Leptophobic $Z'$ bosons in the secluded $U(1)'$ model

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ABSTRACT: We perform a comprehensive analysis of the secluded UMSSM model, consistent with present experimental constraints. We find that in this model the additional $Z'$ gauge boson can be leptophobic without resorting to gauge kinetic mixing and, consequently, also $d$-quark-phobic, thus lowering the LHC bounds on its mass. The model can accommodate very light singlinos as DM candidates, consistent with present day cosmological and collider constraints. Light charginos and neutralinos are responsible for muon anomalous magnetic predictions within $1\sigma$ of the measured experimental value. Finally, we look at the possibility that a lighter $Z'$, expected to decay mainly into di-leptons through charginos, could be observed at 27 TeV.

KEYWORDS: Supersymmetric models, additional gauge bosons

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1 Introduction
With the discovery of the Higgs boson, the last piece of the Standard Model (SM) construction was fit into place. Furthermore, almost all SM predictions have been confirmed by experimental results, even precision tests involving higher order perturbative Electroweak (EW) and Quantum Chromodynamics (QCD) effects. However, as it stands, the SM cannot be the final theory and the quest for physics Beyond the SM (BSM) is very much alive. Among the many proposed BSM scenarios, Supersymmetry (SUSY) appears to be one of the most popular ones, since it provides elegant solutions to the SM drawbacks, such as the stabilization of the EW scale under radiative corrections, an explanation for the baryon asymmetry of the Universe and for the presence of Dark Matter (DM) in it. However, the minimal version of SUSY, the Minimal Supersymmetric SM (MSSM), provides no explanation for the \( \mu \) problem [1–4]. The \( \mu \) parameter, the so-called higgsino mass term, is expected to be at the SUSY-breaking scale but, for successful EW symmetry breaking, its value should be at the scale of the latter. Adding a \( U(1)’ \) gauge symmetry to the MSSM, one solves this problem by replacing the \( \mu \) parameter of the MSSM with an effective one, generated dynamically by the Vacuum Expectation Value (VEV) of the singlet Higgs field responsible for breaking \( U(1)’ \). Furthermore, the additional \( U(1)’ \) symmetry is able to generate neutrino masses by allowing right-handed neutrinos into the superpotential and can account for either Majorana- [5] or Dirac-type neutrinos [6].

Normally, it is expected that both EW and \( U(1)’ \) symmetry breaking are achieved through soft-breaking parameters, which would imply that the mass of the gauge boson associated with \( U(1)’ \), a \( Z’ \), would be of the same order as the EW scale [7–9]. This conflicts with experimental measurements at the Large Hadron Collider (LHC) [10], though, which impose a lower bound on the \( Z’ \) mass, from the Drell-Yan (DY) channel, i.e., di-lepton hadro-production, of \( \mathcal{O}(4) \) TeV or more. The most natural solution to this inconsistency is that the VEV of the singlet Higgs field is large compared to the EW scale, \( \mathcal{O}(1 - 10) \) TeV, pushing the SUSY scale very high and rendering it mostly unobservable at the present LHC. Alternatively, it was observed that fine-tuning the kinetic mixing between the two \( U(1) \) groups could yield \( Z’ \) bosons which do not decay directly into lepton
pairs [11]. Corresponding $Z'$ gauge boson masses are then limited by its di-jet decays, whose bounds are much weaker in comparisons to DY ones [12].

An alternative is represented by a $U(1)'$ model where the SUSY-breaking scale and $Z'$ mass are disjoint: the former is close to the EW scale while a large value for the latter can be generated by the VEVs of additional Higgs fields ($S_1$, $S_2$, $S_3$, so-called secluded singlets) which are charged under the $U(1)'$ group but couple weakly to the SM fields [13]. This BSM scenario is known as the secluded $U(1)'$ model, a realization of the generic class of $U(1)'$-extended MSSMs (UMSSMs). It allows for both explicit and spontaneous CP symmetry breaking and is able to account for baryogenesis [14]. Differences between this UMSSM scenario and the MSSM would likely reveal themselves in the nature of DM, as in the extended scenario several additional singlinos as well as sneutrinos could be viable candidates for it [15].

In a nutshell, the secluded $U(1)'$ model extends the MSSM by an additional Abelian group, to $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'$, and by four Higgs singlets (three in addition to the one needed to break $U(1)'$, to ensure a $Z' - Z$ mass hierarchy). Exotics with Yukawa couplings to a singlet Higgs field must be introduced to ensure the theory is anomaly free. However, despite the presence of these couplings, one can assume their masses to be at the Grand Unification Theory (GUT) scale and thus neglect them in TeV scale phenomenology1. (Note, however, that they have been studied extensively in [16].) Previous studies of this secluded $U(1)'$ model exist, but none consistent with present experimental data on the discovered Higgs boson mass and signal strengths or with $Z'$ gauge boson mass bounds. In this work, we revisit this BSM scenario in detail, with particular interest in addressing the unresolved problems of UMSSMs, by providing light $Z'$ masses yet compatible with current bounds, an acceptable $(g - 2)_\mu$ value and DM relic density plus the viable existence of light SUSY particles, altogether providing one with new distinguishing signals of this BSM realization in LHC experiments.

In showing all this, we shall prove first that, in such a $U(1)'$ secluded model, leptophobia can be achieved easily and without gauge kinetic mixing between the $Z$ and $Z'$, so that a light $Z'$ gauge boson can survive all experimental constraints in presence of finite width effects. Furthermore, we shall show that this BSM scenario can predict corrections to $(g - 2)_\mu$ within $1\sigma$ of the experimentally observed value. Finally, we will also find that, in our UMSSM realization, the Lightest SUSY Particle (LSP), for a large region of its parameter space, is a singlino consistent with all DM constraints accompanied by very light charginos and neutralinos, with masses of $O(100)$ GeV, in turn consistent with collider limits, into which a $Z'$ can then decay yielding sizable signals at the LHC.

Our work is organized as follows. In the next section, Sec. 2, we provide a description of the secluded $U(1)'$ model, with particular emphasis on the gauge and neutralino sectors, i.e., where differences with respect to the MSSM will manifest themselves. We describe the implementation of this BSM scenario, including the free parameters and the constraints imposed on these, in Sec. 3. Then, we explain the implications emerging from a wide scan of its parameter space for $Z'$ physics at colliders, in Sec. 4, and onto the DM candidate in relic density and direct detection experiments, in Sec. 5. Furthermore, in presence of all such constraints on the mass and coupling spectrum of the model, we analyze the consequences for the muon anomalous magnetic moment in Sec. 6. We further study the possibility of observing a light $Z'$ boson via chargino/neutralino decays at the High-Luminosity LHC (HL-LHC) and High-Energy LHC (HE-LHC) in Sec. 7. Finally, in Sec. 8, we summarize our findings and draw our conclusions.

