# Resolving the $(g-2)_\mu$ discrepancy with $\mathcal{F}$–SU(5) intersecting D-branes

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ABSTRACT: A discrepancy between the measured anomalous magnetic moment of the muon $(g-2)_\mu$ and computed Standard Model value now stands at a combined $4.2\sigma$ following experiments at Brookhaven National Lab (BNL) and the Fermi National Accelerator Laboratory (FNAL). A solution to the disagreement is uncovered in flipped SU(5) with additional TeV-Scale vector-like $\mathbf{10} + \overline{\mathbf{10}}$ multiplets and charged singlet derived from local F-Theory, collectively referred to as $\mathcal{F}$–SU(5). Here we engage general No-Scale supersymmetry (SUSY) breaking in $\mathcal{F}$–SU(5) D-brane model building to alleviate the $(g-2)_\mu$ tension between the Standard Model and observations. A robust $\Delta a_\mu(\text{SUSY})$ is realized via mixing of $M_5$ and $M_{1X}$ at the secondary SU(5) × U(1)$_X$ unification scale in $\mathcal{F}$–SU(5) emanating from SU(5) breaking and U(1)$_X$ flux effects. Calculations unveil $\Delta a_\mu(\text{SUSY}) = 19.0$–$22.3 \times 10^{-10}$ for gluino masses of $M(\widetilde{g}) = 2.25$–$2.56\,\text{TeV}$ and higgsino dark matter, aptly residing within the BNL+FNAL $1\sigma$ mean. This $(g-2)_\mu$ favorable region of the model space also generates the correct light Higgs boson mass and branching ratios of companion rare decay processes, and is further consistent with all LHC Run 2 constraints. Finally, we also examine the heavy SUSY Higgs boson in light of recent LHC searches for an extended Higgs sector.

KEYWORDS: Supersymmetry Phenomenology, Strings and branes phenomenology

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# Contents

## 1  Introduction

The Fermi National Accelerator Lab (FNAL) launched an experiment to update the original Brookhaven National Lab (BNL) analysis of the magnetic moment of the muon $(g-2)_\mu$. The BNL measurements showed an enticing $3.7\sigma$ deviation [1] from the theoretical Standard Model calculation [2–31], albeit burdened with a large factor of uncertainty. The independently conducted FNAL venture sought to either confirm or exclude these initial BNL findings. Concluding the anticipation, FNAL announced recently a similar disparity with the Standard Model value, leading to a combined $4.2\sigma$ discrepancy of $\Delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = 25.1 \pm 5.9 \times 10^{-10}$ [32], in conjunction with a reduced uncertainty by a factor of four. Even more intriguing is the magnitude of the discrepancy, which just so happens to be similar in scale to the electroweak contribution [30, 31] to $a_\mu(\text{SM})$, suggesting new physics obscured at the TeV-scale.

A natural explanation for the anomaly is supersymmetry (SUSY), certainly the most auspicious extension to the Standard Model. The muon's magnetic moment maintains the benefit of precision measurements and is rather sensitive to new physics, thus it has long been viewed as a gateway to probing SUSY. The triumphs of SUSY are numerous and well known with regards to stabilizing quantum corrections to the scalar Higgs field, gauge coupling unification, mechanism for radiatively breaking electroweak symmetry, and yielding a dark matter candidate in the form of the lightest supersymmetric particle (LSP) under R-parity. Our model we investigate here showcases intersecting D-branes, therefore a critical feature of SUSY is its fundamental presence in superstring theory.

The SUSY grand unification theory (GUT) model we study merges the realistic intersecting D6-brane model [33–47] with the phenomenologically [48–59] and cosmologically [60–69] favorable No-Scale flipped SU(5). The union of these with extra vector-like matter, dubbed flippons [50], is referred to as the $\mathcal{F}$–SU(5) D-brane model, which in aggregate reinforces deep theoretical constructions, furnishing a compelling natural GUT candidate for our universe. Serving as a viable high-energy candidate though, it must be capable of elegantly explaining any and all empirical observations, so we shall stress test the model to affirm whether or not it can indeed explain the BNL+FNAL $4.2\sigma$ discrepancy

(spoiler alert: it can!). But first we must review the $\mathcal{F}$–SU(5) D-brane model's foundation before we then take the deep dive into the calculations of $(g-2)_\mu$ and corresponding phenomenology later in the paper.

## 2 $\mathcal{F}$–SU(5) intersecting D-branes

The $\mathcal{F}$–SU(5) literature is amply stocked with discussions of the minimal flipped SU(5) model (for instance, see refs. [51, 55, 56, 58, 59, 70–72] and references therein). We shall provide here only a condensed review of the minimal flipped SU(5) model [73–75], where the gauge group $\mathrm{SU(5)} \times \mathrm{U(1)}_X$ is embedded into the SO(10) model. First, the generator $\mathrm{U(1)}_{Y'}$ in SU(5) is defined as

$$T_{\mathrm{U(1)}_{Y'}} = \mathrm{diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right),\qquad(2.1)$$

which provides the hypercharge given by

$$Q_Y = \frac{1}{5}\left(Q_X - Q_{Y'}\right).\qquad(2.2)$$

There are three families of Standard Model fermions, and the quantum numbers under $\mathrm{SU(5)} \times \mathrm{U(1)}_X$ respectively are

$$F_i = (\mathbf{10}, \mathbf{1}), \quad \bar{f}_i = (\mathbf{\bar{5}}, -\mathbf{3}), \quad \bar{l}_i = (\mathbf{1}, \mathbf{5}),\qquad(2.3)$$

with $i = 1, 2, 3$. Relevant for our D-brane model notation, we associate $F_i$, $\bar{f}_i$ and $\bar{l}_i$ with the particle assignments

$$F_i = (Q_i, D_i^c, N_i^c), \quad \overline{f}_i = (U_i^c, L_i), \quad \bar{l}_i = E_i^c,\qquad(2.4)$$

where $Q_i$, $U_i^c$, $D_i^c$, $L_i$, $E_i^c$ and $N_i^c$ are the left-handed quark doublets, right-handed up-type quarks, down-type quarks, left-handed lepton doublets, right-handed charged leptons, and neutrinos, respectively. Three Standard Model singlets $\phi_i$ can be introduced to generate heavy right-handed neutrino masses.

