

Electron and Muon Magnetic Moments and Dark Matter Implications in Nonuniversal $U(1)'$ Models

Cem Salih Ün

Department of Physics, Bursa Uludağ University, Bursa, Turkey;

Departamento de Ciencias Integradas
y Centro de Estudios Avanzados en Física Matemáticas y Computación,
Universidad de Huelva, Huelva, Spain

in collaboration with Mariana Frank, Levent Selbuz, Levent Solmaz,
Yasar Hicyilmaz, Subhadeep Mondal and Ozer Ozdal

Outline

- Standard Model (Pros & Cons)
- LFU
- $U(1)'$ SSM
- Family Dependent Charges - Anomaly Cancellation
- $g - 2$
- Dark Matter Implications
- Secluded $U(1)'$
- Conclusion

Standard Model

- ▶ Spontaneous Symmetry Breaking

- * Higgs Boson, Particle masses

- * Gauge Hierarchy Problem

$$\delta m_h^2 \propto \Lambda^2$$

- ▶ Rare B-meson Decays

$$B_s \rightarrow \mu^+ \mu^-:$$

$$Exp : 3.2_{-1.2}^{+1.5} \times 10^{-9}$$

$$SM : (3.2 \pm 0.2) \times 10^{-9}$$

$$b \rightarrow s \gamma:$$

$$Exp : (3.43 \pm 0.22) \times 10^{-4}$$

$$SM : (3.15 \pm 0.23) \times 10^{-4}$$

- ▶ Anomalous Magnetic Moments ($g - 2$)

$$\Delta a_l \equiv a_l^{\text{exp}} - a_l^{\text{SM}}$$

$$\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$$

$$\Delta a_e = -(8.8 \pm 3.6) \times 10^{-13}$$

$$SM : \frac{\Delta a_e}{\Delta a_\mu} \simeq \frac{m_e^2}{m_\mu^2}$$

$$Exp : \frac{\Delta a_e}{\Delta a_\mu} \simeq (-14) \frac{m_e^2}{m_\mu^2}$$

Lepton Flavor Universality (LFU)

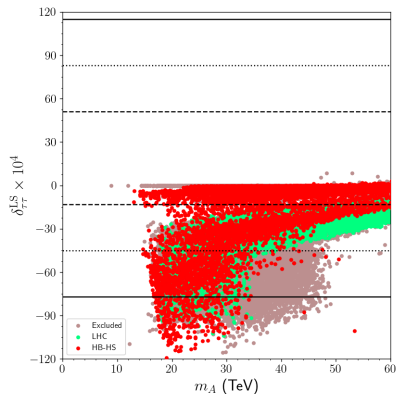
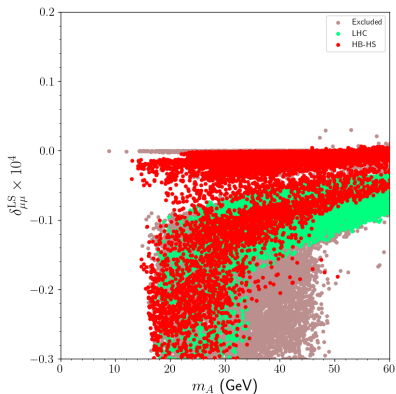
- ▶ Gauge Interactions: Flavor blind
- ▶ Yukawa Interactions: Can distinguish τ .
 - From $Z \rightarrow ll$: $\delta_\tau \simeq 1.9 \times 10^{-3}$, $\delta_\mu \simeq 0.9 \times 10^{-3}$
 - From $W \rightarrow l\nu_l$: $\delta_\tau \simeq 4.3 \times 10^{-2}$, $\delta_\mu \simeq 2.6 \times 10^{-2}$
 - $\tau_{\mu e} \equiv \frac{\text{BR}(\tau \rightarrow \mu\nu_\tau\nu_\mu)}{\text{BR}(\tau \rightarrow e\nu_\tau\nu_e)} \simeq 0.9726$
- ▶ Semi-leptonic B -meson decays:

$$\mathcal{R}(D) = \frac{\text{BR}(B \rightarrow D\tau\bar{\nu}_\tau)}{\text{BR}(B \rightarrow Dl\bar{\nu}_l)}$$
$$\mathcal{R}(D^*) = \frac{\text{BR}(B \rightarrow D^*\tau\bar{\nu}_\tau)}{\text{BR}(B \rightarrow D^*l\bar{\nu}_l)}.$$

