Constraints on low-energy flavor from LFV and $(g-2)_\mu$

Oscar Vives

6th Red LHC workshop, 9 - 11 de Mayo

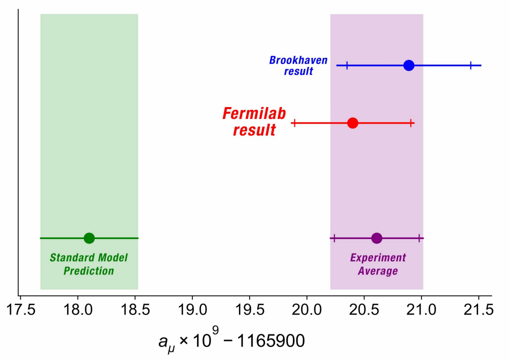
L Calibbi, M.L. López-Ibáñez, A. Melis and O.V., JHEP ***06*** *(2020), 087*

L Calibbi, M.L. López-Ibáñez, A. Melis and O.V., Eur. Phys. J. C ***81*** *(2021) no.10, 929*

M. L. López-Ibáñez, A. Melis, M. J. Pérez, M. H. Rahat and O. V., Phys. Rev. D ***105*** *(2022) 035021*

First results from the Muon g-2 at Fermilab

Run1 in *Muon g-2* confirmed Brookhaven discrepancy:



$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11} \Rightarrow \boxed{4.2\ \sigma}$$

Very large discrepancy, compared with EW contribution,

$$a_\mu^{\rm EW} = 153.6\,(1.0) \times 10^{-11}$$

and at one loop ...

$$a_\mu^{\rm EW(1)} = \frac{G_F}{\sqrt{2}}\frac{m_\mu^2}{8\pi^2}\left[\frac{5}{3}+\frac{1}{3}(1-4\sin^2\theta_W)\right]$$

$$= \frac{\alpha}{4\pi\sin^2\theta_W}\frac{1.67\;\, m_\mu^2}{4\;\, M_w^2} = 194.79\,(1) \times 10^{-11}$$

any "natural" new physics with "minimal" flavor structure

$$a_\mu^{\rm NP} \simeq \frac{\alpha}{4\pi\sin^2\theta_W}\frac{m_\mu^2}{M_X^2} = 251 \times 10^{-11}$$

Very large discrepancy, compared with EW contribution,

$$a_\mu^{\mathrm{EW}} = 153.6\,(1.0) \times 10^{-11}$$

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$$a_\mu^{\mathrm{EW}(1)} = \frac{G_F}{\sqrt{2}} \frac{m_\mu^2}{8\pi^2} \left[\frac{5}{3} + \frac{1}{3}(1 - 4\sin^2\theta_W) \right]$$
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$\Longrightarrow$ $M_X = 106$ GeV. So ... **Where is New Physics??**

Additional enhancing factors in NP contributions are possible ...

$$a_\mu^{\mathrm{NP}} \simeq \frac{\alpha}{4\pi \sin^2\theta_W} \frac{m_\mu^2}{M_X^2}\ \mathsf{k}$$

- In SUSY: $\mathsf{k} = \tan\beta$, Scalar Leptoquarks: $\mathsf{k} = m_t/m_\mu \simeq 1600$

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But ...

Large enhancements in anomalous magnetic moments, produce enormous contributions to the fermion mass !!

$$\Delta a_\mu^{\rm NP} \simeq \frac{\alpha}{4\pi \sin^2\theta_W} \frac{m_\mu^2}{M_X^2}\, \mathsf{k} \;\Rightarrow\; \Delta m_\mu^{\rm NP} \simeq m_\mu \frac{\alpha\, \mathsf{k}}{4\pi \sin^2\theta_W}$$

$$\Downarrow$$

Absence of fine-tuning requires $\mathsf{k} \lesssim 4\pi \sin^2\theta_W/\alpha \simeq 380$

largest possible (fully radiative m_μ) $M_X \lesssim 2$ TeV !!!

Low-energy flavor symmetries

Flavour symmetry explains masses and mixings in Yukawas.

Small couplings generated in Froggatt-Nielsen, as function of small vevs, $Y_{ij} = \left(\left(\frac{\langle\theta\rangle}{M}\right) \ll 1\right)^n$.