1Furthermore, their charges are such that they do not mix with ordinary matter.
2 The secluded $U(1)'$ Model

In this section, we review the secluded $U(1)'$, known also as the secluded UMSSM. In addition to the MSSM superfields, the model has three right-handed neutrino superfields $\hat{N}_i^c$ and four scalar singlets $\hat{S}$, $\hat{S}_1$, $\hat{S}_2$ and $\hat{S}_3$. The superpotential in this model is described by

\[ W = Y_{\nu}^{ij} \hat{Q}_i \hat{H}_u \hat{d}_j^c - Y_{e}^{ij} \hat{Q}_i \hat{H}_d \hat{e}_j^c + Y_{\nu}^{ij} \hat{L}_i \hat{H}_d \hat{e}_j^c + \sum_{n=1}^{n_{\nu}} h_{\nu}^i S \phi \overline{\tau}_j + \sum_{n=1}^{n_{\gamma}} h_{\gamma}^i S T \overline{T}_j, \tag{2.1} \]

where the first line of Eq. 2.1 contains the usual terms of the MSSM while the second line includes the additional interactions of right-handed neutrinos $\hat{N}_i^c$ (assumed to be Dirac fields here) and $\hat{H}_u$, as well as the singlet superfields $\hat{S}$, $\hat{S}_1$, $\hat{S}_2$ and $\hat{S}_3$, and where $T_i$ and $\phi_i$ are the exotics, which, as explained above, are assumed to be heavy and decoupled from the low energy spectrum. The effective $\mu$ term is generated dynamically as $\mu = \lambda(S)$. The scalar potential includes the $F$-term, given by

\[ V_F = \lambda^2 (|H_u|^2 |H_d|^2 + |S|^2 |H_u|^2 + |S|^2 |H_d|^2 + \kappa^2 (|S_1|^2 |S_2|^2 + |S_2|^2 |S_3|^2 + |S_3|^2 |S_1|^2)), \tag{2.2} \]

while the $D$-term scalar potential is

\[ V_D = \frac{g_1^2 + g_2^2}{8} (|H_d|^2 - |H_u|^2)^2 + \frac{1}{2} g'^2 \left( Q_S |S|^2 + Q_{H_u} |H_u|^2 + Q_{H_d} |H_d|^2 + \sum_{n=1}^{3} Q_{S_n} |S_n|^2 \right)^2 \tag{2.3} \]

where $g_1$, $g_2$ and $g'$ are the coupling constants for the $U(1)_Y$, $SU(2)_L$ and $U(1)'$ gauge groups while $Q_\phi$ is the $U(1)'$ charge of the field $\phi$. Finally, the potential includes the SUSY-breaking soft terms,

\[ V_{\text{soft}} = m_{\hat{H}_u}^2 |H_u|^2 + m_{\hat{H}_d}^2 |H_d|^2 + m_{\hat{S}}^2 |S|^2 + \sum_{n=1}^{3} m_{\hat{S}_n}^2 |S_n|^2 - (A_\lambda \lambda S H_u H_d + A_{\nu} \kappa S_1 S_2 S_3 + h.c) \]

\[ + (m_{\hat{S}_1}^2 S S_1 + m_{\hat{S}_2}^2 S S_2 + m_{\hat{S}_3}^2 S_1 S_2 + h.c). \tag{2.4} \]

In Table 1 we give the complete list of the fields in the model, together with their spin, number of generations and charge assignments under the extended gauge group. The secluded $U(1)'$ charge assignments and anomaly cancellation conditions allow for some freedom in the choice of the $U(1)'$ charges, absent in other $U(1)'$ models. In general, the $U(1)'$ charge assignments can be chosen as follows:

\[ Q_Q = \alpha, \quad Q_{H_u} = \beta, \quad Q_S = \gamma, \quad Q_{\ell} = -3\alpha + \frac{\gamma}{3}, \quad Q_{H_d} = -\beta - \gamma, \]

\[ Q_u = -\alpha - \beta, \quad Q_d = -Q_Q - Q_{H_d} = -\alpha + \beta + \gamma, \quad Q_e = -Q_{\ell} - Q_{H_d} = 3\alpha + \beta + \frac{2\gamma}{3}, \]

\[ Q_N = -Q_{\ell} - Q_{H_u} = 3\alpha - \beta - \frac{\gamma}{3}, \quad Q_{S_1} = Q_{S_2} = \delta, \quad Q_{S_3} = -2Q_{S_1} = -2Q_{S_2} = -2\delta. \tag{2.5} \]

Here, $Q_{H_u} = 0$ dictates $\gamma = -\beta$. From the conditions above we can choose, for simplicity, $Q_e = Q_{\ell}$. The leptophobic condition $Q_{\ell} = Q_e = 0$ requires $\alpha = -\frac{\beta}{2}$, so that the leptophobia condition can be achieved without resorting to kinetic mixing between the two $U(1)$ groups.\footnote{This is unlike models where the $U(1)'$ charges are derived from the mixing of, e.g., $\theta_E$ angles [17].} Thus, Eq. 2.5 can be
rewritten in terms of $\alpha$ and $\delta$ only as:

$$
Q_Q = \alpha, \quad Q_{H_u} = -9\alpha, \quad Q_S = 9\alpha, \quad Q_{\ell} = 0, \quad Q_{H_d} = 0, \quad Q_u = 8\alpha, \quad Q_d = -\alpha,
$$
$$
Q_s = 0, \quad Q_N = 9\alpha, \quad Q_{S_4} = Q_{S_5} = \delta, \quad Q_{S_2} = -2Q_{S_1} = -2Q_{S_3} = -2\delta. \quad (2.6)
$$

After the spontaneous breaking of the extended gauge symmetry group down to electromagnetism (EM), the $W^\pm$, $Z$ and $Z'$ bosons acquire masses while the photon remains massless. At tree level, the squared masses of the $Z$ and $Z'$ bosons are given by

$$
M_Z^2 = \frac{g_Z^2 + g_2^2}{2} (\langle H_U^0 \rangle^2 + \langle H_d^0 \rangle^2),
$$
$$
M_{Z'}^2 = g^2 \left( Q_S \langle S \rangle^2 + Q_{H_u} \langle H_u^0 \rangle^2 + Q_{H_d} \langle H_d^0 \rangle^2 + \sum_{n=1}^{3} Q_{S_n} \langle S_n \rangle^2 \right), \quad (2.7)
$$

where $H_u^0 \equiv \frac{v_u}{\sqrt{2}}$ and $H_d^0 \equiv \frac{v_d}{\sqrt{2}}$ stand for the neutral components of the down-type and up-type Higgs fields $H_d$ and $H_u$.

While the chargino sector is unaltered, the neutralino sector of the secluded $U(1)'$ model includes five additional fermion fields: the $U(1)'$ gauge fermion $\tilde{Z}'$ and four singlinos $\tilde{S}$, $\tilde{S}_1$, $\tilde{S}_2$, $\tilde{S}_3$, in total, nine neutralino states $\tilde{\chi}_i^0$ ($i = 1, \ldots, 9$) [13]:

$$
\tilde{\chi}_i^0 = \sum_{a} N_{ia}^0 \tilde{G}_a, \quad (2.8)
$$

where the mixing matrix $N_{ia}^0$ connects the gauge-basis neutral fermion states to the physical-basis neutralinos $\tilde{\chi}_i^0$. The neutralino masses $M_{\tilde{\chi}_i^0}$ are obtained through the diagonalization $N^0 M N^0 = $
Diag \{M_{\tilde{Q}_1}, \ldots, M_{\tilde{Q}_3}\}. The 9 \times 9 neutral fermion mass matrix is

\[
M = \begin{pmatrix}
M_{\tilde{Z}} & 0 & -M_{\tilde{Z}H_d} & M_{\tilde{Z}H_u} & 0 & M_{\tilde{Z}\tilde{Z}} & 0 & 0 & 0 \\
0 & M_{\tilde{W}} & M_{\tilde{W}H_d} & -M_{\tilde{W}H_u} & 0 & 0 & 0 & 0 & 0 \\
-M_{\tilde{Z}H_d} & M_{\tilde{W}H_d} & 0 & -\mu & -\mu_{H_u} & \mu'_{H_d} & 0 & 0 & 0 \\
M_{\tilde{Z}H_u} & -M_{\tilde{W}H_u} & -\mu & 0 & -\mu_{H_d} & \mu'_{H_u} & 0 & 0 & 0 \\
0 & 0 & -\mu_{H_u} & -\mu_{H_d} & 0 & \mu'_S & 0 & 0 & 0 \\
M_{\tilde{Z}\tilde{Z}} & 0 & \mu'_{H_d} & \mu'_S & \mu'_S & \mu'_S & \mu'_S & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \mu'_S & 0 & -\frac{\kappa v_2}{\sqrt{3}} & -\frac{\kappa v_2}{\sqrt{3}} \\
0 & 0 & 0 & 0 & 0 & \mu'_S & -\frac{\kappa v_2}{\sqrt{3}} & 0 & -\frac{\kappa v_2}{\sqrt{3}} \\
0 & 0 & 0 & 0 & 0 & \mu'_S & 0 & -\frac{\kappa v_2}{\sqrt{3}} & 0
\end{pmatrix},
\]