	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$
SM	0.299 ± 0.003	0.258 ± 0.005
LHCb		$0.336 \pm 0.027 \pm 0.030$ $0.283 \pm 0.019 \pm 0.029$
Belle	$0.375 \pm 0.064 \pm 0.026$ $0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$ $0.293 \pm 0.038 \pm 0.015$ $0.270 \pm 0.035^{+0.028}_{-0.025}$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
HFLAV	$0.339 \pm 0.026 \pm 0.014$	$0.295 \pm 0.010 \pm 0.010$

► Light states

(Cici, Nis, Khalil and Un; Nucl.Phys.B 977 (2022) 115728):

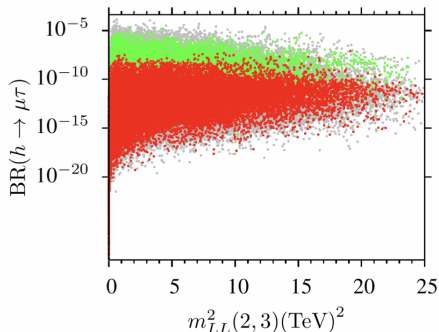
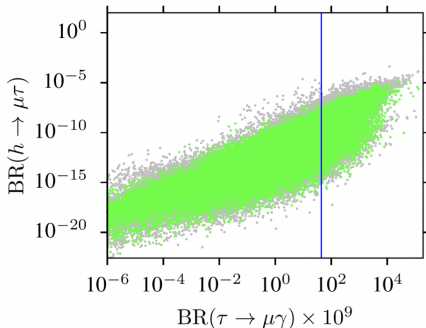


LFU in MSSM

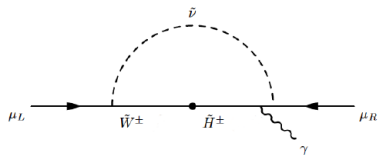
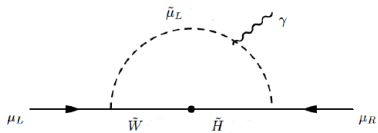
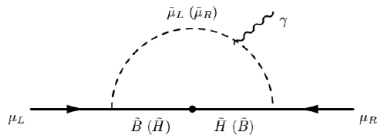
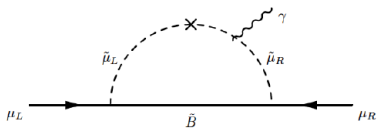
► Off-Diagonal Entries in Slepton Masses

(Hammad, Khalil and Un; Phys.Rev.D 95 (2017) 5, 055028):

$$-\mathcal{L}_{\text{soft}} = \sum_i (M_i \lambda_i \lambda_i - A_u Y_u Q H_u U^c - A_d Y_d Q H_d D^c - A_e Y_e L H_d E) \\ + \sum_{\phi} m_{\phi}^2 |\phi|^2 + \text{h.c.}$$



Muon $g - 2$ in MSSM



(Badziak and Sakurai; JHEP 10 (2019) 024)

- ▶ Opposite sign Gaugino mass terms ($M_1 < 0$, $M_2 > 0$)
 - Light Sleptons ($\mathcal{O}(200)$ GeV), $m_{\tilde{\mu}_R} \gtrsim 2$ TeV
 - Light Neutralino and Chargino ($\mathcal{O}(200)$ GeV)
 - Severe impact from LHC searches
 $m_{\tilde{\chi}_1^\pm} \gtrsim 1$ TeV, $m_{\tilde{\gamma}} \gtrsim 350$ GeV.
 - Lepton Flavor Violation ($\mu \rightarrow e\gamma?$)
- Heavy Higgsinos, zero trilinear terms.
- ▶ Enhancing the Lepton non-universality in the Yukawa sector - Higgs alignment.

