Muon g-2 and scalar leptoquark mixing

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Outline

Motivation

- SM or NP in muon anomalous magnetic moment
- > Explaining $(g-2)_{\mu}$ discrepancy by leptoquarks
- > Mixing of scalar leptoquarks and $(g-2)_{\mu}$
- phenomenological constraints on the LQ mixing
- top, bottom or charm in the loop
- $\succ \mu \rightarrow e \gamma$ selecting scalar LQ solution for (g-2)_{u.e}

Conclusions



I.Doršner, SF and O. Sumensari, 1910.03877 I.Doršner, SF and S. Saad, 2006.1164

Contribution	$a_{\mu} imes 10^{11}$		Reference	
QED (leptons)	116 584 718.85	$3\pm$ 0.036	Aoyama et al. '12	
Electroweak	153.6	\pm 1.0	Gnendiger et al. '13	
HVP: LO	6889.1	± 35.2	Jegerlehner '15	
NLO	-99.2	\pm 1.0	Jegerlehner '15	
NNLO	12.4	\pm 0.1	Kurz et al. '14	
HLbL	102	\pm 39	Jegerlehner '15 (JN '09)	
NLO	3	± 2	Colangelo et al. '14	
Theory (SM)	116 591 780	\pm 53		
Experiment	116 592 089	± 63	Bennett et al. '06	
Experiment - Theory	309	\pm 82	3.8 σ	

116 592 089 ± 63 (recent update by Aoyama et al., 2020)

Brookhaven experiment, 2005/6 Keshavarzi et al, 2018, Davier et al., 2019

$$\Delta a_{\mu} = a_{\mu}^{exp} - a_{\mu}^{SM} = (279 \pm 76) \times 10^{-11}$$

New Physics explanation of Δa_{μ}

assumption
$$\Delta a_{\mu} \simeq a_{\mu}^{NP}$$

In comparison with the weak interaction contribution $a_{\mu}^{\text{weak}} = 1.54 \times 10^{-9}$ NP effects huge!

$$\mathcal{L}_{eff} = \frac{c_d}{\Lambda_{NP}^2} \bar{L} \,\sigma_{\mu\nu} \, l_R \, H \, F^{\mu\nu}$$

$$a_{\mu}^{NP} \simeq C \frac{m_{\mu}^2}{\Lambda_{NP}^2} \qquad \Lambda_{NP} \sim 1.9 \,\mathrm{TeV}$$

$$C \simeq 1 \qquad \text{loop factor } \frac{1}{16 \,\pi^2}$$

$$a_{\mu}^{NP} \simeq C \frac{m_{\mu} \,m_t}{\Lambda_{NP}^2} \qquad \Lambda_{NP} \sim 80 \,\mathrm{TeV}$$



Simplicity: only one new boson scalar or vector

Increase significant for the large mass in the loop! Scalar leptoquark?

Scalar LQs

Symbol	$(SU(3)_c, SU(2)_L, U(1)_Y)$	Interactions	F = 3B + L
S_3	$(\overline{3},3,1/3)$	$\overline{Q}^{C}L$	-2
R_2	$({f 3},{f 2},7/6)$	$\overline{u}_R L, \overline{Q} e_R$	0
\widetilde{R}_2	$({f 3},{f 2},1/6)$	$\overline{d}_R L$	0
\widetilde{S}_1	$(\overline{f 3},{f 1},4/3)$	$\overline{d}_R^C e_R$	-2
S_1	$(\overline{3},1,1/3)$	$\overline{Q}^{C}L, \overline{u}_{R}^{C}e_{R}$	-2

 $Q = I_3 + Y$

Doršner, SF, Greljo, Kamenik, Košnik, Phys. Rep. 641, 1, 2016

Single scalar LQ explanation

F≠0 proton destabilization



 $\bar{\mu}_L t_R S \\ \bar{\mu}_R t_L S$

both couplings are necessary - chirality flip

S₃= (3,3,1/3)

S₁= (3,1,1/3)

both chiralities of quarks/leptons

Only left-handed quarks/leptons

$$S_3 = \begin{cases} S_3^{4/3} \\ S_3^{1/3} \\ S_3^{-2/3} \end{cases}$$
 can mix $S_1 = (\bar{3}, 1, 1/3)$

LQ pairs	Mixing field(s)	$(g-2)_{\mu}$	ν -mass
$S_1 \& S_3$	H H	u	_
$\widetilde{S}_1 \& S_3$	H H	d	—
$\widetilde{R}_2 \& R_2$	H H	d	—
$\widetilde{R}_2 \& S_1$	Н	—	d
$\widetilde{R}_2 \& S_3$	Н	_	d