(2.9)

where the lightest eigenvalue is the DM candidate. In the neutralino mass matrix, the mass mixing terms are defined in terms of \(\tan \beta = \frac{v_d}{v_u}\), \(\langle S \rangle = \frac{v_S}{\sqrt{2}}\) and \(\langle S_i \rangle = \frac{v_i}{\sqrt{2}}\) \((i = 1, 2, 3)\), as

\[
M_{\tilde{Z} H_d} = M_Z \sin \theta_W \cos \beta, \quad M_{\tilde{Z} H_u} = M_Z \sin \theta_W \sin \beta,
\]

\[
M_{\tilde{W} H_d} = M_Z \cos \theta_W \cos \beta, \quad M_{\tilde{W} H_u} = M_Z \cos \theta_W \sin \beta,
\]

(2.11)

where \(\mu_i, \mu'_i\) stand for the effective couplings in each sector, given in terms of \(h_s\) or \(g'\), the coupling constant of \(U(1)'\), as

\[
\mu_{H_d} = \frac{h_s v_d}{\sqrt{2}}, \quad \mu_{H_u} = h_s \frac{v_u}{\sqrt{2}}, \quad \mu'_{H_d} = g' Q_{H_d} v_d, \quad \mu'_{H_u} = g' Q_{H_u} v_u,
\]

\[
\mu'_S = g' Q_S v_S, \quad \mu'_S = g' Q_S v_i.
\]

(2.12)

3 Computational Setup

Following the development of the model as in Sec. 2, to enable our analysis and impose constraints coming from experimental data, we implement the model within a computational framework. We have then made use of SARAH (version 4.13.0) [20–22] to generate CalcHep [27] model files and a UFO [28] version of the model [29], so that we could employ MicrOMEGAs (version 5.0.9) [25] for the computation of the predictions relevant for our dark matter study, and MG5aMC (version 2.7.2) [30] for generating the hard-scattering event samples necessary for our collider study, and SPHENO (version 4.0.4) [18, 19] package for spectrum analysis. We make use of HiggsBounds [23] to constrain the possibility of BSM Higgs bosons detection at colliders and HiggsSignals [24] to test the signal strengths of the SM-like Higgs state. During the numerical analysis performed in this work, SUSY Les Houches Accord (SLHA) files were manipulated by means of PySLHA 3.2.4 package [26].

We performed random scans over the parameter space, illustrated in Table 2, where we restrict ourselves only to universal boundary conditions. Here \(m_0\) denotes the Spontaneous Symmetry Breaking (SSB) mass term for all the scalars while \(M_{1/2}\) stands for the SSB mass terms for the gauginos including the one associated with the \(U(1)'\) gauge group. As before, \(\tan \beta\) is the ratio of VEVs of the MSSM Higgs doublets, \(A_0\) is the SSB trilinear scalar interacting term, \(\lambda\) is the coupling associated with the interaction of the \(H_u\), \(H_d\) and \(S\) fields while \(\kappa\) is the coupling of the
| Parameter | Scanned range | Parameter | Scanned range |
|-----------|---------------|-----------|---------------|
| $m_0$     | [0.3, 3] TeV  | $v_S$     | [0.97, 15.8] TeV |
| $M_{1/2}$ | [0.3, 3] TeV  | $v_1$     | [1.6, 15.] TeV |
| $\tan \beta$ | [1, 55.] | $v_2$     | [0.8, 11.2] TeV |
| $A_0/m0$  | [−3, 3] GeV   | $v_3$     | [1.6, 15.] TeV |
| $\lambda$ | [3. $\times$ 10$^{-2}$, 0.6] | $\kappa$ | [0.3, 2.65] |
| $A_\lambda$ | [1.8, 7.5] TeV | $A_\kappa$ | [−8.3, −0.2] TeV |
| $Y_{ij}, (i = j)$ | [1 $\times$ 10$^{-8}$, 1 $\times$ 10$^{-7}$] | $Y_{ij}, (i \neq j)$ | 0. |

Table 2. Scanning range of parameter space of the secluded $U(1)'$ model.

interaction of the $\hat{S}_1$, $\hat{S}_2$ and $\hat{S}_3$ fields. Trilinear couplings for $\lambda$ and $\kappa$ are defined as $A_\lambda \lambda$ and $A_\kappa \kappa$, respectively, at the SUSY scale. Here, $Y_{ij}'$ is the Yukawa coupling of the term $\hat{L}_i \hat{H}_u \hat{N}_c$ and we vary only the diagonal elements in the range of $1 \times 10^{-11} - 1 \times 10^{-7}$ while setting the off-diagonal elements to zero.

We followed [31] where a simple method for analyzing the impact of precision EW data above and below the $Z$ peak on flavor-conserving heavy new physics is implemented. There, the corrections to all leptonic data can be converted into oblique corrections to the vector boson propagators and condensed into seven parameters. Numerical fits for the new physics parameters are included and the method is applied to generic $Z'$ gauge bosons highlighting parameter combinations most strongly constrained. The authors report the 99% Confidence Level (CL) iso-contours of bounds on $M_{Z'}/g'$ for a set of $Z'$'s. Their constraints depend only on the leptonic and Higgs $U(1)'$ charges, $Q_{H_u}, Q_{H_d}, Q_{\ell}, Q_e$, and the assumption that their arbitrary overall normalization is fixed, $Q_{H_u}^2 + Q_{H_d}^2 + Q_{\ell}^2 + Q_e^2 = 2$. Given that we fix $Q_{\ell} = Q_e = Q_{H_d} = 0$, the $Z'$ gauge boson in our model cannot be considered as one of the given set of $Z'$'s, so that the bounds on $M_{Z'}/g'$ given by [31] are not applicable in a straightforward way. Therefore, we require a $2\sigma$ (i.e. 95% CL) agreement with EW precision observables, parametrized through the oblique parameters $S, T, U$ [32–35]. The constraints from the latter are included by evaluating

$$\chi^2_{STU} = X^T C^{-1} X, \quad (3.1)$$

with $X^T = (S - \hat{S}, T - \hat{T}, U - \hat{U})$. The observed parameters deviations are given by [36]

$$\hat{S} = 0.05, \quad \hat{T} = 0.09, \quad \hat{U} = 0.01, \quad (3.2)$$

where the unhatted quantities denote the model predictions. The covariance matrix is [36]

$$C_{ij} = \begin{bmatrix} 0.0121 & 0.0129 & -0.0071 \\ 0.0129 & 0.0169 & -0.0119 \\ -0.0071 & -0.0119 & 0.0121 \end{bmatrix}.$$

