\text{displaced}} \)

Finally, the displaced binos will decay through an off-shell \( W \) mediated by a diagram including the RPV mixing bino-neutrino. Among the possible decays, the five relevant channels are

a) \( \tilde{\chi}^0_1 \rightarrow 2e + \nu \)

Figure 11: Production of chargino/neutralino pair decaying to muon left sneutrino, which in turn decays to a long-lived Bino giving rise to a displaced signal.
b) $\tilde{\chi}_1^0 \rightarrow \mu e + \nu$

c) $\tilde{\chi}_1^0 \rightarrow 2\mu + \nu$

d) $\tilde{\chi}_1^0 \rightarrow q\bar{q}' + \mu$

e) $\tilde{\chi}_1^0 \rightarrow q\bar{q}' + e$

where each of the 5 channels constitutes a different signal. The ATLAS search found no candidate events in any of the signal regions, which are defined to be background free. Hence any point predicting more than 3 events in any of the signal regions corresponding to the aforementioned channels will be excluded at the 95 confidence level.

We follow the prescription of Refs. [28,29] for recasting the ATLAS 8 TeV search [39], but adding to the analysis also the channels corresponding to the decays $\tilde{\chi}_1^0 \rightarrow q\bar{q}'\ell$. The number of displaced vertices corresponding to each channel is calculated as described below and summarized in Eq. (25) below. We extract the displaced vertex selection efficiency from the plots stating an upper limit on the number of LLP decays provided by ATLAS. Unlike the case studied in Refs. [28,29], the LLP will be produced here with different expected boosts depending of the mass gap $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. This is solved using an interpolation between the values extracted for the different lines in the figures of the ATLAS analysis, where the boost factors of the LLP in our proposed model as well as in the benchmark scenarios proposed by ATLAS are estimated according to

$$\gamma = \left(1 + \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)^2}{2m_{\tilde{\chi}_2^0}^2 m_{\tilde{\chi}_1^0}^2}\right)^{1/2}. \quad (24)$$

In addition, the efficiency passing the trigger selection requirements is simulated for a sample of points with masses $m_{\tilde{\chi}_2^0} \in [60, 700]$ GeV and $m_{\tilde{\chi}_1^0} \in [60, 350]$ GeV, and the mass of the muon left sneutrinos considered to be in the middle of both. Events are generated using MadGraph5_aMC@NLO 2.6.7 [83] and PYTHIA 8.243 [84] and we use DELPHES v3.4.2 [85] for the detector simulation. For each point of the parameter space, the value of the trigger efficiency is calculated using a linear interpolation between the points simulated as described before. For the points where the mass $m_{\tilde{\chi}_1^0}$ is above 700 GeV we use the corresponding upper simulated value, since the efficiency saturates the upper value around this mass.

The number of displaced vertices detectable for each channel is then calculated as

$$N_{X}^{DV} = \mathcal{L} \times \left\{ \sigma_{\text{atnstev}}(pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^+) \times [\epsilon_{1X}^T \times \text{BR}(\tilde{\chi}_2^0 \rightarrow \mu \tilde{\mu}) \times \text{BR}(\tilde{\chi}_1^+ \rightarrow \mu \tilde{\mu})] + \epsilon_{1X}^T \times \text{BR}(\tilde{\chi}_2^0 \rightarrow \mu \tilde{\mu}) \times \text{BR}(\tilde{\chi}_1^+ \rightarrow \nu \tilde{\mu}) + \epsilon_{3X}^T \times \text{BR}(\tilde{\chi}_2^0 \rightarrow \nu \tilde{\mu}) \times \text{BR}(\tilde{\chi}_1^+ \rightarrow \mu \tilde{\mu}) + \epsilon_{3X}^T \times \text{BR}(\tilde{\chi}_2^0 \rightarrow \nu \tilde{\mu}) \times \text{BR}(\tilde{\chi}_1^+ \rightarrow \nu \tilde{\mu}) + \sigma_{\text{atnstev}}(pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-) \times \epsilon_{2X}^T \times \left[ \text{BR}(\tilde{\chi}_1^+ \rightarrow \mu \tilde{\mu}) \times \text{BR}(\tilde{\chi}_1^- \rightarrow \nu \tilde{\mu}) + \text{BR}(\tilde{\chi}_1^+ \rightarrow \nu \tilde{\mu}) \times \text{BR}(\tilde{\chi}_1^- \rightarrow \mu \tilde{\mu}) \right]^2 \right\} \times \epsilon_{X}^{\text{sel}} \times 2 \times \text{BR}(\tilde{\chi}_1^0 \rightarrow X),$$

where $\epsilon_{1,2,3X}^T$ refers to the trigger efficiency associated to each intermediate chain, 1), 2) or 3), and each final decay of the bino ($X = a, b, c, d, e$). For example, $\epsilon_{1a}^T$ correspond to the trigger efficiency when the binos are produced through the channel 1) and decay
to electrons and neutrinos as in a). Also $\epsilon_{sel}^X$ correspond to the selection efficiency of the displaced vertex originated in the decay of the binos through the channel $X$.