- ▶ Right-handed neutrinos
 - Type-I Seesaw: LFV is under control
 - Inverse Seesaw: LFV should be taken under control
 - Deviations in semi-leptonic B -meson decays
- ▶ Flavor symmetries: $U(1)$, $SU(2)$, $SU(3)$
 - Removing the tension between m_h and muon $g - 2$ in GUTs
 - Correct the Fermion masses
 - Accommodating muon and electron $g - 2$?

$U(1)'$ Extensions of MSSM

► $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)' \in E_6, SO(10)$

► Superpotential:

$$W = \lambda S H_d H_u + Y_u \bar{Q} H_u U^c + Y_d \bar{Q} H_d D^c + Y_e \bar{L} H_u E^c + \kappa S D_x \bar{D}_x$$

$$\mu_{\text{eff}} = \lambda \langle S \rangle$$

► 6 Neutralinos - (MSSM + $\tilde{B}', \tilde{S}$)

► Extra Higgs bosons (mostly MSSM singlet)

$U(1)'$ Extensions of MSSM

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$U(1)_Y \otimes SU(2)_L \otimes SU(3)_C \otimes U(1)'$
$\hat{Q}_i$	$\tilde{Q}_i$	Q_i	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, Q_{Q_i})$
$\hat{L}_i$	$\tilde{L}_i$	l_i	3	$(-\frac{1}{2}, \mathbf{3}, \mathbf{1}, Q_{L_i})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, Q_{H_d})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, Q_{H_u})$
$\hat{D}_i^c$	$\tilde{D}_{Ri}^*$	d_{Ri}^*	3	$(\frac{1}{3}, \mathbf{1}, \bar{\mathbf{3}}, Q_{D_i^c})$
$\hat{U}_i^c$	$\tilde{U}_{Ri}^*$	u_{Ri}^*	3	$(-\frac{2}{3}, \mathbf{1}, \bar{\mathbf{3}}, Q_{U_i^c})$
$\hat{N}_i^c$	$\tilde{N}_i^c$	N_i^c	3	$(\mathbf{1}, \mathbf{3}, \mathbf{1}, Q_{N_i^c})$
$\hat{E}_i^c$	$\tilde{E}_{iR}^*$	E_{iR}^*	3	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, Q_{E_i^c})$
$\hat{S}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1}, Q_S)$

Charge Assignments and Anomaly Cancellation

$$\left. \begin{aligned} Q_{Q_i} + Q_{U_i^c} + Q_{H_u} &= 0 , \\ Q_{Q_i} + Q_{D_i^c} + Q_{H_d} &= 0 , \\ Q_{L_3} + Q_{E_3^c} + Q_{H_d} &= 0 , \\ Q_{L_3} + Q_{N_3^c} + Q_{H_u} &= 0 , \\ Q_S + Q_{H_u} + Q_{H_d} &= 0 , \end{aligned} \right\} \text{Superpotential}$$
$$\left. \begin{aligned} Q_{L_1} + Q_{E_1^c} + Q_{H_u} &= 0 , \\ Q_{L_2} + Q_{E_2^c} + Q_{H_u} &= 0 . \end{aligned} \right\} \text{Non - Holomorphic Terms}$$