The GUT and electroweak gauge symmetries can now be broken, and this is accomplished by introducing two pairs of Higgs representations

$$\begin{aligned} H &= (\mathbf{10}, \mathbf{1}), \quad \overline{H} = (\mathbf{\overline{10}}, -\mathbf{1}),\\ h &= (\mathbf{5}, -\mathbf{2}), \quad \overline{h} = (\mathbf{\bar{5}}, \mathbf{2}). \end{aligned}\qquad(2.5)$$

The $H$ and $F$ multiplet states are labeled similarly, including only a "bar" added above the fields for $\overline{H}$. More precisely, the Higgs particles are

$$H = (Q_H, D_H^c, N_H^c), \qquad \overline{H} = (\overline{Q}_{\overline{H}}, \overline{D}_{\overline{H}}^c, \overline{N}_{\overline{H}}^c),\qquad(2.6)$$

$$h = (D_h, D_h, D_h, H_d), \quad \overline{h} = (\overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, H_u),\qquad(2.7)$$

such that $H_d$ and $H_u$ are a single pair of MSSM Higgs doublets.

We introduce this GUT scale Higgs superpotential to break the $\mathrm{SU}(5) \times \mathrm{U}(1)_X$ gauge symmetry down to the Standard Model gauge symmetry:

$$W_{\mathrm{GUT}} = \lambda_1 HHh + \lambda_2 \overline{HH}\overline{h} + \Phi(\overline{H}H - M_{\mathrm{H}}^2). \tag{2.8}$$

Consequently, there is only one F-flat and D-flat direction existing, which can certainly be rotated along the $N_H^c$ and $\overline{N}_{\overline{H}}^c$ directions. As a result, we obtain $\langle N_H^c \rangle = \langle \overline{N}_{\overline{H}}^c \rangle = M_{\mathrm{H}}$. Additionally, the supersymmetric Higgs mechanism allows the superfields $H$ and $\overline{H}$ to be consumed and thus acquire large masses, except $D_H^c$ and $\overline{D}_{\overline{H}}^c$. Moreover, the superpotential terms $\lambda_1 HHh$ and $\lambda_2 \overline{HH}\overline{h}$ couple $D_H^c$ and $\overline{D}_{\overline{H}}^c$ respectively with $D_h$ and $\overline{D}_{\overline{h}}$, which forms massive eigenstates with masses $2\lambda_1\langle N_H^c \rangle$ and $2\lambda_2\langle \overline{N}_{\overline{H}}^c \rangle$. Accordingly, doublet-triplet splitting naturally occurs due to the missing partner mechanism [75]. There is only a small mixing through the $\mu$ term in the triplets $h$ and $\overline{h}$, so colored higgsino-exchange mediated proton decay remains negligible, i.e., the dimension-5 proton decay problem is absent [76].

String-scale gauge coupling unification at about $10^{17}$ GeV can be realized by introducing the following vector-like particles (referred to as flippons) at the TeV scale derived from local F-theory model building [77–79]

$$\begin{aligned} XF &= (\mathbf{10}, \mathbf{1}), \quad \overline{XF} = (\overline{\mathbf{10}}, -\mathbf{1}), \\ Xl &= (\mathbf{1}, -\mathbf{5}), \quad \overline{Xl} = (\mathbf{1}, \mathbf{5}). \end{aligned} \tag{2.9}$$

Under Standard Model gauge symmetry, the particle content resulting from decompositions of $XF$, $\overline{XF}$, $Xl$, and $\overline{Xl}$ are

$$\begin{aligned} XF &= (XQ, XD^c, XN^c), \quad \overline{XF} = (XQ^c, XD, XN), \\ Xl &= XE, \quad \overline{Xl} = XE^c. \end{aligned} \tag{2.10}$$

The additional vector-like particles under the $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge symmetry have the quantum numbers

$$XQ = \left(\mathbf{3}, \mathbf{2}, \frac{1}{6}\right), \quad XQ^c = \left(\overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6}\right), \tag{2.11}$$

$$XD = \left(\mathbf{3}, \mathbf{1}, -\frac{1}{3}\right), \quad XD^c = \left(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right), \tag{2.12}$$

$$XN = (\mathbf{1}, \mathbf{1}, \mathbf{0}), \quad XN^c = (\mathbf{1}, \mathbf{1}, \mathbf{0}), \tag{2.13}$$

$$XE = (\mathbf{1}, \mathbf{1}, -\mathbf{1}), \quad XE^c = (\mathbf{1}, \mathbf{1}, \mathbf{1}). \tag{2.14}$$