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Magnetic moments and Yukawas have identical flavor charges.
$\Rightarrow$ identical flavons enter the Dipole and Yukawa matrices !!

$$Y_\ell \;=\; y_{33} \begin{pmatrix} \lambda^{5+a} & \lambda^{2+b} & \lambda^c \\ \lambda^{2+d} & \lambda^{2+e} & \lambda^f \\ \lambda^g & \lambda^h & 1 \end{pmatrix}$$

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with $\lambda = 0.2$ and $a, b, c, d, e, f, g, h \geq 0$.

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For low Λ_f , lepton flavor violation, $\mu \to e\gamma$, require nearly diagonal charged-lepton Yukawa matrices, $a, e = 0,\ b, d \geq 6.6,\ g, h, c, f \geq 2.7$.

T_{13} Model

$T_{13} = Z_{13} \rtimes Z_3$, O(39) finite subgroup of $SU(3)$, with two ineq. complex triplets, $3_1, 3_2$.

Fields	$\bar{L}$	l	H	φ_{33}	φ_{22}	φ_{13}	Δ	χ	χ'
$SU(2)_L$	2	1	2	1	1	1	1	1	1
T_{13}	3_1	3_1	1	$\bar{3}_1$	$\bar{3}_1$	3_1	$\bar{3}_1$	1	1
Z_4	η^1	1	η^1	η^1	η^3	η^2	η^2	η^3	η^1

Diagonal and off-diagonal in different T_{13} representations.

$$\begin{pmatrix} \bar{L}_1 \\ \bar{L}_2 \\ \bar{L}_3 \end{pmatrix}_{3_1} \otimes \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix}_{3_1} = \begin{pmatrix} \bar{L}_1 l_1 \\ \bar{L}_2 l_2 \\ \bar{L}_3 l_3 \end{pmatrix}_{3_2} \oplus \begin{pmatrix} \bar{L}_2 l_3 \\ \bar{L}_3 l_1 \\ \bar{L}_1 l_2 \end{pmatrix}_{\bar{3}_1} \oplus \begin{pmatrix} \bar{L}_3 l_2 \\ \bar{L}_1 l_3 \\ \bar{L}_2 l_1 \end{pmatrix}_{\bar{3}_1} .$$

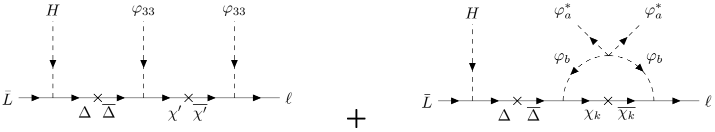
Three flavons: $\varphi_{33} \sim \bar{3}_1,\ \varphi_{22} \sim \bar{3}_1,\ \varphi_{13} \sim 3_1,$

$$\langle \varphi_{33} \rangle = \epsilon\,(0,0,1)\,\Lambda_f\,, \qquad \langle \varphi_{22} \rangle = \epsilon^2\,(0,1,0)\,\Lambda_f\,,$$
$$\langle \varphi_{13} \rangle = \epsilon^{5/2}\,(0,1,0)\,\Lambda_f\,,$$

Yukawas Langrangian:

$$L_Y^e = \bar{L} l H \left[\frac{1}{\Lambda_f} \varphi_{13} + \frac{1}{\Lambda_f^2} \varphi_{22}\varphi_{22} + \frac{1}{\Lambda_f^2} \varphi_{33}\varphi_{33} \right].$$

Tree-level + loop Yukawas:



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Tree-level + loop Yukawas:

$$Y_l/\epsilon^2 = \begin{pmatrix} 0 & 0 & \epsilon^{5/2} \\ 0 & \epsilon^2 & 0 \\ \epsilon^{5/2} & 0 & y_1 \end{pmatrix} + \frac{f_1(x_\varphi^2)}{32\,\pi^2} \begin{pmatrix} 0 & 0 & 2\,y_2\,y_4\,\epsilon^{5/2} \\ 0 & \beta_2\,y_2\epsilon^2 & 0 \\ 2\,y_2\,y_4\,\epsilon^{5/2} & 0 & y_1\,\beta_3\,y_3 \end{pmatrix}$$

But, Dipole matrix similar structure

$$C_l = \frac{f_2(x_\varphi^2)}{16}\,\frac{\epsilon^2}{\Lambda_f^2}\begin{pmatrix} 0 & 0 & 2\,y_2\,y_4\,\epsilon^{5/2} \\ 0 & \beta_2\,y_2\epsilon^2 & 0 \\ 2\,y_2\,y_4\,\epsilon^{5/2} & 0 & y_1\,\beta_3\,y_3 \end{pmatrix},$$

Can we consistently reproduce $(g-2)_\mu$?