Charge Assignments and Anomaly Cancellation

$$0 = \sum_i (2Q_{Q_i} + Q_{U_i^c} + Q_{D_i}) + n_{D_x} (Q_{D_x} + Q_{\bar{D}_x})$$

$$0 = \sum_i (3Q_{Q_i} + Q_{L_i}) + Q_{H_d} + Q_{H_u}$$

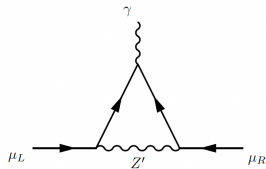
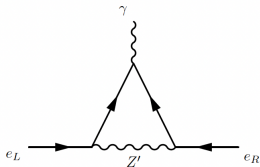
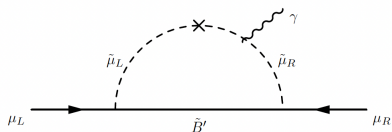
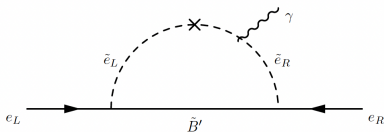
$$0 = \sum_i \left(\frac{1}{6} Q_{Q_i} + \frac{1}{3} Q_{D_i^c} + \frac{4}{3} Q_{U_i^c} + \frac{1}{2} Q_{L_i} + Q_{E_i^c} \right) + \frac{1}{2} (Q_{H_d} + Q_{H_u}) + 3n_{D_x} Y_{D_x}^2 (Q_{D_x} + Q_{\bar{D}_x})$$

$$0 = \sum_i (6Q_{Q_i} + 3Q_{U_i^c} + 3Q_{D_i^c} + 2Q_{L_i} + Q_{E_i^c}) + 2Q_{H_d} + 2Q_{H_u} + Q_S + 3n_{D_x} (Q_{D_x} + Q_{\bar{D}_x})$$

$$0 = \sum_i (Q_{Q_i}^2 + Q_{D_i^c}^2 - 2Q_{U_i^c}^2 - Q_{L_i}^2 + Q_{E_i^c}^2) - Q_{H_d}^2 + Q_{H_u}^2 + 3n_{D_x} Y_{D_x} (Q_{D_x}^2 - Q_{\bar{D}_x}^2)$$

$$0 = \sum_i (6Q_{Q_i}^3 + 3Q_{D_i^c}^3 + 3Q_{U_i^c}^3 + 2Q_{L_i}^3 + Q_{E_i^c}^3) + 2Q_{H_d}^3 + 2Q_{H_u}^3 + Q_S^3 + 3n_{D_x} (Q_{D_x}^3 + Q_{\bar{D}_x}^3)$$

$g - 2$



$M_{Z'} \simeq g' v_S$; Suppressed by the heavy Z'

Parameters

(Frank, Hicyilmaz, Mondal, Ozdal and Un; JHEP 10 (2021) 063)

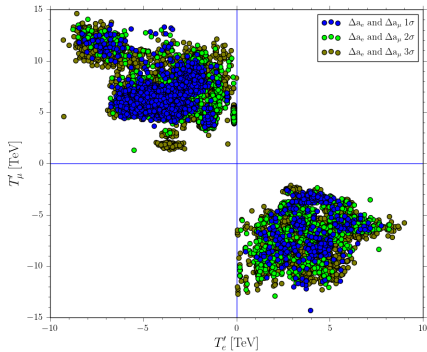
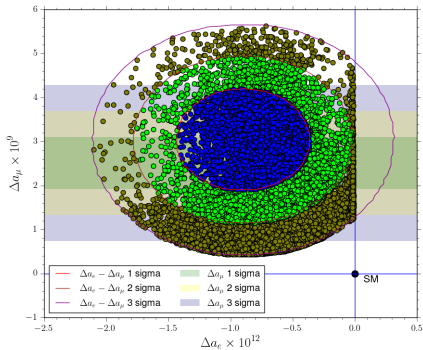
$$-\mathcal{L}_{\text{soft}} = \sum_i M_i \lambda_i \lambda_i - A_\lambda \lambda S H_d H_u - A_u Y_u Q H_u U^c - A_d Y_d Q H_d D^c \\ - A_\tau Y_\tau L_3 H_d E_3 - A_\kappa \kappa S D_x \bar{D}_x + \sum_\phi m_\phi^2 |\phi|^2 + \text{h.c.}$$

$$-\mathcal{L}_{\text{non-holomorphic}} = T'_e L_1 H_u^* E_1^c + T'_\mu L_2 H_u^* E_2^c$$