The superpotential is

$$\begin{aligned} W_{\mathrm{Yukawa}} = {}& y_{ij}^D F_i F_j h + y_{ij}^{U\nu} F_i \overline{f}_j \overline{h} + y_{ij}^E \overline{l}_i \overline{f}_j h + \mu h\overline{h} + y_{ij}^N \phi_i \overline{H} F_j + M_{ij}^\phi \phi_i \phi_j \\ & + y_{XF} XFXFh + y_{\overline{XF}} \overline{XF}\,\overline{XF}\,\overline{h} + M_{XF} \overline{XF}XF + M_{Xl} \overline{Xl}Xl, \end{aligned} \tag{2.15}$$

and after the $\mathrm{SU}(5) \times \mathrm{U}(1)_X$ gauge symmetry is broken down to the Standard Model gauge symmetry, the superpotential presented directly above gives

$$
\begin{aligned}
W_{\mathrm{SSM}} = {} & y_{ij}^D D_i^c Q_j H_d + y_{ji}^{U\nu} U_i^c Q_j H_u + y_{ij}^E E_i^c L_j H_d + y_{ij}^{U\nu} N_i^c L_j H_u + \mu H_d H_u + y_{ij}^N \langle \overline{N_{\overline{H}}^c} \rangle \phi_i N_j^c \\
& + y_{XF} XQXD^c H_d + y_{\overline{XF}} XQ^c XD H_u + M_{XF} \left( XQ^c XQ + XD^c XD \right) \\
& + M_{Xl} XE^c XE + M_{ij}^\phi \phi_i \phi_j + \cdots \text{(decoupled below } M_{\mathrm{GUT}}\text{)}.
\end{aligned}
\tag{2.16}
$$

where $y_{ij}^D$, $y_{ij}^{U\nu}$, $y_{ij}^E$, $y_{ij}^N$, $y_{XF}$, and $y_{\overline{XF}}$ are Yukawa couplings, $\mu$ is the bilinear Higgs mass term, and $M_{ij}^\phi$, $M_{XF}$ and $M_{Xl}$ are new particle masses. The vector-like particle flippons are of course these new particles. The masses $M_{ij}^\phi$, $M_{XF}$, and $M_{Xl}$ have not been explicitly computed yet, reserving that in-depth project for the future. Regardless, a common mass decoupling scale $M_V$ for the vector-like multiplets is implemented.

Contributions from vector-like multiplets require changes to the one-loop gauge $\beta$-function coefficients $b_i$ that promote a flat $\mathrm{SU}(3)$ Renormalization Group Equation (RGE) running ($b_3 = 0$) [49], separating the secondary $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L$ unification around $10^{16}$ GeV, which we refer to as the mass scale $M_{32}$, and the primary $\mathrm{SU}(5) \times \mathrm{U}(1)_X$ unification near the string scale $10^{17}$ GeV, defined as the mass scale $M_{\mathcal{F}}$. This is significant as it elevates unification close to the Planck mass. The $M3$ and $M2$ gaugino mass terms and couplings $\alpha_3$ and $\alpha_2$ unify at the scale $M_{32}$ into a single mass parameter $M5$ and coupling $\alpha_5$ [48], where $M5 = M3 = M2$ and $\alpha_5 = \alpha_3 = \alpha_2$ between $M_{32}$ and $M_{\mathcal{F}}$ [49]. The flattening of the $M_3$ gaugino RGE running between $M_{32}$ and $M_V$ produces a characteristic mass texture of $M(\widetilde{t}_1) < M(\widetilde{g}) < M(\widetilde{q})$, spawning a light stop and gluino that are lighter than all other squarks [55].

Two critical effects naturally transpire at the scale $M_{32}$. First, $\mathrm{U}(1)_X$ flux effects [48] cause a small increase in $M_1$ from the evolution of $M_{1X}$ via the following

$$
\frac{M_1}{\alpha_1} = \frac{24}{25} \frac{M_{1X}}{\alpha_{1X}} + \frac{1}{25} \frac{M_5}{\alpha_5}
\tag{2.17}
$$

where $\alpha_1 = 5\alpha_Y/3$ is the $\mathrm{U}(1)_Y$ gauge coupling. Second, in the $\mathrm{SU}(5) \times \mathrm{U}(1)_X$ models motivated by D-brane model building, there exist three chiral multiplets in the $\mathrm{SU}(5)$ adjoint representation, for example, see ref. [80]. These chiral multiplets can obtain vacuum expectation values around the $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L$ unification scale $M_{32}$, and then the gaugino masses for $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_{Y'}$ of $\mathrm{SU}(5)$ can be split due to the high-dimensional operators [81, 82]. Because the bino mass is a linear combination of the $\mathrm{U}(1)_{Y'}$ and $\mathrm{U}(1)_X$ gaugino masses, the bino mass $M_1$, wino mass $M_2$, and gluino mass $M_3$ can be independent free parameters at $M_{32}$. Thus, we shall consider such effects by introducing the following relationship at the scale $M_{32}$ that stimulates mixing between $M_5$ and $M_{1X}$:

$$
M_2 = \frac{18}{25} M_5 - \frac{7}{25} M_{1X} .
\tag{2.18}
$$

This effect drives the wino to small values at the electroweak scale and we use the resulting phenomenology to constrain the coefficients in eq. (2.18). A larger contribution from $M_5$ decreases the wino contribution to $(g-2)_\mu$. On the contrary, a smaller contribution from

$M_5$ shifts the $SU(3)_C \times SU(2)_L$ unification scale $M_{32}$ lower, to below $10^{16}$ GeV. The lower $M_{32}$ in turn pushes the proton decay rate $\tau_p(p \to e^+\pi^0)$ down to unacceptably fast time periods of $10^{34}$ yrs or less. We study the nominal mixing highlighted in eq. (2.18) in this analysis, though plan a more in-depth study later regarding maximum limits on the mixing parameters of eq. (2.18).

