Low-energy Flavor breaking and $(g-2)_\mu$ at LHC

Oscar Vives

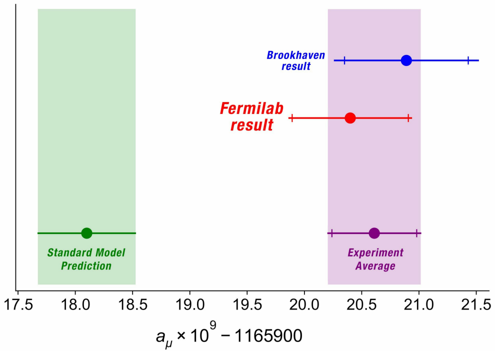
5th Red LHC workshop, 10 - 12 de Mayo

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., arXiv:2104.03296 [hep-ph]

First results from the Muon g-2 at Fermilab

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



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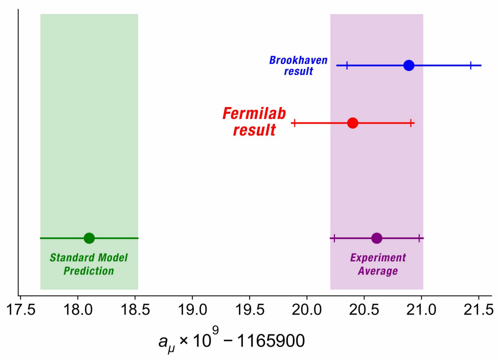

$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11} \Rightarrow \boxed{4.2\ \sigma}$$

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

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$\Longrightarrow$ $M_X = 106$ GeV. So ... **Where is New Physics??**

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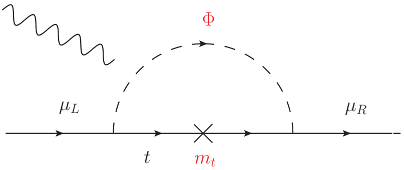

Mass correction!!

$\Longrightarrow$ **Large enhancements in anomalous magnetic moments, produce enormous contributions to the fermion mass !!**

New contributions to $(g-2)_\mu$ of size:

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

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$$\Downarrow$$

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

$U(1)$ Simplified Model

- Two generations: μ, e, flavon fields, ϕ, and mediators, χ :

Field	μ_L	μ_R	e_L	e_R	χ_R	ϕ_1	ϕ_3	ϕ_a	ϕ_b	H
$U(1)_f$	-2	0	8	3	$1\ldots7,8$	1	3	$2/5$	$8/5$	0
Z_2	$+$	$+$	$-$	$+$	$\pm$	$-$	$-$	$+$	$+$	$+$

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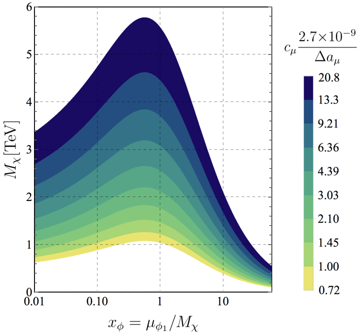
Reproduce $\Delta a_\mu^{\rm NP}$ $\Rightarrow$



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: $p\ p \to \chi^+ \chi^-$
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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.**

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).
- Vector-like fermions with muon quantum numbers and new scalars at reach in LHC.
- Events with many muons expected with electroweak cross sections.

Backup

LFV Constraints

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

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

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

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

Simplified $U(1)$ model

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$$
\begin{aligned}
V \;=\;& \mu_1^2\,\phi_1^\dagger\phi_1 + \mu_3^2\,\phi_3^\dagger\phi_3 + \mu_a^2\,\phi_a^\dagger\phi_a + \mu_b^2\,\phi_b^\dagger\phi_b \\
&+ \lambda_1\left(\phi_1^\dagger\phi_1\right)^2 + \lambda_3\left(\phi_3^\dagger\phi_3\right)^2 + \lambda_a\left(\phi_a^\dagger\phi_a\right)^2 + \lambda_b\left(\phi_b^\dagger\phi_b\right)^2 \\
&+ \lambda_{13}\left(\phi_1^\dagger\phi_1\right)\left(\phi_3^\dagger\phi_3\right) + \lambda_{1a}\left(\phi_1^\dagger\phi_1\right)\left(\phi_a^\dagger\phi_a\right) + \lambda_{1b}\left(\phi_1^\dagger\phi_1\right)\left(\phi_b^\dagger\phi_b\right) \\
&+ \lambda_{3a}\left(\phi_3^\dagger\phi_3\right)\left(\phi_a^\dagger\phi_a\right) + \lambda_{3b}\left(\phi_3^\dagger\phi_3\right)\left(\phi_b^\dagger\phi_b\right) + \lambda_{ab}\left(\phi_a^\dagger\phi_a\right)\left(\phi_b^\dagger\phi_b\right) \\
&+ \left(\lambda_{1ab}\,\phi_a^\dagger\phi_b^\dagger\phi_1^2 + \lambda'_{13}\,\phi_3^\dagger\phi_1^3 + {\mu'_a}^2\,\phi_a^2 + {\mu'_b}^2\,\phi_b^2 + \mathrm{h.c.}\right),
\end{aligned}
$$

$$
m_{S_1}^2 \simeq 2\upsilon_1^2\left(2\lambda_1 - \lambda_{13} - \frac{9}{4}\lambda'_{13}\right) \quad , \quad m_{P_1}^2 \simeq -2\,\upsilon_a^2\left(\lambda_{1ab} + \frac{\upsilon_1^2}{2\upsilon_a^2}(\lambda_{1ab} - 18\lambda'_{13})\right)
$$

$$
m_{S_2}^2 \simeq 2\,\upsilon_1^2\left(2\lambda_1 + 4\lambda_{13} - 6\lambda'_{13} - \frac{5}{4}\frac{(2\lambda_{1a} + \lambda_{1ab})^2}{2\lambda_a + \lambda_{ab}}\right)
$$

Benchmark point. Masses in GeV.

M_χ	m_{S_1}	m_{S_2}	m_{S_3}	m_{S_4}	m_{P_1}	m_{P_2}	m_{P_3}	m_{P_4}
1658	123	337	1245	1430	611	23	18	18
λ_1	λ_3	$\lambda_{(a,b)}$	λ_{13}	$\lambda_{1(a,b)}$	$\lambda_{3(a,b)}$	λ_{ab}	λ'_{13}	λ_{1ab}
5.93	3.31	6.54	6.08	0.97	-0.31	1.82	0.65	-2.50
v_1	v_3	$v_{(a,b)}$	g_e	$\mu_{(1,3)}$	$\mu_{(a,b)}$	$\mu'_{(a,b)}$	g_μ	
42	-84	262	0.72	122	1010	9	0.85	

With these parameters, we obtain:

$$\Delta a_\mu = 1.6 \times 10^{-9} \text{ and } \Delta a_e = -1.8 \times 10^{-13}.$$