We then require $\chi^2_{STU} \leq 8.025$, corresponding to a maximal $2\sigma$ deviation given the 3 degrees of freedom.
4 Gauge boson mass constraints

After imposing the constraints from the previous section, we turn our attention to gauge bosons. From the SSB of the $SU(2)_L \otimes U(1)_Y \otimes U(1)'$ symmetry, the gauge bosons $Z$ and $Z'$ mix to form physical mass eigenstates. The $Z - Z'$ mixing mass matrix is

$$M_Z^2 = \begin{pmatrix} M_{ZZ}^2 & M_{ZZ'}^2 \\ M_{ZZ'}^2 & M_{Z'Z'}^2 \end{pmatrix}. \quad (4.1)$$

As the mixing between the $Z$ and $Z'$ bosons is very small, to a good approximation, these are good physical states, with masses given in Eq. 2.7. Following the methodology described in the previous section, we can scan the parameter space imposing constraints on SUSY particles, rare $B$-meson decays and oblique parameters so that the SM $Z$ gauge boson properties are consistent with experimental data, as indicated in Table 3. In the following, we analyze the properties of the gauge sector for all scenarios accepted in our scanning procedure. In Fig. 1, we depict the relations between the parameters $M_{Z'}$, $g'_{SUSY}$, $Q_Q$, the ratio of $M_{Z'}/g'_{SUSY}$ and $\chi^2_{STU}$. Here, $g'_{SUSY}$ is the coupling constant for the $U(1)'$ group at the SUSY-breaking scale. The color bar of the upper panels shows the $\chi^2_{STU}$ values for solutions with $\chi^2_{STU} \leq 8.025$ while the color bar of the left bottom panel represents the gauge coupling $g_{SUSY}$. According to the top left panel of Fig. 1, the ratio $M_{Z'}/g'_{SUSY}$ can be as low as 2.2 TeV when the charge $Q_Q$ is small (i.e., $[1.3 \times 10^{-2}]$) while the bound on $M_{Z'}/g'_{SUSY}$ tends to increase up to 8 TeV for larger $Q_Q$ values (i.e., $1 \times 10^{-1}$). Further, the top right and bottom left panel of Fig. 1 shows that light $Z'$ solutions consistent with the constraints given in Table 3 can be found to lie around 1.5 TeV. For heavier $Z'$ masses, the range for the ratio $M_{Z'}/g'_{SUSY}$ opens up to a larger interval. As seen from the bottom panels of the figure, the lowest bound on the ratio $M_{Z'}/g'_{SUSY}$ can be fulfilled at 2117 GeV when $M_{Z'} = 1388$ GeV, the corresponding gauge coupling being $g'_{SUSY} \simeq 0.66$, $Q_Q = 1.11 \times 10^{-2}$ and $\chi^2_{STU} = 2.64$. The lowest bound on $M_{Z'}/g'_{SUSY}$ increases drastically, up to 15.7 TeV, when $g'_{SUSY}$ has its minimum value 0.25, $M_{Z'} = 3940$ GeV and $\chi^2_{STU} = 6.01$.

In Fig. 2 top left panel, we present the comparison of $\sigma(pp \to Z') \times \text{BR}(Z' \to \ell\ell)$ vs $M_{Z'}$ consistent with the ATLAS data of [10], scanning through the whole parameter space and displaying the values of $\text{BR}(Z' \to \ell\ell)$ in different color codes. The experimental constraints are the same as in Fig. 1 except that we relax the $\chi^2_{STU}$ value, since we want to plot the branching ratios (BR) also for light $Z'$ solutions which are excluded by the $\chi^2_{STU}$ bound. Since we fix $Q_\ell = Q_\tau = 0$, the $Z'$ state does not couple to $\ell\ell$. However, the small mass mixing $Z - Z'$ still allows the $Z'$ to decay into

| Observable         | Constraints       | Ref. | Observable         | Constraints       | Ref. |
|--------------------|-------------------|------|--------------------|-------------------|------|
| $m_{h_1}$          | $[122, 128]$ GeV  | [37] | $m_{h_1}$          | $\geq 730$ GeV    | [38] |
| $m_{\tilde{g}}$    | $> 1.75$ TeV      | [38] | $m_{\chi_i^+}$    | $\geq 103.5$ GeV  | [38] |
| $m_{\tilde{\tau}_1}$ | $\geq 105$ GeV    | [38] | $m_{\tilde{\tau}_1}$ | $> 81$ GeV       | [38] |
| $m_{\tilde{\ell}}$ | $> 107$ GeV       | [38] | $m_{\tilde{\ell}}$ | $> 94$ GeV        | [38] |
| $\chi^2_{STU}$     | $\leq 8.025$      |      | $\text{BR}(B \to \tau\nu)$ | $[1.1, 6.4] \times 10^{-9}$ | [39] |
| $\chi^2_{SM}(B \to \tau\nu)$ | [0.15, 2.41] | [40] | $\text{BR}(B \to X_s \gamma)$ | $[2.99, 3.87] \times 10^{-4}$ | [41] |

Table 3. Current experimental and theoretical bounds used to determine consistent solutions in our scans.
Figure 1. The effect of oblique parameters and $(g - 2)_\mu$ experimental bounds on the ratio $M_{Z'}/g'$.

$\ell\ell$ states, but only with BRs of 0.01% for $M_{Z'} \simeq 600$ GeV while the BR decreases drastically for heavier $Z'$ masses. The ATLAS observed limit on the fiducial cross section times BR ranges from 3.6 (13.1) fb at 250 GeV to about 0.014 (0.018) fb at 6 TeV for a zero (10%) relative width signal in the combined di-lepton channel [10]. Therefore, our results imply a lower limit of $\sim 700$ GeV at the 95% CL on $M_{Z'}$ for the $Z'$ boson in the combined di-lepton channel. In the top right panel of Fig. 2 we compare the CMS high-mass di-jet yield from Ref. [12] with our predictions for $\sigma(pp \to Z') \times \text{BR}(Z' \to q\bar{q})$, obtained after scanning the secluded UMSSM parameters as described in Table 2 and imposing the constraints of Table 3. For the sake of consistency with the experimental analysis, the $\sigma \times \text{BR}$ rate is multiplied by an acceptance factor $A = 0.5$ and the fraction of $Z' \to t\bar{t}$ events is not included in the calculation.