Following upon the $F_i$, $\bar{f}_i$, and $\bar{l}_i$ of eq. (2.4), the general No-Scale SUSY breaking soft terms at $M_{\mathcal{F}}$ are $M_5$, $M_{1X}$, $M_{QD^cN^c}$, $M_{U^cL}$, $M_{E^c}$, $M_{H_u}$, $M_{H_d}$, $A_\tau$, $A_t$, and $A_b$. Note that $M_{QD^cN^c}$ is the **10**, $M_{U^cL}$ is the $\bar{\mathbf{5}}$, and $M_{E^c}$ is the **1** of eq. (2.3). General SUSY breaking soft terms of this type are motivated by D-brane model building [80], where $F_i$, $\bar{f}_i$, $\bar{l}_i$, and $h/\bar{h}$ arise from intersections of different stacks of D-branes. As a result, the SUSY breaking soft mass terms and trilinear $A$ terms will be different. The Yukawa terms $HHh$ and $\overline{HHh}$ of eq. (2.8) and $F_iF_jh$, $XFXFh$, and $\overline{XFXFh}$ of eq. (2.15) are forbidden by the anomalous global U(1) symmetry of U(5), nonetheless, these Yukawa terms can be generated from high-dimensional operators or instanton effects. Differing from SU(5) models, the Yukawa term $F_iF_jh$ in the $\mathcal{F}$–SU(5) model gives down-type quark masses, so these Yukawa couplings can be small and hence generated via high-dimensional operators or instanton effects.

## 3 Phenomenological results

The general No-Scale soft SUSY breaking terms in the $\mathcal{F}$–SU(5) D-brane model are implemented at the $SU(5) \times U(1)_X$ unification scale $M_{\mathcal{F}}$, and we concurrenly float the low-energy parameters $\tan\beta$, $m_t$, and $M_V$. Over 1.2 billion points in the model space are sampled by computing the SUSY mass spectra, rare decay process branching ratios, spin-independent dark matter cross-sections, and relic density using a proprietary mpi codebase built on scaled down versions of `Micromegas 2.1` [83] and `SuSpect 2.34` [84]. The intervals scanned are:

$$100\,\text{GeV} \leq M_5 \leq 1700\,\text{GeV}$$
$$100\,\text{GeV} \leq M_{1X} \leq 3800\,\text{GeV}$$
$$10\,\text{eV} \leq M_{U^cL} \leq 1500\,\text{GeV}$$
$$1\,\text{GeV} \leq M_{E^c} \leq 2400\,\text{GeV}$$
$$1\,\text{keV} \leq M_{QD^cN^c} \leq 1900\,\text{GeV}$$
$$100\,\text{GeV} \leq M_{H_u} \leq 4000\,\text{GeV}$$
$$100\,\text{GeV} \leq M_{H_d} \leq 4000\,\text{GeV}$$
$$-10\,\text{TeV} \leq A_\tau \leq 10\,\text{TeV}$$
$$-10\,\text{TeV} \leq A_t \leq 13\,\text{TeV}$$
$$-10\,\text{TeV} \leq A_b \leq 15\,\text{TeV}$$
$$2 \leq \tan\beta \leq 60$$
$$1\,\text{TeV} \leq M_V \leq 8000\,\text{TeV}\,.$$

A small tolerance of $172.3 \leq m_t \leq 174.4\,\text{GeV}$ is applied around the World Average top quark mass [85]. We only consider a positive Higgs bilinear mass term $\mu$, and the strong coupling constant is fixed at $\alpha_S(M_Z) = 0.1184$, within the Particle Data Group $1\sigma$ variation [85]. The SUSY contribution to $\Delta a_\mu$ is calculated using `GM2Calc 1.7.5` [86].

The computational results are constrained by filtering the data through current limits on pertinent beyond the Standard Model (BSM) experiments. A tolerance of $2\sigma$ is allowed around the branching ratio $\text{Br}(b \to s\gamma)$ of the b-quark decay [89] and branching ratio $\text{Br}(B_S^0 \to \mu^+\mu^-)$ of the rare B-meson decay to a dimuon [90]. The WMAP 9-year [91] and 2015–18 Planck [92, 93] upper limit of about $\Omega h^2 \simeq 0.12$ is required, though no lower limit on the relic density is applied. A lower bound on the proton decay rate $\tau_p(p \to e^+\pi^0) \geq 1.7 \times 10^{34}\,\text{yrs}$ [94] is also enforced. In summary, the points are filtered to ensure consistency with the following requirements:

$$2.99 \leq \text{Br}(b \to s\gamma) \leq 3.87 \times 10^{-4}$$
$$0.8 \leq \text{Br}(B_S^0 \to \mu^+\mu^-) \leq 6.2 \times 10^{-9}$$
$$0 \leq \Omega h^2 \leq 0.12$$
$$\tau_p(p \to e^+\pi^0) \geq 1.7 \times 10^{34}\,\text{yrs}$$
$$123 \leq m_h \leq 127\,\text{GeV}\,.$$

A $2\sigma$ experimental uncertainty and reasonable theoretical uncertainty is permitted around the observed light Higgs boson mass of $m_h = 125.09\,\text{GeV}$ [95, 96], providing a range of $123 \leq m_h \leq 127\,\text{GeV}$ on the computed total $m_h$. The total light Higgs boson mass calculation includes the vector-like particle contribution, which couples through the vector-like multiplet Yukawa coupling. We assume a maximum coupling, implying the $(XD, XD^c)$ Yukawa coupling is $Y_{XD} = 0$ and the $(XU, XU^c)$ Yukawa coupling is $Y_{XU} = 1$, and furthermore, the trilinear coupling $A$-term is $A_{XD} = 0$ while the $(XU, XU^c)$ $A$-term is $A_{XU} = A_U$ [55, 97]. These numerical values ensure a maximal coupling between the vector-like particles and light Higgs boson.