Mixing of S_a and S_b

Two states after mixing

$$\mathcal{M}^2 = \begin{pmatrix} m_{S_a}^2 & \Omega\\ \Omega & m_{S_b}^2 \end{pmatrix} \qquad \begin{pmatrix} S_+^{(1/3)}\\ S_-^{(1/3)} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta\\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S_3^{(1/3)}\\ S_1^{(1/3)} \end{pmatrix} \qquad \tan 2\theta = \frac{2\Omega}{m_{S_a}^2 - m_{S_b}^2}$$

$$m_{S_{\pm}^{(Q)}}^{2} = \frac{m_{S_{a}}^{2} + m_{S_{b}}^{2}}{2} \pm \frac{1}{2}\sqrt{(m_{S_{a}}^{2} - m_{S_{b}}^{2})^{2} + 4\Omega^{2}}$$

We consider mixing of

$$\mathcal{L}_{\text{mix}}^{S_1 \& S_3} = \xi H^{\dagger}(\vec{\tau} \cdot \vec{S_3})HS_1^* + \text{h.c.}$$

$$\mathcal{L}_{\text{mix}}^{\tilde{S}_1 \& S_3} = \xi H^T i\tau_2(\vec{\tau} \cdot \vec{S_3})H\tilde{S}_1^* + \text{h.c.}$$

$$\mathcal{L}_{\text{mix}}^{\tilde{R}_2 \& R_2} = -\xi \left(R_2^{\dagger}H\right) \left(\tilde{R}_2^T i\tau_2 H\right) + \text{h.c.}$$

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$$\mathcal{L}_{\text{mix}}^{\tilde{R}_2 \& R_2 = -\xi \left(R_2^{\dagger}H\right) \left(\tilde{R}_2^T i\tau_2 H\right) + \text{h.c.}$$

$$\mathcal{L}_{\text{mix}}^{\tilde{R}_2 \to R_2^{\tilde{R}_2 \to R_2^{\tilde$$

Additional constraints

$$Z \to l \, l \, \& \, Z \to \nu \bar{\nu}$$



 $m_S > 1.6 \,\mathrm{TeV}$

CMS-PAS-EX17-003

ATLAS:1707.0242;1709.07242



Four mass eigenstates $m_S = m_{S_3}^{(4/3)} = m_{S_3}^{(-2/3)}$ $m_{S_{\pm}} = m_{S_{\pm}}^{(1/3)}$

$$\mathcal{L}_{S_1 \& S_3} = y_R^{ij} \, \bar{u}_{Ri}^C e_{Rj} \, S_1^{(1/3)} - y_L^{ij} \bar{d}_{Li}^C \nu_{Lj} \, S_3^{(1/3)} - \sqrt{2} y_L^{ij} \bar{d}_{Li}^C e_{Lj} \, S_3^{(4/3)} + \sqrt{2} \, (V^* y_L)^{ij} \, \bar{u}_{Li}^C \nu_{Lj} \, S_3^{(-2/3)} - (V^* y_L)^{ij} \, \bar{u}_{Li}^C e_{Lj} \, S_3^{(1/3)} + \text{h.c.} \,,$$

$$\mathcal{L}_{\text{mix}}^{S_1 \& S_3} = \xi \, H^{\dagger}(\vec{\tau} \cdot \vec{S_3}) H S_1^* + \text{h.c.}$$

Parameters in our study $\{m_{S_3}, m_{S_1}, \xi, y_L^{b\mu}, y_R^{t\mu}\}$



the T-parameter constraint is weaker than the naive perturbative bound



Allowed values for masses of $\rm S_3 \ \& \ S_1$ that can address (g-2)_{\mu}

Limit considerably lower than for the single LQ solutions of the (g-2) with the maximal LQ mass $\sim 100 \text{ TeV}$

(et al. 2014, Biggio et al. 2014, Bauer et al. 2015, Coluccio-Leskow et al.2016, Kowalska et al. 2018, Mandal et al. 2019)

2) b quark in the loop

$$R_2 = (3, 2, 7/6) \& \tilde{R}_2 = (3, 2, 1/6)$$

$$\mathcal{L}_{\widetilde{R}_2} = -y_L^{ij} \,\overline{d}_{Ri} \widetilde{R}_2 i \tau_2 L_j + \text{h.c.},$$

 $\mathcal{L}_{R_2} = y_R^{ij} \,\overline{Q}_i e_{Rj} R_2 + \text{h.c.}.$ $\mu \text{b constraints}$

$$\mathcal{L}_{\mathrm{mix}}^{\widetilde{R}_2 \& R_2} = -\xi \left(R_2^{\dagger} H \right) \left(\widetilde{R}_2^T i \tau_2 H \right) + \mathrm{h.c.}$$

T parameter allows mass splitting \leq 50 GeV (Keith and Ma, 1997; Froggatt et al, 1992)

Mixing of $R_2 \& \tilde{R}_2$ (considered by Košnik, 2012) 2/3 charge states mix

b coupling contributes only!