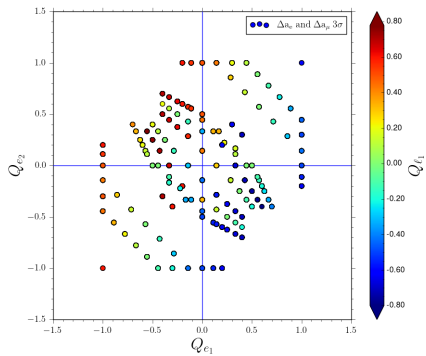
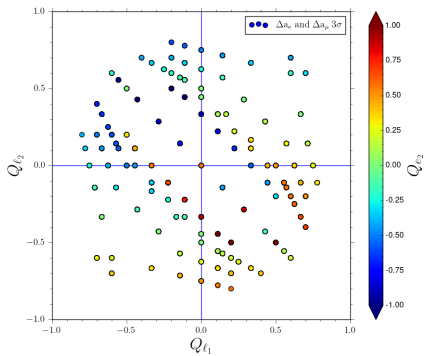
Parameter	Scanned range	Parameter	Scanned range
$\tan \beta$	[2., 60.]	ν_S	[10., 25.] TeV
M_1	[-3., 3.] TeV	M_3	[1., 60.] TeV
M_2	[-5., 5.] TeV	M_4	[-4., 4.] TeV
λ	[0.02, 0.5]	T'_e	[-10., 10.] TeV
A_λ	[-3., 15.] TeV	T'_μ	[-15., 15.] TeV

Observable	Constraints	Observable	Constraints
m_{h_1}	[122, 128] GeV	$m_{\tilde{t}_1}$	≥ 730 GeV
$m_{\tilde{g}}$	> 2.1 TeV	$m_{\tilde{\chi}_1^\pm}$	≥ 103.5 GeV
$m_{\tilde{\tau}_1}$	≥ 105 GeV	$m_{\tilde{b}_1}$	≥ 222 GeV
$m_{\tilde{q}}$	≥ 1400 GeV	$m_{\tilde{\mu}_1}$	> 94 GeV
$m_{\tilde{e}_1}$	> 107 GeV	$ \alpha_{ZZ'} $	$< \mathcal{O}(10^{-3})$
$M_{Z'}$	> 5 TeV	$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-)$	$[1.1, 6.4] \times 10^{-9}$
$\frac{\text{BR}(B \rightarrow \tau \nu_\tau)}{\text{BR}_{SM}(B \rightarrow \tau \nu_\tau)}$	[0.15, 2.41]	$\text{BR}(B^0 \rightarrow X_s \gamma)$	$[2.99, 3.87] \times 10^{-4}$

$g - 2$

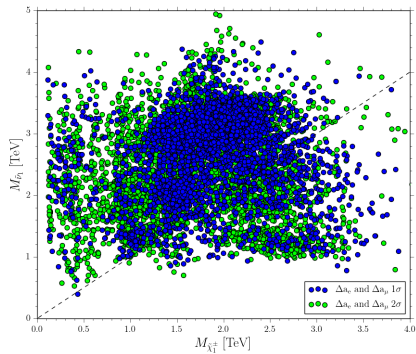
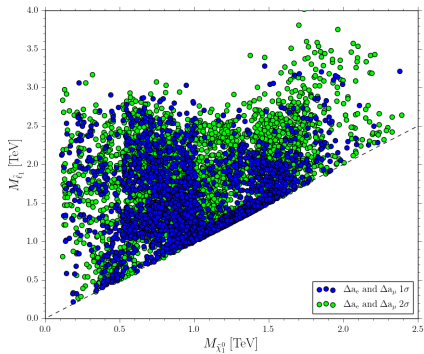