Given only an upper limit established on the abundance of the lightest neutralino $\widetilde{\chi}_1^0$, multi-component dark matter is generally necessary. Therefore, we rescale the spin-independent cross-section $\sigma_{\text{SI}}$ on nucleon-neutralino collisions as such:

$$\sigma_{\text{SI}}^{\text{rescaled}} = \sigma_{\text{SI}} \frac{\Omega h^2}{0.12}\,. \tag{3.1}$$

The SU(5) breaking effects drive the wino to near degeneracy with the lightest neutralino, generating higgsino LSPs. Compressed spectra with $M(\widetilde{\chi}_1^\pm) - M(\widetilde{\chi}_1^0) = 3\text{–}7\,\text{GeV}$ and $M(\widetilde{\chi}_2^0) < 0$ are typical conditions identifying higgsino spectra, and indeed these are the characteristics of the $\mathcal{F}$–SU(5) D-brane points. Twelve sample benchmark points are presented in table 1, with the higgsino LSP composition percent shown. Given the small wino, the most stringent LHC constraints on the $\mathcal{F}$–SU(5) D-brane model are ATLAS electroweakino production searches for higgsino LSP [87]. The small wino though does provide ample contribution to $\Delta a_\mu(\text{SUSY})$ to explain the BNL+FNAL $4.2\sigma$ discrepancy. The D-brane model has a large region within both the $1\sigma$ and $2\sigma$ limits around the BNL+FNAL

| $M_1$ (GeV) | 2700 | 2700 | 2500 | 2700 | 2900 | 2500 | 2800 | 3100 | 3400 | 3600 | 3500 | 3600 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $M_5$ (GeV) | 1510 | 1510 | 1530 | 1570 | 1600 | 1600 | 1600 | 1600 | 1610 | 1640 | 1660 | 1700 |
| $M_{U^c L}$ (keV) | 10 | 10 | 10 | 10 | 10 | 100 | 10 | 10 | 10 | 10 | 10 | 10 |
| $M_{Q D^c N^c}$ (keV) | 10 | 10 | 10 | 10 | 10 | 100 | 10 | 10 | 10 | 10 | 10 | 10 |
| $M_{E^c}$ (GeV) | 1200 | 1200 | 1400 | 1200 | 1300 | 1400 | 1200 | 1200 | 900 | 1000 | 1000 | 900 |
| $M_{H_u}$ (GeV) | 1800 | 1800 | 1900 | 1900 | 2100 | 2000 | 1900 | 2000 | 1900 | 2000 | 1900 | 1900 |
| $M_{H_d}$ (GeV) | 2300 | 2300 | 2300 | 2300 | 2400 | 2500 | 2400 | 2500 | 2400 | 2600 | 2600 | 2600 |
| $A_\tau$ (GeV) | 800 | 800 | 1200 | 400 | 1200 | 700 | 600 | 800 | 1200 | 1200 | 600 | 800 |
| $A_t$ (GeV) | 600 | 600 | 200 | 400 | 0 | 300 | 500 | 100 | 400 | 200 | 800 | 1000 |
| $A_b$ (GeV) | $-4600$ | $-4900$ | $-4900$ | $-5200$ | $-4300$ | $-4500$ | $-5200$ | $-4900$ | $-5000$ | $-4700$ | $-5000$ | $-5000$ |
| $M_V$ (TeV) | 4000 | 7000 | 7000 | 4000 | 4000 | 5500 | 5500 | 7000 | 8000 | 7000 | 8000 | 8000 |
| $\tan\beta$ | 60 | 60 | 60 | 60 | 60 | 59 | 59 | 60 | 60 | 60 | 60 | 60 |
| $m_{\rm top}$ (GeV) | 173.3 | 173.1 | 172.7 | 173.3 | 173.7 | 173.3 | 172.7 | 172.9 | 172.3 | 173.1 | 172.3 | 172.5 |
| $\mathbf{\Delta a_\mu(SUSY)}$ $(\times 10^{-10})$ | **21.1** | **22.3** | **21.1** | **20.1** | **19.3** | **19.0** | **19.4** | **20.2** | **20.6** | **19.0** | **19.5** | **19.0** |
| $\mathrm{Br}(b \to s\gamma)$ $(\times 10^{-4})$ | 3.01 | 3.04 | 2.99 | 3.09 | 3.01 | 3.02 | 3.10 | 2.99 | 3.14 | 2.99 | 3.16 | 3.26 |
| $\mathrm{Br}(B_S^0 \to \mu^+\mu^-)$ $(\times 10^{-9})$ | 5.8 | 4.9 | 5.7 | 6.2 | 6.2 | 4.6 | 4.6 | 5.6 | 5.7 | 5.2 | 4.3 | 4.1 |
| $\sigma_{\rm SI}^{\rm rescaled}$ $(\times 10^{-9}\mathrm{pb})$ | 8.6 | 6.7 | 6.8 | 8.7 | 6.5 | 4.9 | 6.2 | 6.7 | 7.8 | 4.9 | 6.1 | 6.2 |
| $\tau_p(p \to e^+\pi^0)$ $(\times 10^{35}\,\mathrm{yrs})$ | 1.3 | 1.3 | 1.5 | 1.4 | 1.0 | 1.4 | 1.5 | 1.1 | 1.0 | 0.9 | 1.0 | 1.0 |
| $\Omega h^2$ | 0.0039 | 0.0041 | 0.0049 | 0.0048 | 0.0043 | 0.0055 | 0.0050 | 0.0039 | 0.0030 | 0.0024 | 0.0032 | 0.0035 |
| $M_{\widetilde\chi_1^0}$ (GeV) | 235 | 201 | 202 | 217 | 185 | 207 | 215 | 197 | 190 | 210 | 197 | 185 |
| $M_{\widetilde\chi_2^0}$ (GeV) | $-282$ | $-237$ | $-232$ | $-251$ | $-215$ | $-234$ | $-247$ | $-233$ | $-234$ | $-271$ | $-240$ | $-222$ |
| $M_{\widetilde\chi_1^\pm}$ (GeV) | 239 | 206 | 208 | 223 | 191 | 213 | 220 | 202 | 195 | 213 | 201 | 190 |
| $M_{\widetilde\tau_1^\pm}$ (GeV) | 412 | 380 | 352 | 463 | 458 | 355 | 475 | 396 | 416 | 396 | 416 | 374 |
| $M_{\widetilde e_R,\widetilde\mu_R}$ (GeV) | 1074 | 1054 | 1076 | 1109 | 1155 | 1115 | 1113 | 1129 | 1133 | 1174 | 1162 | 1184 |
| $M_{\widetilde t_1}$ (GeV) | 1737 | 1738 | 1710 | 1784 | 1727 | 1770 | 1833 | 1753 | 1829 | 1814 | 1903 | 1968 |
| $\mathbf{M_{\widetilde g}}$ **(GeV)** | **2254** | **2281** | **2306** | **2341** | **2372** | **2388** | **2397** | **2406** | **2428** | **2463** | **2500** | **2554** |
| $M_{\widetilde u_R}$ (GeV) | 2522 | 2507 | 2537 | 2619 | 2658 | 2651 | 2655 | 2650 | 2660 | 2713 | 2739 | 2798 |
| $\mathbf{m_h}$ **(GeV)** | **123.3** | **123.3** | **123.6** | **124.0** | **124.6** | **124.0** | **123.6** | **124.2** | **123.4** | **124.3** | **123.1** | **123.0** |
| $M_{H^0}$ (GeV) | 936 | 946 | 889 | 847 | 831 | 1014 | 1000 | 904 | 813 | 1010 | 962 | 904 |
| $M_{32}$ $(\times 10^{16}\,\mathrm{GeV})$ | 1.0 | 1.0 | 1.1 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 1.0 | 0.9 | 1.0 | 1.0 |
| $M_{\mathcal F}$ $(\times 10^{17}\,\mathrm{GeV})$ | 1.9 | 1.8 | 1.8 | 1.9 | 1.8 | 1.8 | 1.8 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| LSP Higgsino Composition | 67% | 80% | 86% | 82% | 86% | 89% | 84% | 79% | 71% | 52% | 72% | 79% |