These results are similar to those found in $Z'$ models which employ gauge kinetic mixing to achieve leptophobia. However, there are some differences. One is that, while in these other scenarios the di-jet BR of the $Z'$ cannot be lowered below 36%, in the secluded UMSSM it can be lowered to 5%. Another important aspect is that the model is also $d$-quark-phobic (the BR of $Z'$ to $d$-type quarks is only about 1.4%). This is a direct consequence of different $U(1)'$ charge assignments. Leptophobia and $d$-quark-phobia have thus further lowered the bound on the $Z'$ mass by lowering its production cross section. Also, we benefit from new experimental acceptance ($A = 0.5$ with the new data at $\mathcal{L} = 137$ fb$^{-1}$ [12], compared to $A = 0.6$ at $\mathcal{L} = 27$ fb$^{-1}$ and 36 fb$^{-1}$ [42]). From the top right panel of Fig. 2, one learns that the computed $\sigma \times \text{BR}$ is always below the CMS exclusion limits [12, 42] in the range $1.5$ TeV $< M_{Z'} < 6$ TeV at the 95% CL, with the exception of a tiny region around $M_{Z'} \simeq 2.3$ TeV. One can, therefore, conclude that much lighter $Z'$ bosons consistent
with the constraints given in Table 3 could be allowed by data when leptophobic secluded UMSSM realizations, such as the one introduced in section 2, are considered. In the middle left panel, we check the ratio $\Gamma(Z')/M_{Z'}$ to assure that the Narrow Width Approximation (NWA) can be used consistently while in the middle right panel we investigate the variation of the $Z'$ mass limit with the $Q_Q$ charge, $Q_Q = \alpha$, the free parameter for the matter fields in the secluded $U(1)'$ group. As seen from the color bar in the middle left panel, the $Z'$ is quite narrow for the solutions found while the color bar of the middle right panel indicates that also the $\alpha$ parameter should be quite small (less than $\alpha < 2 \times 10^{-1}$). Moreover, one can see the correlation between $\alpha$ and $\Gamma(Z')/M_{Z'}$. When $\alpha$ is increased, the $\Gamma(Z')/M_{Z'}$ ratio also increases and approaches the CMS observed limits. As seen from the bottom left panel of Fig. 2, $M_{Z'}/g'$ ratios below $\sim 3$ TeV require a decay width smaller than 1% and a $Q_Q$ value smaller than $\sim 2 \times 10^{-2}$. Finally, the bottom right panel of Fig. 2 shows the relation between various $Z'$ masses and the $U(1)'$ charges for the $S_1$, $S_2$ and $S_3$ secluded singlets, where we set $Q_{S_1} = Q_{S_3} = -Q_{S_2}/2 = \delta$ for simplicity. Solutions with lighter $Z'$ masses necessitate smaller $\delta$ values while $\delta$ values increase for heavier $Z'$ masses. This relation can be understood via Eq. 2.7.
Figure 2. Leptophobic $Z'$ mass limits ($Q_e = Q_\ell = 0$). We investigate the $Z'$ production cross section multiplied by the di-lepton and di-jet BR (and by the acceptance $A = 0.5$ for the latter), respectively. We compare theoretical predictions of the secluded UMSSM to the bounds obtained by the ATLAS [10] and CMS [12] collaborations.

5 Dark Matter

In this section, we analyze the model parameters which survive cosmological bounds from the DM experiments. We investigate the constraints on the model arising from requiring the lightest neutralino to be a viable DM candidate, with properties compatible with current cosmological data. First, we demand that the predicted relic density agrees within 20% (to conservatively allow for uncertainties on the predictions) with the recent Planck results, $\Omega_{\text{DM}} h^2 = 0.12$ [43, 44]. We calculate, for all points returned by our scanning procedure in Table 2 that are in addition
compatible with current experimental bounds given in Table 3, the associated DM relic density. We present our results in Fig. 3.

In all the subfigures, the relic density is plotted as a function of the mass of the lightest neutralino, denoted by $M_{\tilde{\chi}_1^0}$. As seen from the panels, solutions consistent with the relic density constraint emerge for almost all values of $M_{\tilde{\chi}_1^0}$ depending on the $\tilde{\chi}_1^0$ composition, which is given in the following basis: ($\tilde{B}'$, $\tilde{B}$, $\tilde{W}$, $\tilde{H}_u$, $\tilde{H}_d$, $\tilde{S}$, $\tilde{S}_1$, $\tilde{S}_2$, $\tilde{S}_3$). The color bar of the top left panel of Fig. 3 shows the $S$ content, as we are particularly interested in singlinos as non-MSSM LSP candidates. One can learn from this panel that the relic density observed by the Planck collaboration can be accommodated by $S$-like $\tilde{\chi}_1^0$'s lying roughly in the [25, 300] GeV window, region largely disallowed for MSSM neutralinos. Once the lightest neutralino spectrum becomes heavier, the contribution of the combination of $\tilde{S}_1$, $\tilde{S}_2$ and $\tilde{S}_3$ singlets increases, so as to become dominant for $M_{\tilde{\chi}_1^0}$ heavier than 400 GeV, as seen from the upper right panel of Fig. 3. In the middle left panel, we focus on the combined contribution of all singlinos, that is, $S$, $\tilde{S}_1$, $\tilde{S}_2$ and $\tilde{S}_3$. As seen from the panel, singlino-like LSP solutions largely dominate the parameter space. The middle right panel shows the higgsino-like neutralino content. As observed from the panel, the relic density is at the scale of $10^{-3}$ for higgsino-like neutralino with $M_{\tilde{\chi}_1^0} \sim 100$ GeV, but it increases dramatically for heavier higgsino-like neutralino masses. As in the MSSM, the relic density observed by the Planck collaboration can be accommodated by higgsino-like solutions at roughly $\sim 1$ TeV. Since TeV scale neutralino solutions are naturally less appealing from a collider point of view and we want to pay particular attention to singlino LSP scenarios, we did not increase the scanned neutralino mass range beyond 1 TeV. Although potentially viable scenarios could be obtained for even heavier neutralinos (in particular, for winos), for the purpose of this work, we ignore this regime throughout. The bottom left panel of Fig. 3 represents the bino composition of the lightest neutralino. Note that only solutions with bino contribution larger than 20% are represented in the panel. Although there are some bino dominated $\tilde{\chi}_1^0$ solutions in our spectrum, their corresponding relic density mostly tends to lie in the [10, 100] range. An important fact is that the lightest bino-like solutions can be obtained near 300 GeV. Bino contributions start to decrease, yielding lower values of the relic density, and giving a maximum 50% contribution, when the relic density constraint is satisfied and $M_{\tilde{\chi}_1^0} \sim 400$ GeV. The other $\sim 50\%$ contributions to mostly bino-like solutions consistent with the relic density constraint mainly come from higgsinos and winos, both of which contribute more significantly for heavier $\tilde{\chi}_1^0$ masses, up to roughly 850 GeV, where we can classify the DM as mixed neutralino states. We summarize the various lightest neutralino DM compositions in the bottom right panel of Fig. 3. As seen from this panel, bino dominated neutralino solutions cannot be good candidates for DM since they do not satisfy the relic density constraints. Viable mixed (mostly bino and higgsino) neutralino DM solutions can be found with a mass lying in the $400-800$ GeV range. When the spectrum is heavier, i.e., with a lightest neutralino $M_{\tilde{\chi}_1^0} \in [0.8-1.0]$ TeV, the relic density as observed by the Planck collaboration can be accommodated by higgsino or singlino dominated solutions. It should be noted that $\tilde{B}'$ contributions are no more than 5% in the whole parameter space. Given that we mostly focus on small $Q_Q$ values, this leads to small couplings with the gaugino $\tilde{B}'$ associated with the $U(1)'$ gauge group, so relatively small $\tilde{B}'$ contributions are expected.

