## Muon g-2 and scalar leptoquark mixing

Svjetlana Fajfer

Physics Department, University of Ljubljana and
J. Stefan Institute, Ljubljana, Slovenia


## ICHEP 2020 |PRAGUE

## Outline

> Motivation
$\Rightarrow$ SM or NP in muon anomalous magnetic moment
$>$ Explaining (g-2) discrepancy by leptoquarks
$>$ Mixing of scalar leptoquarks and $(\mathrm{g}-2)_{\mu}$

- phenomenological constraints on the LQ mixing
- top, bottom or charm in the loop
$>\mu \rightarrow \mathrm{e} \psi$ selecting scalar LQ solution for $(\mathrm{g}-2)_{\mu, \mathrm{e}}$
$>$ Conclusions
I.Doršner, SF and O. Sumensari, 1910.03877
I.Doršner, SF and S. Saad, 2006.1164

| Contribution | $a_{\mu} \times 10^{11}$ | Reference |  |
| :--- | :---: | :--- | :---: |
| QED (leptons) | $116584718.853 \pm 0.036$ | Aoyama et al. '12 |  |
| Electroweak | 153.6 | $\pm 1.0$ |  |
| HVP: LO | 6889.1 | $\pm 35.2$ |  |
| NLO | -99.2 | $\pm 1.0$ |  |
| NNLO | 12.4 | $\pm 0.1$ |  |
| HLbL | Jegendiger et al. '13 |  |  |
| NLO | 102 | $\pm 39$ |  |
| Kurz et al. '14 |  |  |  |
| Theory (SM) | 3 | $\pm 2$ |  |
| Experiment | 116591.780 | $\pm 53$ |  |
| Experiment - Theory | 116592 | 089 |  |
| 309 | $\pm 63$ | Colangelo et al. '14 |  |
|  |  |  |  |

Brookhaven experiment, 2005/6

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

Keshavarzi et al, 2018,
Davier et al., 2019

New Physics explanation of $\Delta a_{\mu}$ assumption $\Delta a_{\mu} \simeq a_{\mu}^{N P}$

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

$$
\begin{aligned}
& \mathcal{L}_{e f f}=\frac{c_{d}}{\Lambda_{N P}^{2}} \bar{L} \sigma_{\mu \nu} l_{R} H F^{\mu \nu} \\
& a_{\mu}^{N P} \simeq C \frac{m_{\mu}^{2}}{\Lambda_{N, P}^{2}} \rightarrow \Lambda_{N P} \sim 1.9 \mathrm{TeV} \\
& C \simeq 1 \quad \text { loop factor } \frac{1}{16 \pi^{2}} \\
& a_{\mu}^{N P} \simeq C \frac{m_{\mu} m_{t}}{\Lambda_{N P}^{2}} \quad \Lambda_{N P} \sim 80 \mathrm{TeV}
\end{aligned}
$$



- SM fermion + new boson
- new fermions + SM bosons
- new fermions + new bosons

Simplicity: only one new boson scalar or vector

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

## Scalar LQs

| Symbol | $\left(S U(3)_{c}, S U(2)_{L}, U(1)_{Y}\right)$ | Interactions | $F=3 B+L$ |
| :---: | :---: | :---: | :---: |
| $S_{3}$ | $(\overline{\mathbf{3}}, \mathbf{3}, 1 / 3)$ | $\bar{Q}^{C} L$ | -2 |
| $R_{2}$ | $(\mathbf{3}, \mathbf{2}, 7 / 6)$ | $\bar{u}_{R} L, \bar{Q} e_{R}$ | 0 |
| $\widetilde{R}_{2}$ | $(\mathbf{3}, \mathbf{2}, 1 / 6)$ | $\bar{d}_{R} L$ | 0 |
| $\widetilde{S}_{1}$ | $(\overline{\mathbf{3}}, \mathbf{1}, 4 / 3)$ | $\bar{d}_{R}^{C} e_{R}$ | -2 |
| $S_{1}$ | $(\overline{\mathbf{3}}, \mathbf{1}, 1 / 3)$ | $\bar{Q}^{C} L, \bar{u}_{R}^{C} e_{R}$ | -2 |
| Doršner, SF, Greljo, Kamenik, Košnik, Phys. Rep. 641, 1, 2016 |  |  |  |

Single scalar LQ explanation

both couplings are necessary - chirality flip

$$
\begin{gathered}
\begin{array}{c}
\mathcal{L}^{F=0}=\bar{q}_{i}\left(l^{i j} P_{R}+r^{i j} P_{L}\right) \ell_{j} S+\text { h.c. } \\
\mathcal{L}^{|F|=2}=\bar{q}_{i}^{C}\left(l^{i j} P_{L}+r^{i j} P_{R}\right) \ell_{j} S+\text { h.c. } . \\
\left.a_{\mu}=-\frac{N_{c} m_{\mu}}{8 \pi^{2} m_{S}^{2}} \sum_{q} \simeq m_{\mu}\left(\left|l^{q \mu}\right|^{2}+\left|r^{q \mu}\right|^{2}\right) \mathcal{F}_{Q_{S}}\left(x_{q}\right)+m_{q}\right] \\
a_{\mu P}^{N P}
\end{array} \quad \text { the same chirality } \quad a_{\mu}^{N P} \simeq C \frac{m_{\mu}^{2} m_{t}}{\Lambda_{N P}^{2}}
\end{gathered}
$$