On the other hand, as mentioned above the selection requirements defined to identify the displaced vertex by the ATLAS collaboration \cite{39} set a lower bound on the proper decay length of about 1 mm, for which the particle could be detected. However, when the mass of the bino is $m_{\tilde{B}_0} \gtrsim 130$ GeV the two-body nature of its decay implies that $c\tau$ becomes smaller than 1 mm. In that case, we can apply ATLAS searches based on the promptly produced leptons in the decay of the heavier chargino/neutralino, as we already did in Subsec. 6.1 using the auxiliary material of Ref. \cite{38}. If $c\tau \lesssim 1$ mm, a fraction of $\tilde{\chi}_0^1$ will decay with a large impact parameter and the corresponding tracks will be discarded from further analysis in prompt searches. Thus we can compare the events generated as in Fig. 11 without considering the bino products, with the ATLAS search \cite{38} where signal leptons are required to have $|d_0|/\sigma(d_0) < n$ with $d_0$ the transverse impact parameter relative to the reconstructed primary vertex, $\sigma(d_0)$ its error, and $n = 3$ for muons and 5 for electrons. The fraction of LSP decays with impact parameters larger than $d_0$ is then expressed by

$$\epsilon = e^{-\frac{\sqrt{\sigma(d_0)}}{c\tau\beta\gamma}},$$

where $\sigma(d_0)$ is taken to be 0.03 mm according to \cite{86}. For each point of the parameter space, if the production cross section of the process in Fig. 11 times the result of Eq. (26) is above the upper limit obtained by ATLAS in Ref. \cite{38}, the point is regarded as excluded.

6.3 Case iii) $m_{\tilde{B}_0} < m_{\tilde{W}_0} < m_{\tilde{\nu}_\mu}$

The situation in this case is similar to the one presented in the previous subsection, with the difference in the particles produced in the intermediate decay, as shown in Fig. 12. While in Subsec. 6.2 this corresponds in most cases to muons, now the intermediate decay will mainly produce hadrons. The LHC constraints are applied in an analogous way, depending also on the value of the proper decay length, larger or smaller than 1 mm. In the former situation, the number of displaced vertices expected to be detectable at ATLAS is now given by

$$N_{DV}^X = \mathcal{L} \times \left\{ \sigma_{@8\text{TeV}}(pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^+) \times \epsilon_{1X}^T \times \text{BR}(\tilde{\chi}_2^0 \to Z^0\tilde{\chi}_1^0) \times \text{BR}(\tilde{\chi}_1^+ \to W^{\pm}\tilde{\chi}_1^0) + \sigma_{@8\text{TeV}}(pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) \times \epsilon_{2X}^T \times \left[\text{BR}(\tilde{\chi}_1^+ \to W^{\pm}\tilde{\chi}_1^0)\right]^2 \right\} \times \epsilon_{sel}^X \times 2 \times \text{BR}(\tilde{\chi}_0^0 \to X),$$

where the efficiencies $\epsilon_{1,2X}$ are calculated again with events simulated based on the new scenario. Note that when $m_{\tilde{W}_\pm}\tilde{\nu}_\mu < m_{\tilde{W}_0}/m_{\tilde{B}_0}$ the intermediate BRs correspond to three-body decays. If $c\tau < 1$ mm, a similar analysis as in the previous subsection follows.

6.4 Results

The points obtained in the scan of Sec. 5 and summarized in Fig. 9 are compatible with experimental data on neutrino and Higgs physics, as well as flavor observables, and explain the discrepancy of the muon $g - 2$. In the previous subsections, we have shown that they present a rich collider phenomenology. Depending on the different masses and orderings of
the light SUSY particles of the spectrum, we expect different possible signal at colliders. Then, we have argued that this variety of possible signals can be constrained using LHC searches, and explained the analysis to be carried out.

The results of this computation of the LHC limits imposed on the parameter space of our scenario are presented in Fig. 13 which can be compared with Fig. 9. The (green and blue) viable points of Fig. 9 are shown in Fig. 13 with light colors when they are excluded by LHC searches. Let us point out in this sense, that the processes considered relevant for LHC searches are all of them initiated by $\tilde{\chi}^0_2\tilde{\chi}^\pm_1$ or $\tilde{\chi}^\pm_1\tilde{\chi}^0_1$ production, consequently it is expected that the exclusion power of the searches drops with increasing values of $M_2$. (That is precisely the situation in Fig. 13, where many (sneutrino LSP-like) points are allowed in the right part of the plot, still compatible with the measured value of $\Delta a_\mu$ at the 2$\sigma$ level). However, the limits imposed on the higgsino-like chargino pair production when $M_2 > \mu$ exclude all of those points for the fixed value of $\mu$.