Constraints allow to explain $(g-2)_{\mu}at 2\sigma$ level!

$$S_3 = (\bar{3}, 3, 4/3) \& \tilde{S}_1 = (3, 1, 4/3)$$

Neither of these can explain $\mbox{(g-2)}_{\mu}$ separately

$$\mathcal{L}_{\widetilde{S}_{1}} = y_{R}^{ij} \, \overline{d}_{Ri}^{C} \, e_{Rj} \, \widetilde{S}_{1} + \text{h.c.} \qquad \mathcal{L}_{S_{3}} = y_{L}^{ij} \, \overline{Q}_{i}^{C} \, i\tau_{2} (\vec{\tau} \cdot \vec{S}_{3}) L_{j} + \text{h.c.}$$
$$\mathcal{L}_{\widetilde{S}_{1}}^{\widetilde{S}_{1} \& S_{3}} = \xi \, H^{T} \, i\tau_{2} (\vec{\tau} \cdot \vec{S}_{3}) H \widetilde{S}_{1}^{*} + \text{h.c.}$$



Constraints allow to explain $(g-2)_{\mu}at 2\sigma$ level!

3) Charm quark in the loop

$$S_1 = (\bar{3},\,1,\,1/3)\,\&\,S_3 = (\bar{3},\,3,\,1/3)$$
 mixing

Chiral enhancement not significant $(m_c << m_t)$

$$\delta a_{\mu} \approx -3 \times 10^{-9} \left(\frac{\xi}{1.9}\right) \left(\frac{\operatorname{Re}(y_L^{s\mu} y_R^{c\mu})}{1.5}\right) \left(\frac{1 \,\mathrm{TeV}}{m_S}\right)^4$$

for the maximal ξ < 1.9 $m_S pprox 1\,{
m TeV}$

from T-parameter in agreement with LHC data and perturbative limit

Strong constraints from

$$\frac{BR(D^0 \to \mu\mu) < 6.2 \times 10^{-9}}{\frac{|y_L^{s\mu} y_R^{c\mu}|}{m_S^2}} \lesssim 0.12 \,\text{TeV}^{-2}$$

This allows only a marginal improvement of a_{μ} !

Electron anomalous magnetic moment

$$\Delta a_e = a_e^{\exp} - a_e^{\rm SM} = -(8.7 \pm 3.6) \times 10^{-13}, \text{ Parker et al., 2018}$$
$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\rm SM} = (2.79 \pm 0.76) \times 10^{-9}$$

opposite sign of a_{μ}

Is it possible to explain both using the same NP model? LQs?

For example S₁ (single LQ solution) can have both chiralities $S_1(\overline{3}, 1, 1/3)$

$$\Delta a_e = -\frac{3m_e^2}{8\pi^2 M^2} \left[\frac{m_t}{m_e} Re\left(V_{tb}^* y_{31}^L (y_{31}^R)^* \right) \left(\frac{7}{6} + \frac{2}{3} \ln x_t \right) - \frac{1}{12} \left(|y_{31}^R|^2 + |y_{31}^L|^2 \right) \right],$$

$$\Delta a_\mu = -\frac{3m_\mu^2}{8\pi^2 M^2} \left[\frac{m_t}{m_\mu} Re\left(V_{tb}^* y_{32}^L (y_{32}^R)^* \right) \left(\frac{7}{6} + \frac{2}{3} \ln x_t \right) - \frac{1}{12} \left(|y_{32}^R|^2 + |y_{32}^L|^2 \right) \right],$$

However, MEG experimental bound Bennet et al., 2016

$$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

$$x = y_{31}^R / y_{32}^R \qquad BR(\mu \to e\gamma) = \frac{\tau_\mu \alpha \ m_\mu^3}{16} \left(\frac{\Delta a_e^2}{m_e^2} \ \frac{1}{x^2} + \frac{\Delta a_\mu^2}{m_\mu^2} \ x^2 \right)$$

 $(BR(\mu \to e\gamma))^{\min} = \frac{\tau_{\mu} \alpha \ m_{\mu}^3}{8} \frac{|\Delta a_e \Delta a_{\mu}|}{m_e m_{\mu}} = 1.6 \times 10^{-4} \text{ independent on LQ mass!}$

This cannot satisfy experimental bound!

Dorsner, SF, Saad 2006.1164

Single LQ scenario S_1 and R_2 top loops for both (μ and e) and top loops (μ) and charm loops (e) LQ mixing $S_1 \& S_{3}$, top for both $S_1 \& S_{3}$, top loops (µ) and charm loops (e)

 $R_2 \& \tilde{R}_2$ Top for μ , bottom for e

Due to $\mu
ightarrow e \gamma ~~$ constraints none of these scenarios can work for both $a_{\mu}~$ and $a_{e}~~!$

The only solution is either S₁ for a_e and R₂ for a_μ or vice versa !

Summary of LQ-mixing in $(g-2)_{\mu}$

- Fermilab measurement will help to understand whether is (g-2)_u SM;
- Two light scalar LQ can resolve existing discrepancy $(S_1 \& S_3, top in the loop);$
- We showed that mixing of two scalar LQs might generate couplings of μ with quark having both chiralities and resolved the (g-2)_{μ} discrepancy;
- $(g-2)_{\mu}$ and $(g-2)_{e}$ cannot be explained either by single LQ or by LQ mixing due to the bound from $\mu \to e\gamma$.