**Table 1**. The $\mathcal{F}$–SU(5) D-brane model general No-Scale SUSY breaking soft terms along with their associated mass spectra and other pertinent data for 12 benchmark spectra representative of that region of model space that can explain the BNL+FNAL $4.2\sigma$ discrepancy. All spectra have higgsino LSP, with the higgsino percentage listed in the bottom line.

$25.1 \times 10^{-10}$ central value. This is graphically illustrated in figure 1, where $\Delta a_\mu(\mathrm{SUSY})$ is plot versus the gluino mass. The points are distinguished by satisfaction of the ATLAS light chargino constraint for those spectra with higgsino LSP [87]. The uncertainty on all $\Delta a_\mu$ calculations is about $\pm 2.4 \times 10^{-10}$. For the amount of $M_5$ and $M_{1X}$ mixing in eq. (2.18), $\Delta a_\mu(\mathrm{SUSY})$ remains in the BNL+FNAL $1\sigma$ range up to $M(\widetilde g) \approx 2.56\,\mathrm{TeV}$. It is clear in figure 1 that the current LHC Run 2 gluino constraint of $M(\widetilde g) \gtrsim 2.25\,\mathrm{TeV}$ [98–104] correlates to the current chargino constraint for higgsino LSP since the BNL+FNAL $1\sigma$ and $2\sigma$ points that satisfy the ATLAS chargino constraint show a coincident lower bound of $M(\widetilde g) \simeq 2.25\,\mathrm{TeV}$.

To more accurately assess any tension with LHC electroweakino production constraints so that we can provide a frame of reference for our relatively small wino, we superimpose the D-brane model points of figure 1 onto the ATLAS electroweakino production summary plot
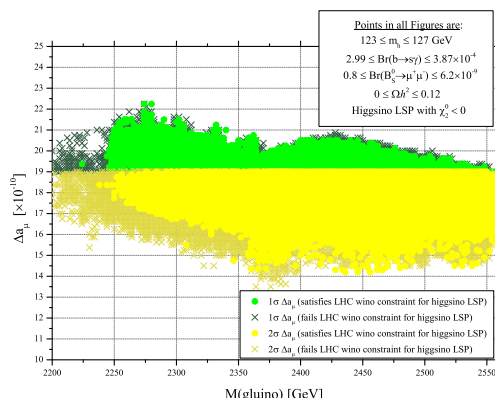
**Figure 1**. Depiction of $\Delta a_\mu(\text{SUSY})$ as a function of the gluino mass $M(\widetilde{g})$, distinguished by whether the spectra satisfy the BNL+FNAL $1\sigma$ or $2\sigma$ limits on $\Delta a_\mu$. The points are also separated into groups regarding consistency with the LHC constraints on electroweakinos for those spectra with higgsino LSP, namely chargino production. The uncertainty on all $\Delta a_\mu(\text{SUSY})$ calculations is about $\pm 2.4 \times 10^{-10}$.