On the other hand, some (bino LSP-like) points represented by green crosses in the region of $280 \lesssim M_2 \lesssim 350$ GeV and $m_{\tilde{\nu}_\mu} \lesssim 270$ GeV are still compatible with $\Delta a_\mu$ at the 1$\sigma$ level. The values of $M_2$ correspond to bino and wino masses in the ranges about $137 - 168$ and $272 - 320$ GeV, respectively. These points are inside the region where the proper decay length of the bino LSP is smaller than 1 mm corresponding to $280 \lesssim M_2 \lesssim 460$ GeV.

There we have checked that most of the points survive the constraints from LHC searches discussed in Subsec. 6.2 and 6.3. On the contrary, most of the (bino LSP-like) points with $c\tau > 1$ mm, i.e. with $152 \lesssim M_2 \lesssim 280$ GeV, turn out to be excluded.

There is a small number of (sneutrino LSP-like) points non excluded for values of $M_2$ in the range $220 - 350$ GeV. Those points lie just slightly below the upper limits on signal cross section of the process shown in Fig. 10. A smaller chargino-chargino production cross section for larger values of $M_2$, or a reduced exclusion power due to the reduced available energy for the final states in the case of lower values of $M_2$ and $m_{\tilde{\nu}_\mu}$, explain that some points remain allowed while the surrounding points are not. Notice that a small increase in the accumulated luminosity will be enough to test these points.
7 Conclusions

We have analyzed within the framework of the $\mu\nu$-SSM, the regions of the parameter space that can explain the 3.5$\sigma$ deviation of the measured value of the muon anomalous magnetic moment with respect to the SM prediction. We have shown that the $\mu\nu$-SSM can naturally produce light muon left sneutrinos and electroweak gauginos, that are consistent with Higgs and neutrino data as well as with flavor observables. The presence of these light sparticles in the spectrum is known to enhance the SUSY contribution to $a_\mu$, and thus it is crucial for accommodating the discrepancy between experimental and SM values.

We have obtained this result sampling the $\mu\nu$-SSM in order to reproduce the latest value of $\Delta a_\mu$, simultaneously achieving the latest Higgs and neutrino data. We found significant regions of the parameter space with these characteristics. In particular, there are points in the 1$\sigma$ region of $\Delta a_\mu$ with the mass ranges $72 \lesssim m_{\tilde{\nu}_\mu} \lesssim 302$ GeV and $152 \lesssim M_2 \lesssim 510$ GeV. Points in the 2$\sigma$ region are in the wider ranges $64 \lesssim m_{\tilde{\nu}_\mu} \lesssim 422$ GeV and $152 \lesssim M_2 \lesssim 920$ GeV. These results can be found summarized in Fig. 9. Concerning the physical gaugino masses, these ranges of $M_2$ correspond to bino and wino masses in the ranges $73 - 465$ and $152 - 945$ GeV, respectively.

Note nevertheless that we have only scanned the model over the parameters controlling neutrino/sneutrino physics, fixing those controlling Higgs physics (see Tables 2 and 3). Although this simplification was necessary to relax our demanding computing task, it also indicates that more solutions could be found in other regions of the parameters relevant for Higgs physics. Actually, a similar comment applies to the parameters controlling neutrino
physics where the scan was carried out. We worked with a solution with diagonal neutrino Yukawas fulfilling in a simple way neutrino physics through the dominance of the gaugino seesaw, but if a different hierarchy of Yukawas (and sneutrino VEVs) is considered, or off-diagonal Yukawas are allowed, more solutions could be found. Thus the result summarized in Fig. 9 can be considered a subset of all the solutions that could have been found if a general scan of the parameter space of the model would have been carried out.

In the final part of our work, we have studied the constraints from LHC searches on the solutions obtained. They have a rich collider phenomenology with the possibilities of muon left sneutrino or bino-like neutralino as LSPs. In particular, we found that multi-lepton + MET searches \cite{38,39} can probe our scenario through chargino/chargino and chargino/neutralino production. One of the conclusions is that although many of the points obtained compatible with $\Delta a_\mu$ at the 1$\sigma$ level turn out to be excluded by LHC searches, still there is a bunch of allowed points in the ranges of masses $84 \lesssim m_{\tilde{\nu}} \lesssim 270$ GeV and $220 \lesssim M_2 \lesssim 470$, with the latter corresponding to bino and wino masses in the ranges $107 - 226$ and $218 - 520$ GeV, respectively. Besides, other points compatible at the 2$\sigma$ level survive. In this case, the ranges of masses are $66 \lesssim m_{\tilde{\nu}} \lesssim 410$ GeV and $265 \lesssim M_2 \lesssim 480$ GeV, with the latter corresponding to bino and wino masses in the ranges $126 - 465$ and $255 - 500$ GeV, respectively. All this is summarized in Fig. 13 which can be compared with Fig. 9 where the LHC constraints are not included.

Let us finally point out that these results concerning muon $g - 2$ can have important implications for future LHC searches. If the deviation with respect to the SM persists in the future, then the prediction of the $\mu\nu$SSM can be used for pinning down the mass of the muon left sneutrino, as well as for narrowing down the mass scale for a potential discovery of electroweak gauginos.

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