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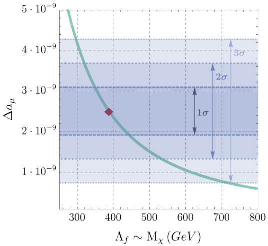

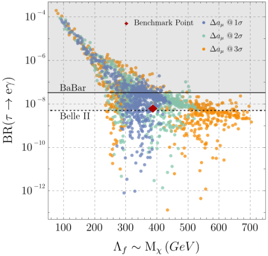

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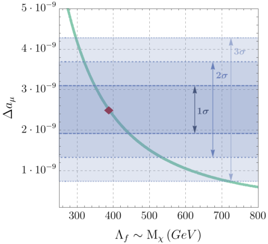

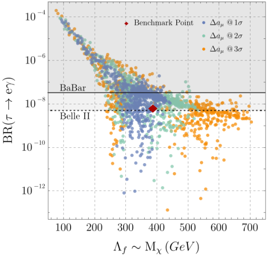

y_1	y_2	y_3	y_4	β_2	β_3	β_4	ϵ	x_φ
0.50	0.50	3.50	0.70	0.25	1.56	−6.24	0.15	0.08

Conclusions

- Low scale New Physics required to explain the muon (g-2) anomaly.
- Absence of fine-tuning requires electroweak-charged particles with $M_X \lesssim 1$ TeV
- Low-energy flavor symmetries can explain the muon (and electron anomalies).
- Realistic low-energy T_{13}(others...) possible to explain $(g-2)_\mu$.
- Vector-like fermions with muon quantum numbers and new scalars at reach in LHC.

Backup

LHC searches

- Vector-like fermions with muon quantum numbers required with $M_x \lesssim 1$ TeV (in absence of fine-tuning) .
- Weak-production at LHC: $p\,p \to \chi^+\chi^-$
- Large couplings, $\mathcal{O}(1)$, to muon and scalar flavons
- Flavons, ϕ, decay to heavier fermions, $\mu^+\mu^-$ (τ with three generations)

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Typical signature

$$p\,p \to \chi^+\chi^- \to \phi_1(\to \mu^+\mu^-)\,\ell^+\,\phi_1(\to \mu^+\mu^-)\,\ell^-, \qquad \text{with} \quad \ell = e, \mu$$

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$\Rightarrow$ **New Physics associated with $(g-2)_\mu$ should be visible at LHC.**

LFV Constraints

$$\mathcal{L} \supset \frac{e\,v}{8\,\pi^2}\, C_{\ell\ell'}\, \left(\bar{\ell}\sigma_{\mu\nu}P_R\ell'\right)\, F^{\mu\nu} \;+\; \mathrm{h.c.} \qquad \ell,\ell' = e,\mu,\tau$$

- $\Delta a_\ell = \frac{m_\ell v}{2\pi^2}\,\mathrm{Re}(C_{\ell\ell}),\ \mathrm{B}_{\ell\to\ell'\gamma} = \frac{3\alpha}{\sqrt{2}\pi\, G_F^3\, m_\ell^2}\left(|C_{\ell\ell'}|^2 + |C_{\ell'\ell}|^2\right)\mathrm{B}_{\ell\to\ell'\nu\bar{\nu}'}$

	$M_X = 520\sqrt{\kappa}$ GeV	
$\mathrm{Re}(C_{\mu\mu})$	$[1.5,\ 2.4] \times 10^{-9}\ \ \mathrm{GeV}^{-2}$	λ^2
$\mathrm{Re}(C_{ee})$	$[-1.9,\ 1.7] \times 10^{-10}\ \ \mathrm{GeV}^{-2}$	λ^5
$\mathrm{Re}(C_{\tau\tau})$	$[-3.7,\ 1.7] \times 10^{-4}\ \mathrm{GeV}^{-2}$	1
$\|C_{e\mu}\|,\ \|C_{\mu e}\|$	$\lesssim 3.9 \times 10^{-14}\ \ \mathrm{GeV}^{-2}$	$\lambda^{\geq 8.6}$
$\|C_{\tau\mu}\|,\ \|C_{\mu\tau}\|$	$\lesssim 5.0 \times 10^{-10}\ \ \mathrm{GeV}^{-2}$	$\lambda^{\geq 2.6}$
$\|C_{\tau e}\|,\ \|C_{e\tau}\|$	$\lesssim 4.3 \times 10^{-10}\ \ \mathrm{GeV}^{-2}$	$\lambda^{\geq 2.7}$

with $\kappa \simeq 20$ if mass is fully radiative