for higgsino LSP [87], as displayed in figure 2, and also the CMS electroweakino production plot for higgsino LSP [88], as shown in figure 3. The points are likewise separated into those that reside within either the BNL+FNAL $1\sigma$ or $2\sigma$ limits on $\Delta a_\mu$. Given the compressed nature of the D-brane spectra, these higgsino simplified models appear to be the only search regions capable of probing the D-brane model space that resolves the BNL+FNAL $4.2\sigma$ discrepancy. In the CMS plot in figure 3, for clarity we show only those points that satisfy the ATLAS chargino constraint of figure 2. The CMS simplified model scenario applied in figure 3 is not a precise fit for the $\mathcal{F}$–SU(5) D-brane model space, but it does give a good summary as to how our model stands against the current chargino constraints. The CMS analysis of ref. [88] also studies the higgsino model in the phenomenological MSSM (pMSSM), though constraints are given in terms of the wino mass as a function of $\mu$ and all points in our model are well beyond these exclusion limits due to the large $\mu$ term.

Other than the small wino, the only other class of measurements the D-brane model would seem to be experiencing tension with are the direct-detection spin-independent cross-sections, which we rescale for small $\Omega h^2$. However, given the difficulty with which higgsino LSPs can be detected, we are not alarmed by the larger $\sigma_{\text{SI}}^{\text{rescaled}} \sim 10^{-9}$ pb cross-section.

Recently, ATLAS and CMS have completed searches for heavy resonances that would include heavy Higgs bosons found in an extended Higgs sector. The ATLAS search [105] involves b-jet and $\tau$-lepton final states, whereas the CMS search [106] focuses on $b$-quark pairs. All 261,562 points that pass the LHC chargino constraints on higgsino spectra and concurrently reside within either the BNL+FNAL $1\sigma$ or $2\sigma$ limits on $\Delta a_\mu$ are binned in the histogram of figure 4, using 10 GeV bin widths. The histogram peak resides in the $(985, 995]$ GeV bin, or $M(H^0) \simeq 1$ TeV.

## 4 Conclusions

The recent FNAL confirmation of the BNL discrepancy between the measured value of the anomalous magnetic moment of the muon $(g-2)_\mu$ and the Standard Model (SM) prediction
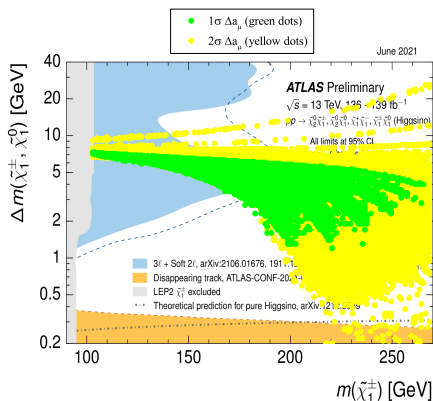
**Figure 2**. Illustration of the $\mathcal{F}$–SU(5) D-brane model points that can explain the BNL+FNAL 4.2$\sigma$ discrepancy on $\Delta a_\mu$ evaluated against the ATLAS constraints on electroweakinos for those spectra with higgsino LSP. The points are superimposed upon the ATLAS exclusion curves of ref. [87] that addresses electroweakino production in compressed spectra, namely, higgsino. The SU(5) breaking effects drive the wino to small values, engendering some tension with the lower LHC bound on chargino masses. However, as this figure exhibits, there remains a large region that handily satisfies this constraint.
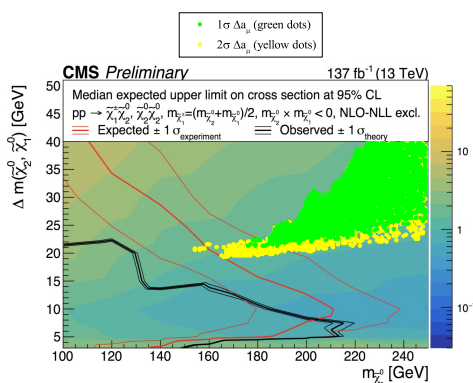


**Figure 3**. Depiction of the $\mathcal{F}$–SU(5) D-brane model points that can explain the BNL+FNAL 4.2$\sigma$ discrepancy on $\Delta a_\mu$ evaluated against the CMS constraints on electroweakinos for those spectra with higgsino LSP. The points are superimposed upon the CMS exclusion curves of ref. [88] that addresses electroweakino production in compressed spectra, namely, higgsino. In this plot for clarity we only show those points that survive the ATLAS electroweakino constraint of ref. [87], as displayed in figure 2. The CMS simplified model scenario applied is not an exact match for the $\mathcal{F}$–SU(5) D-brane model space, but it is nonetheless instructive as to how our model measures against the latest chargino constraints.