Finally, we depict, in Fig. 4, the constraints coming from direct detection experiments. The top panels show the spin-independent cross section for the nucleon as a function of the mass of the lightest neutralino. Note that the results for spin-independent cross sections for proton and neutron are almost the same. Therefore, we denoted it as $\sigma_{\text{nucleon}}^\text{SI}$ and normalised it to the present-day relic density. The top left plane shows how the spin-independent cross section for the nucleon depends on the composition of the lightest neutralino for solutions which survive all the constraints given in Table 3. Blue solutions in the top right panel refer to all solutions represented in the top left plane whilst all the other colors are subsets of blue and represent solutions consistent with the relic
Figure 3. Relic density predictions for secluded UMSSM scenarios satisfying all the constraints imposed during our scan and compatible with $Z'$ bounds from the LHC, indicating the dependence on the mass of the lightest neutralino. In each panel of the figure, we analyze the composition of the LSP for different parameter regions. In the upper left panel, we represent by a color code the $\tilde{S}$-like contribution, whilst in the upper right panel, we show the combined contribution of $\tilde{S}_1$, $\tilde{S}_2$ and $\tilde{S}_3$. In the middle left panel, we show the total contribution from the singlinos while, in the middle right panel, we present the composition of MSSM-like higgsinos. The bottom left panel shows the contributions of the mostly-bino solution while, in the bottom right panel, we indicate the parameter space populated by all the solutions. The horizontal green band in all panels indicates the measured value of the relic density, consistent at 2σ with the Planck experiment [43, 44].

density constraint in addition to the ones in Table 3. The black line indicates the limits from the Xenon 1T [45] with the region above the curve being excluded. In addition, the blue and red lines
show the prospects for XENON nT and DARWIN [46] collaborations, respectively. As seen from the top left plane, almost all singlino solutions survive the results of the Xenon 1T experiment [45] while some portion of higgsino and bino dominated solutions are excluded. Another important feature is that all mixed neutralino solutions are strictly excluded by Xenon 1T. Once we compare our solutions consistent with the relic density bound to the result of Xenon 1T, a large fraction of higgsino dominated solutions consistent with the former are excluded by the latter as seen from the top right figure. In contrast, singlino DM solutions consistent with the relic density bound are always below the excluded region by Xenon 1T and can be probed by the next generation of DM experiments such as Xenon nT and Darwin.

Whilst we have demonstrated that the singlino-type lightest neutralino could be a viable DM candidate from the point of view of the relic density and direct detection bounds, at the same time it is important to verify that DM indirect detection bounds are also satisfied. In the bottom panels of Fig. 4, we present the value of the total DM annihilation cross section at zero velocity as a function of the lightest LSP neutralino mass for all scanned scenarios satisfying the $Z'$ boson limits from the LHC. Configurations for which the relic density is found in agreement with Planck data are shown along with their higgsino, singlino and mixed compositions in the bottom right panel, whilst any other setup returned by the scan is shown in light sky-blue and tagged as “Main Constraints”, referring to those given in Table 3. In our predictions, we rescaled also the DM annihilation cross section to its present-day density. We compare our predictions to the latest bounds derived from the Fermi-LAT data [47, 48]. We depict, as a yellow area, the parameter space region that is found out to be excluded. The bottom panel of Fig. 4 indicates that, unlike relic density and direct detection bounds, which impose strong constraints on the model parameters, indirect detection experiments are easily satisfied for a large portion of the parameter space. Most singlino DM scenarios naturally feature an annihilation cross section that is at least 3 or 4 orders of magnitude too small to leave any potentially visible signal in Fermi-LAT data. Therefore, singlino DM solutions are unaffected by current indirect detection limits and will potentially stay so for some time by virtue of their correspondingly small annihilation cross sections. In contrast, the annihilation cross sections of higgsino and mixed neutralino solutions are about $10^{-26}$ cm$^3$ s$^{-1}$, hence, they are more likely to be probed by Fermi-LAT when the precision of the annihilation cross section measurement will be improved.
Figure 4. DM direct and indirect detection constraints on the parameter space on the secluded UMSSM model. The top panels show the constraints from the spin-independent cross section for the nucleon while the bottom panels show the corresponding annihilation cross sections.

6 Muon anomalous magnetic moment

The measurement of the muon anomalous magnetic moment exhibits an intriguing discrepancy between the value found from the E821 experiment at BNL [49] and the value predicted by the SM. Adding uncertainties, the deviations amount to 3.5 $\sigma$ [38, 50] while recent theory predictions for $a_\mu$ find values as large as 4.1 $\sigma$,

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \times 10^{-11}.$$ 

Several models have been constructed and dedicated entirely to explain this discrepancy. Conversely, whether the discrepancy is real or not, it has been used as a test of how well BSM scenarios perform.

In the secluded UMSSM, loop diagrams with additional neutralinos and sleptons as well as with (right) sneutrinos and charginos provide additional contributions to the $(g - 2)_\mu$ observable. We present the results of our analysis in Fig. 5, where we show solutions consistent with the muon anomalous magnetic moment within 1$\sigma$ of the experimental value. Here, we indicate the model solutions over the following planes: $(M_{\tilde{\chi}^\pm_1}, M_{\tilde{\chi}^0_1})$ (top left); $(M_{\tilde{\chi}^\pm_1}, M_{\tilde{\chi}^0_2})$ (top right); $(M_{\tilde{\chi}^\pm_1}, M_{\tilde{\chi}^0_3})$ (bottom left) and $(M_{\tilde{\nu}_1}, M_{\tilde{\tau}_1})$ (bottom right). When the lightest neutralino is singlino, the second and the third lightest ones are higgsino-like, rather light and almost degenerate in mass. The main contribution to the muon anomalous magnetic moment comes from these two heavier states as well.

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3Leading order hadronic vacuum polarization contributions represent the main limitation of theoretical calculations of non-perturbative low-energy QCD behavior.
Figure 5. Parameter regions of chargino, neutralino, (right) sneutrino and stau masses consistent with $\Delta a_\mu$ within 1σ. We show the following mass mappings: (top left) lightest chargino versus lightest neutralino; (top right) lightest chargino versus second lightest neutralino; (bottom left) lightest chargino versus third lightest neutralino; (bottom right) lightest (right) sneutrino versus lightest stau. The grey region is ruled out by ATLAS searches for chargino-neutralino states [51, 52]. The model solutions to the $(g-2)_\mu$ discrepancy are dominated by the neutralino (higgsino-like)-slepton and chargino-sneutrino loop contributions, where, in particular, the contributing neutralinos and charginos are light yet consistent with all experimental constraints.

as (albeit more marginally) from the lightest (right) sneutrino and (through slepton-mixing) stau states, in the appropriate diagrammatic combinations. As seen from the figure, a large portion of the solutions satisfies the $\Delta a_\mu$ bound within 1σ. The grey region below the black curve represents the parameter space ruled out by ATLAS searches [51, 52], close to which most solutions are found.

7 $Z'$ signal at colliders

In this section, we investigate the observability of a secluded UMSSM scenario with light $Z'$ masses at LHC. To choose correct benchmarks, we first compare the range of chargino and neutralino masses with restrictions from the ATLAS searches for chargino/neutralino states [51, 52]. We make use of SModelS (version 1.2.2) [53–56] in order to calculate the upper limit on the chargino-neutralino cross sections based on ATLAS-SUSY-2019-08 [51] and ATLAS-SUSY-2018-32 [52] implemented and validated with the SModelS authors. Fig. 6 showcases our results in terms of the lightest chargino and neutralino masses, as functions of the ratio between our calculated cross sections versus the upper limit on the chargino-neutralino cross sections. We exclude all solutions with signal strength value exceeding 1. This plot is complementary to the one shown in Fig. 5 top left panel, with the grey region in that plot corresponding to the area below the curve. While in the former plot we indicate muon $(g-2)_\mu$ values consistent with experiment, here we explore neutralino and chargino masses constrained by bounds given in Table 3, with the aim to choose benchmarks compatible with allowed EW-ino masses. Our plot indicates, however, that the parameter space
Figure 6. (Left) Neutralino-chargino mass limits in secluded UMSSM. The black curve represents mass limits from ATLAS [51, 52], while our analysis rules out only points which exceed the upper limits on the chargino-neutralino cross sections, as indicated on the right-side color bar (which gives our predicted cross section measured against the limits from ATLAS). (Right) $Z'$ production cross sections multiplied by the di-jet BRs (and by the acceptance $A = 0.5$).