$$\Delta a_l \propto \mu \cot \beta - T'_l, \quad l = e, \mu$$

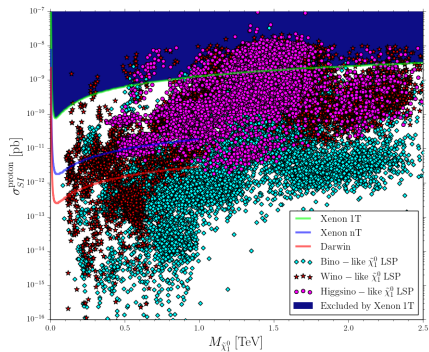
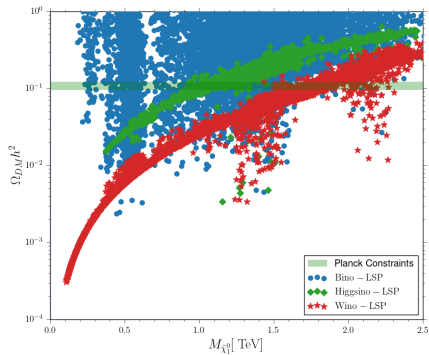


	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Q_u	0.166667	0.142857	0.444444	0.4	-0.3	-0.4	-0.444444	-0.142857	-0.166667	0.3
Q_d	0.333333	0.285714	0.222222	0.2	-0.2	-0.2	-0.222222	-0.285714	-0.333333	0.2
$Q_{E_1^c}$	0.333333	0.428571	-1.000000	-1.0	1.0	1.0	1.000000	-0.428571	-0.333333	-1.0
$Q_{E_2^c}$	0.000000	-0.142857	-0.444444	-0.3	0.4	0.3	0.444444	0.142857	0.000000	-0.4
$Q_{E_3^c}$	0.166667	0.142857	0.777778	0.7	0.1	-0.7	-0.777778	-0.142857	-0.166667	-0.1
Q_Q	0.166667	0.142857	0.111111	0.1	0.1	-0.1	-0.111111	-0.142857	-0.166667	-0.1
Q_{L_1}	-0.666667	-0.714286	0.444444	0.5	-0.8	-0.5	-0.444444	0.714286	0.666667	0.8
Q_{L_2}	-0.333333	-0.142857	-0.111111	-0.2	-0.2	0.2	0.111111	0.142857	-0.333333	0.2
Q_{L_3}	-0.333333	0.285714	-0.444444	-0.4	-0.2	0.4	0.444444	-0.285714	-0.333333	0.2
$Q_{N_1^c}$	1.000000	1.000000	0.111111	0.0	0.6	0.0	-0.111111	-1.000000	-1.000000	-0.6
$Q_{N_2^c}$	0.666667	0.428571	0.166667	0.7	0.0	-0.7	-0.666667	-0.428571	-0.666667	0.0
$Q_{N_3^c}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Q_{H_u}	-0.333333	-0.285714	-0.555556	-0.5	0.2	0.5	0.555556	0.285714	0.333333	-0.2
Q_{H_d}	-0.500000	-0.428571	-0.333333	-0.3	0.1	0.3	0.333333	0.428571	0.500000	-0.1
Q_S	0.833333	0.714286	0.888889	0.8	-0.3	-0.8	-0.888889	-0.714286	-0.833333	0.3
Q_{D_x}	-0.333333	-0.285714	-0.555556	-0.5	0.2	0.5	0.555556	0.285714	0.333333	-0.2
$Q_{\bar{D}_x}$	-0.500000	-0.428571	-0.333333	-0.3	0.1	0.3	0.333333	0.428571	0.500000	-0.1