presents a combined deviation of 4.2$\sigma$. Given the possible confirmation of a statistically significant 5$\sigma$ discovery in forthcoming years, all natural GUT model candidates should be capable of elegantly explaining these experimental anomalies. Supersymmetry (SUSY) persists as one promising extension of the SM, hence we study in this work a merging of a realistic D-brane model with the supersymmetric GUT model flipped SU(5) with extra TeV-scale string derived vector-like multiplets, referred to collectively as the $\mathcal{F}$–
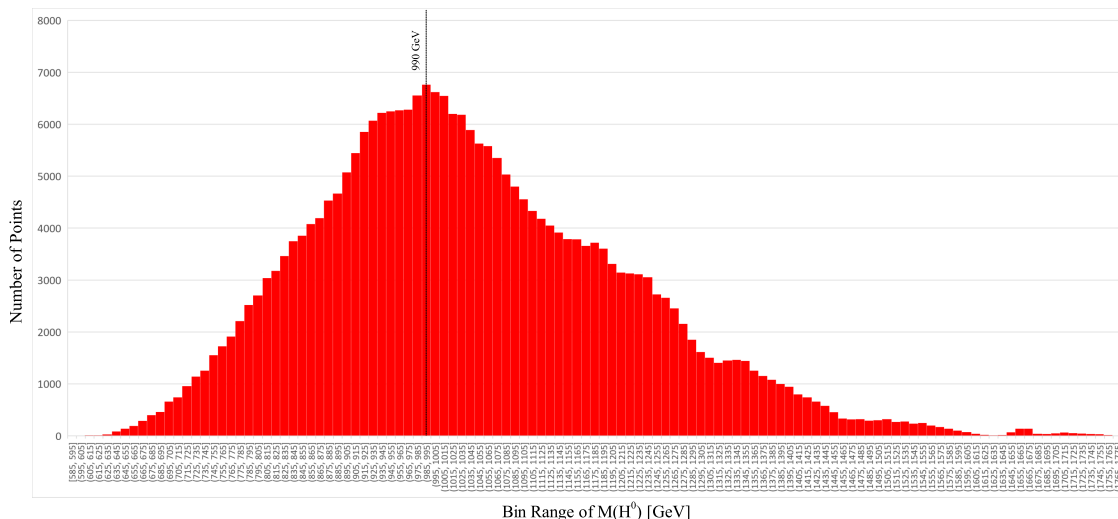
**Figure 4**. Histogram binned by counts of the heavy SUSY Higgs mass $M(H^0)$. All 261,562 points that satisfy the LHC electroweakino constraints and reside within either the BNL+FNAL $1\sigma$ or $2\sigma$ limits on $\Delta a_\mu$ are counted in the bins. The bin width is $10\,\text{GeV}$. The peak lies in the $(985, 995]$ bin, or $M(H^0) \simeq 1\,\text{TeV}$.

SU(5) D-brane model. Flipped SU(5) has been shown to be both phenomenologically and cosmologically favorable, therefore, it is an ideal candidate to pursue whether it can indeed resolve the BNL+FNAL observed disparity with the SM calculations. The supersymmetric GUT model $\mathcal{F}$–SU(5) produces a distinctive two-stage unification process. The primary unification occurs at the $\text{SU}(5) \times \text{U}(1)_X$ scale where $M_1 = M_2 = M_3$, then a secondary unification at the $\text{SU}(3)_C \times \text{SU}(2)_L$ scale. However, the large wino mass $M_2$ at $\text{SU}(5) \times \text{U}(1)_X$ due to the primary unification presents difficulties since a light wino at low-energy provides a large contribution to the muon $(g-2)_\mu$. This dilemma can be resolved when the three chiral multiplets in the SU(5) adjoint representation acquire vevs around the scale $\text{SU}(3)_C \times \text{SU}(2)_L$, and then the gaugino masses for $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_{Y'}$ of SU(5) can be split due to high-dimensional operators, leading to independent bino, wino, and gluino masses. These effects from SU(5) breaking can drive the wino $M_2$ to small values at the electroweak scale, which in consequence generates a large contribution to the muon $(g-2)_\mu$.

A deep analysis of the parameter space uncovered a region in the model that can explain the BNL+FNAL muon $(g - 2)_\mu$ measurements of $\Delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = 25.1 \pm 5.9 \times 10^{-10}$. Calculations show that the model can produce an anomalous magnetic moment as large as $\Delta a_\mu(\text{SUSY}) = 22.3 \times 10^{-10}$ for a gluino mass of $M(\widetilde{g}) = 2281\,\text{GeV}$, well within the $1\sigma$ uncertainty on the observed value. Moreover, we completed computations for gluino masses as large as $M(\widetilde{g}) = 2560\,\text{GeV}$, sufficient to ensure probing of the model space for several years to come at the LHC Run 2. We found that $\Delta a_\mu(\text{SUSY})$ can remain tucked just above the lower $1\sigma$ bound of $\Delta a_\mu(\text{SUSY}) \simeq 19.0 \times 10^{-10}$ all the way up to the 2560 GeV gluino mass. The small $M_2$ does drive the chargino mass $M(\widetilde{\chi}_1^\pm)$ to near degeneracy with the LSP mass $M(\widetilde{\chi}_1^0)$ along with a small negative neutralino mass $M(\widetilde{\chi}_2^0)$, generating higgsino dark matter. In addition to the favorable $\Delta a_\mu(\text{SUSY})$, these

same points in the model space are consistent with the observed light Higgs boson mass and other rare decay branching ratios, and also all LHC constraints, particularly those on electroweakinos, given the small chargino. Lastly, in light of recent LHC searches for heavy Higgs bosons in an extended Higgs sector, for this same region that can explain the BNL+FNAL measurements, we examined the heavy SUSY Higgs by plotting all viable $(g-2)_\mu$ points in a histogram with $10\,\mathrm{GeV}$ bin widths and discovered that the histogram peak resides at $M(H^0) \simeq 1\,\mathrm{TeV}$.

## Acknowledgments

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