\[
\tan \beta \quad \lambda \quad A_\lambda \quad \kappa \quad A_\kappa \quad \alpha \quad \delta \quad Y^{ij}_{\nu}
\]

|   | m_0 | $M_{1/2}$ | $A_0$ | $v_S$ | $v_{S_1} = v_{S_2} = v_{S_3}$ |
|---|-----|----------|------|-------|--------------------------------|
| BM I | 942 | 2821 | 662 | 2421 | 5401 |
| BM II | 1722 | 2568 | -1092 | 2282 | 6935 |

Table 4. Set values for the free secluded UMSSM parameters defining our benchmark scenarios BM I and BM II. Here, $m_0$ is the universal scalar mass and $M_{1/2}$ the gaugino mass.

allowed by this model is less restrictive than the one in the ATLAS analysis. We rule out some points for low chargino-neutralino masses (in red, lower left-hand corner) but allow the purple-blue points in the upper right-hand corner. Of particular interest is a region specific to this model, which allows singlino masses $\lesssim 50$ GeV and chargino masses $\lesssim 350$ GeV, region ruled out for neutralinos and charginos in the MSSM. We shall concentrate our analysis in this parameter region.

Scanning over the whole range of allowed $Z'$ mass values, we find that consistency with ATLAS production and di-lepton decay results allows $M_{Z'}$ to be quite light. However, for the parameter space to satisfy both DM and muon anomalous magnetic moment constraints to at least 2$\sigma$, the $Z'$ mass must be $M_{Z'} \gtrsim O(3)$ TeV as seen from the right plane of figure 6. To highlight the model characteristics, we chose two benchmarks, BM I and BM II. The first benchmark is consistent with all constraints, including relic density, and satisfies the bounds on the $g - 2$ factor of the muon at 1$\sigma$. The second benchmark satisfies the same constraints, except that we relax requirements on consistency with the anomalous magnetic moment of the muon. We list the values of the relevant free parameters in the model in Table 4 and the corresponding mass values for the fermions and bosons in the model in Table 5.

While scanning over the parameter space consistent with all constraints, we were unable to find any allowed parameter space for which $M_{Z'} < 3.3$ TeV (BM I). Relaxing the imposed constraints on the anomalous magnetic moment of the muon completely (for BM II), while requiring agreement
with the measured relic density, still poses rigid constraints on the parameter space, but allows a lower $M_{Z'} \sim 2.3$ TeV. The relevant predictions for BM I and BM II for the DM and $(g-2)_\mu$ observables discussed in the above sections are shown in Table 6. To test the signal coming from production and decay of the leptophobic $Z'$ boson, we use its decay into supersymmetric particles, here into chargino pairs, followed by the decay into lepton pairs or jets plus missing energy$^4$. The decay of the lightest chargino yielding lepton or jet final states is into $\tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 W^\pm$ and we choose points for which this BR is almost 1, as shown in Table 7. In the same table, we show predictions for the LHC phenomenology of our two benchmark scenarios, including the production cross sections at a centre-of-mass energy $\sqrt{s} = 13, 14, 27$ and 100 TeV, plus the dominant BRs of the $Z'$. For both scenarios, $Z'$ boson production is small enough relatively to the LHC limits at a centre-of-mass energy of 13 TeV. The cross section is about 0.016 fb for BM I and 0.1889 fb for BM II after accounting for the $Z'$ bosons decaying into electron and muon pairs through two chargino states. Consequently this makes the $Z'$ signal difficult to observe, even with more luminosity at a centre-of-mass energy of 13 TeV.

The $Z'$ production cross section is therefore about 0.33 fb for BM I and 3.82 fb for BM II at 13 TeV, after accounting for the $Z'$ bosons decaying into all SM fermions (quarks + leptons) via two chargino states, giving rise to a multi-jet plus missing energy signature. The latter is also typically expected from supersymmetric squark/gluino production and decay, so that the results of SUSY searches in the multi-jet plus missing energy mode could be reinterpreted to constrain the secluded UMSSM. We therefore recast these results from [57–60] with MadAnalysis 5. However, such a rate is far beyond the reach of typical multi-jet plus missing transverse momentum searches at the LHC, as confirmed by reinterpreting and extrapolating the results of the CMS search in [59] and the results of the ATLAS search in [57, 58, 60] targeting superpartner production and decay in the jets plus missing transverse momentum mode to integrated luminosity of 3 ab$^{-1}$ with MadAnalysis 5. Consequently, this makes the $Z'$ signal difficult to observe in di-jet final states, even with more luminosity. We therefore focus on $Z'$ signals that instead involve di-leptons in the final state at a centre-of-mass energy of 14 TeV and 27 TeV.

The study of [11] provides a prescription for finding leptophobic $Z'$ bosons at the center-of-mass energy $\sqrt{s} = 14$ TeV and 3 ab$^{-1}$ of luminosity in the di-lepton channel. The signal process consists of the resonant production of a chargino pair, followed by the decay of each chargino into a charged lepton and missing energy,

$$pp \rightarrow Z' \rightarrow \tilde{\chi}^+_1 \tilde{\chi}^-_1 \rightarrow \ell^+ \ell^- + E_T.$$  \hspace{1cm} (7.1)

$^4$The decay into chargino pairs is not the only one yielding the required di-lepton (or jets) + missing $E_T$ signal, but it dominates other intermediate steps by a few orders of magnitude.
We followed the same procedure and carried out a full Monte Carlo (MC) event simulation at the LHC, for a center-of-mass energy $\sqrt{s} = 14$ TeV and applied the cuts as in [11]. The production cross section of $Z'$ boson is 17.1 fb for BM I and 146.1 fb for BM II for a center-of-mass energy $\sqrt{s} = 14$ TeV as given in Table 7. We have made use of SARAH to generate a UFO [28] version of the model, so that we could employ MG5_aMC (version 2.7.2) [30] for generating the hard-scattering signal event samples necessary for our collider study. These events, obtained by convoluting the hard-scattering matrix elements with the leading-order set of NNPDF 3.1 parton densities [61], were subsequently matched with Pythia 8 (version 8.244) [62] parton showering and hadronisation algorithms, plus we simulated the typical response of an LHC detector by means of the Delphes 3 [63] programme (version 3.4.2) employing the Snowmass parameterization [64, 65] that relies on the anti-$k_T$ algorithm [66] with a radius parameter $R = 0.6$ as implemented into FastJet [67] (version 3.3.3) for event reconstruction. We have employed MadAnalysis 5 [68] (version 1.8.23) and normalized our results to an integrated luminosity of $3 \text{ ab}^{-1}$ for the collider analysis.

We select events featuring two well-separated muons and veto the presence of jets, by requiring

$$N^\ell = 2, \quad \Delta R(\ell_1, \ell_2) > 2.5, \quad N^j = 0.$$  \hfill (7.2)

The transverse momenta of the two leptons and the missing transverse energy are required to fulfil

$$p_T(\ell_1) > 300 \text{ GeV}, \quad p_T(\ell_2) > 200 \text{ GeV}, \quad E_T > 100 \text{ GeV}. \hfill (7.3)$$

To investigate the observability of the two benchmarks at the HL-LHC, we use of two standard significance parameters, labelled as $s$ and $Z_A$ (the Asimov significance), defined as:

$$s = \frac{S}{\sqrt{B + \sigma_B^2}}, \hfill (7.4)$$

$$Z_A = \sqrt{2 \left( (S + B) \ln \left[ \frac{(S + B)(S + \sigma_B^2)}{B^2 + (S + B)\sigma_B^2} \right] - \frac{B^2}{\sigma_B^2} \ln \left[ 1 + \frac{\sigma_B^2 S}{B(B + \sigma_B^2)} \right] \right)}, \hfill (7.5)$$

where $S$ is the number of signal events, $B$ of background events and $\sigma_B$ is the standard deviation of background events.