$g - 2$ and Spectrum



Dark Matter

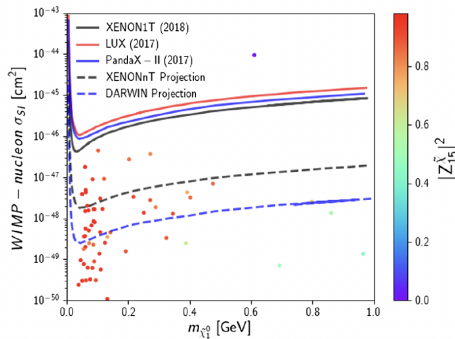
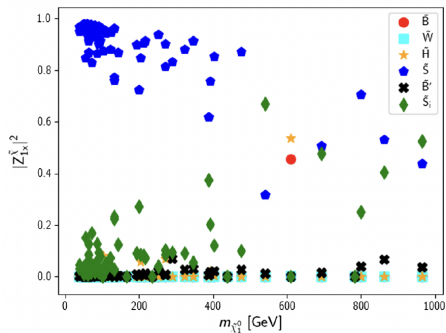


Drawbacks and Prospects: Secluded $U(1)'$

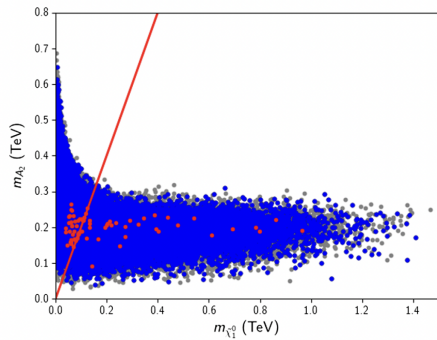
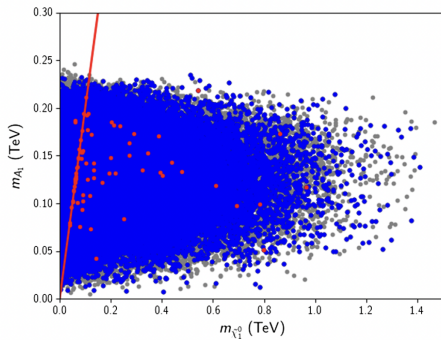
- ▶ Large non-holomorphic T -terms: Higgs potential stability
- ▶ Democratic Scales: $v_S \sim v_d \sim v_u$; vanishing $Z - Z'$ hierarchy
- ▶ Vanishing electroweak vacua ($v_u \sim v_d \sim 0$)
- Extending the Singlet sector: $\frac{\kappa}{3} S_1 S_2 S_3$
- $M_{Z'}^2, g'^2(v_S^2 + \sum_{i=1}^3 v_{S_i}^2)$: Heavy Z' , low symmetry breaking scale
- Relatively lighter singlets:
 - S, S_i, B' : Actively interfering in the DM composition
 - Light SM singlet Higgs bosons ($\lesssim \mathcal{O}(100)$ GeV)

DM in Secluded $U(1)'$

(Hicyilmaz, Selbuz, Solmaz and Un; Phys.Rev.D 105 (2022) 5, 055029)



DM in Secluded $U(1)'$



Conclusion

- ▶ Deviation from LFU:
 - Semileptonic decays of B -meson
 - $g - 2$ of electron and muon
- ▶ Light particles: Very limited in deviating muon from electron
- ▶ Non-trivially family dependent symmetries:
 - Distinguishing muon from electron (or the other way around)
 - Minimal Setup:
 - Enhancing flavor dependence of Yukawa sector
 - Sufficiently accommodating muon and electron $g - 2$ simultaneously
 - Low scale phenomenology $\simeq$ MSSM
 - Vacua should be under control
 - Secluded:
 - Lighter singlet states actively participating in DM and LHC phenomena
 - $g - 2$ contributions: in progress
 - Singlet LSPs - Long Lived MSSM particles?