The corresponding cutflows are shown in Table 8, where we give our original and final number of signal events, and the ones surviving each cut, shown in the left-handed column. We assume that we would get the same cut efficiency of the background as in [11]. One can see that the significance of the benchmarks at 14 TeV and with integrated luminosity $3 \text{ ab}^{-1}$ is very small, making it unlikely to be observed, even at the HL-LHC. Therefore, we extend the analysis of our benchmark scenarios at 27 TeV, and in Table 8, we give our original and final number of signal events in parentheses. We estimate the number of background events at 27 TeV by using a boost factor calculated from the dominant background channel, the di-boson production. While BM I remains below the $3\sigma$ minimum significance required for a positive identification, the BM II significance rises above $3\sigma$ at $\sqrt{s} = 27$ TeV and integrated luminosity $3 \text{ ab}^{-1}$, making this benchmark promising at the HE-LHC. That this indeed so is seen in Fig. 7, where we plot significance curves for $s$ and $Z_A$ at $\sqrt{s} = 27$ TeV, for both BM I and BM II, as a function of the total integrated luminosity $L$. While BM I would be observable at high integrated luminosity $3 \text{ ab}^{-1}$ at $3\sigma$ under only the most optimistic scenario, in which we assume small systematic errors ($\Delta_{\text{syst}} = 5\%$), BM II shows promise for observability even for larger systematic errors, $\Delta_{\text{syst}} = 20\%$. Of course, we stress that, while BM II is promising, it was obtained by relaxing the condition that the model satisfies $(g-2)_{\mu}$ to (1-2)$\sigma$. 

Table 6. Predictions for the BM I and BM II scenarios, of the observables discussed in our dark matter analysis.

|          | σ(pp → Z') | BR(Z' → \tilde{\chi}_1^± \tilde{\chi}_1^∓) | BR(Z' → jj) | BR(\tilde{\chi}_1^± → \tilde{\chi}_0^W\tilde{\chi}_1^±) |
|----------|-------------|-------------------|--------------|----------------|
|          | 13 TeV  | 14 TeV | 27 TeV | 100 TeV |
| BM I     | 12.09 | 17.1 | 169.3 | 2474 | 0.059 | 0.309 | 0.99 |
| BM II    | 113.7 | 146.1 | 862.2 | 8638 | 0.066 | 0.340 | 1.0 |

Table 7. Z' production cross section at \(\sqrt{s} = 13, 14, 27\) and 100 TeV and branching ratios for the BM I and BM II scenarios, relevant for the associated LHC phenomenology.

Step Requirements | BM I | BM II |
|------------------|------|-------|
| 0 Initial        | 71   | 726   |
| 1 \(N^f = 2\)   | 45   | 386   |
| 2 Electron Veto  | 13   | 115   |
| 3 \(|p_T^f| < 1.5\)| 13   | 112   |
| 4 \(p_T^{\ell} < 0.15\) | 13   | 107   |
| 5 \(\Delta R(\ell_1, \ell_2) > 2.5\) | 11   | 107   |
| 6 \(N^j = 0\)   | 11   | 60    |
| 7 \(p_T(\ell) > 300\) GeV | 6    | 17    |
| 8 \(p_T(\ell) > 200\) GeV | 2    | 6     |
| 9 \(E_T > 100\) GeV | 2    | 4     |

Table 8. Events surviving after each cut (as given in the left column) and significance of BM I and BM II at 14 (27) TeV and integrated luminosity 3 ab\(^{-1}\).

Figure 7. Significance of benchmarks BM I (left panel) and BM II (right panel) at \(\sqrt{s} = 27\) TeV, as a function of the luminosity \(L\). In each panel we plot the usual significance \(s\) and the Asimov significance \(Z_A\). Different curves are obtained assuming different systematic errors, as indicated in the upper left-hand panel.
8 Summary and Conclusions

We have presented an analysis of the secluded UMSSM, a non-minimal SUSY scenario wherein the gauge symmetry of the MSSM is augmented by a $U(1)'$ group and where a secluded sector is also added in the form of three additional scalar superfields. Their role is to separate the SUSY-breaking scale from the mass of the $Z'$, the gauge boson introduced by the additional gauge symmetry following its spontaneous breaking, so that the latter can have a value well within the LHC reach irrespectively of the SUSY mass scale.

Our analysis here has highlighted, in particular, some novel phenomenological features pertaining to this BSM scenario, which would make it distinguishable from the MSSM or $E_6$ motivated UMSSM scenarios. For a start, the $Z'$ can be leptophobic without invoking gauge kinetic mixing. Thus one can naturally lower the experimentally imposed limits on its mass coming from its LHC hadroproduction followed by di-lepton and di-jet decays. In addition, and setting it apart from that of $U(1)'$ scenarios with gauge kinetic mixing, the $Z'$ is also $d$-quark-phobic, allowing one to reduce its mass constraints even further.

Then, we have shown that the model predicts the existence of very light charginos and neutralinos, the lightest of the latter being a singlino-like DM candidate satisfying relic density constraints as well as direct and indirect detection bounds. In fact, alongside this new singlino state, an LSP with mass $M_{\tilde{\chi}_1^0} \lesssim 50$ GeV, our BSM scenario also accommodates a similarly lightest chargino companion, with $M_{\tilde{\chi}_1^\pm} \lesssim 350$ GeV, both of which are respecting collider constraints. Furthermore, the next-to-LSP and next-to-next-to-LSP are higgsinos and, together with the lightest chargino, they are largely responsible (once appropriately combined with the lightest sleptons in one-loop Feynman diagrams) for obtaining a value for the muon anomalous moment consistent with experimental measurements at $1\sigma$.

Finally, armed with such specific model setup, we have investigated the prospects of detecting such a light $Z'$ boson in its SUSY cascade decays via the aforementioned lightest charginos and neutralinos, eventually yielding a di-lepton final state in presence of significant missing transverse energy. The fact that the model is $d$-quark phobic, useful to reduce the mass constraints, has an adverse effect on the production cross section for $Z'$, rendering it smaller than in the $E_6$ motivated UMSSM. In addition, the $S,T,U$ parameters impose conditions on the $U(1)'$ associated charges, constraining them to be small. The secluded UMSSM is a good model for loosening $Z'$ mass bounds, but no so promising for signal observability.

Requiring the parameter space to satisfy all experimental conditions, including the DM and $(g-2)_\mu$ ones simultaneously, or just the relic density, we have devised most favourable benchmark points with $M_{Z'} \approx 3.3$ TeV. Relaxing the $(g-2)_\mu$ requirement, our second benchmark allows $M_{Z'} \approx 2.3$ TeV. Of the two benchmarks, the latter one shows more promise to be observed at the HE-LHC at $3\sigma$ or better, as proved from a prototypical MC analysis performed, while the former would be observed only assuming small systematic errors. Our analysis should justify dedicated searches with real data from ATLAS and/or CMS.

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