$$
\text { only } S_{1} \text { and } R_{2} \text { can explain } a_{\mu}
$$

both chiralities

$$
x_{q}=\frac{m_{q}^{2}}{m_{S}^{2}}
$$

Scalar LQ mixing

$$
S_{3}=(\overline{3}, 3,1 / 3) \quad S_{1}=(\overline{3}, 1,1 / 3)
$$

both chiralities of quarks/leptons
Only left-handed quarks/leptons

$$
S_{3}=\left\{\begin{array}{l}
S_{3}^{4 / 3} \\
S_{3}^{1 / 3} \\
S_{3}^{-2 / 3}
\end{array} \text { can mix } S_{1}=(\overline{3}, 1,1 / 3)\right.
$$

| LQ pairs | Mixing field(s) | $(g-2)_{\mu}$ | $\nu$-mass |
| :---: | :---: | :---: | :---: |
| $S_{1} \& S_{3}$ | $H H$ | $u$ | - |
| $\widetilde{S}_{1} \& S_{3}$ | $H H$ | $d$ | - |
| $\widetilde{R}_{2} \& R_{2}$ | $H H$ | $d$ | - |
| $\widetilde{R}_{2} \& S_{1}$ | $H$ | - | $d$ |
| $\widetilde{R}_{2} \& S_{3}$ | $H$ | - | $d$ |

## Mixing of $S_{a}$ and $S_{b}$

Two states after mixing

$$
\begin{gathered}
\mathcal{M}^{2}=\left(\begin{array}{cc}
m_{S_{a}}^{2} & \Omega \\
\Omega & m_{S_{b}}^{2}
\end{array}\right) \quad\binom{S_{+}^{(1 / 3)}}{S_{-}^{(1 / 3)}}=\left(\begin{array}{cc}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{array}\right)\binom{S_{3}^{(1 / 3)}}{S_{1}^{(1 / 3)}} \quad \tan 2 \theta=\frac{2 \Omega}{m_{S_{a}}^{2}-m_{S_{b}}^{2}} \\
m_{S_{ \pm}^{(Q)}}^{2}=\frac{m_{S_{a}}^{2}+m_{S_{b}}^{2}}{2} \pm \frac{1}{2} \sqrt{\left(m_{S_{a}}^{2}-m_{S_{b}}^{2}\right)^{2}+4 \Omega^{2}}
\end{gathered}
$$

We consider mixing of

$$
\begin{aligned}
& \mathcal{L}_{\text {mix }}^{S_{1} \& S_{3}}=\xi H^{\dagger}\left(\vec{\tau} \cdot \overrightarrow{S_{3}}\right) H S_{1}^{*}+\text { h.c. } \\
& \mathcal{L}_{\text {mix }}^{\widetilde{S}_{1} \& S_{3}}=\xi H^{T} i \tau_{2}\left(\vec{\tau} \cdot \vec{S}_{3}\right) H \widetilde{S}_{1}^{*}+\text { h.c. } \\
& \mathcal{L}_{\text {mix }}^{\widetilde{R}_{2} \& R_{2}}=-\xi\left(R_{2}^{\dagger} H\right)\left(\widetilde{R}_{2}^{T} i \tau_{2} H\right)+\text { h.c. }
\end{aligned}
$$

mixing parameter

$$
\Omega=-\xi v^{2} / 2
$$

relevant constraint on $\xi$ oblique corrections ( $\Delta \mathrm{T}$ parameter)

$$
\begin{gathered}
\Delta T=T-T^{\mathrm{SM}} \quad \Delta T=0.05(12) \\
\text { e.g. } \quad m_{S_{1}} \gg m_{S_{3}}>|\Omega|
\end{gathered}
$$

$$
\Delta T_{S_{1} \& S_{3}}=\frac{N_{c}}{4 \pi s_{W}^{2}} \frac{1}{m_{W}^{2}} \frac{\Omega^{2}}{m_{S_{1}}^{2}}+\mathcal{O}\left(\frac{\Omega^{2}}{m_{S_{1}}^{4}}\right)
$$

$$
\widetilde{m}_{S_{3}}=m_{S_{1}}=1.6 \mathrm{TeV} \quad|\xi|<3.1(3.9) \text { at } 1 \sigma(2 \sigma)
$$

$$
m_{S_{3}}=1.6 \mathrm{TeV}, m_{S_{1}}=3 \mathrm{TeV} \quad|\xi|<4.4(5.6)
$$

## Additional constraints

## $Z \rightarrow l l \& Z \rightarrow \nu \bar{\nu}$

$$
\begin{aligned}
\delta \mathcal{L}_{\text {eff }}^{Z}= & \frac{g}{\cos \theta_{W}} \sum_{i, j} \bar{\ell}_{i} \gamma^{\mu}\left[g_{\ell_{L}}^{i j} P_{L}+g_{\ell_{R}}^{i j} P_{R}\right] \ell_{j} Z_{\mu} \\
& g_{\ell_{L(R)}}^{i j}=\delta_{i j} g_{\ell_{L(R)}}^{\mathrm{SM}}+\delta g_{\ell_{L(R)}}^{i j} \\
& \text { LHC constraints }
\end{aligned}
$$

$$
g g(q \bar{q}) \rightarrow S^{*} S
$$

most constraining

$$
\begin{array}{r}
\mathcal{B}(S \rightarrow t \mu)=1, \quad(\mathcal{B}(S \rightarrow b \mu)=1) \\
m_{S} \gtrsim 1400 \mathrm{GeV}\left(m_{S} \gtrsim 1420 \mathrm{GeV}\right)
\end{array}
$$

$$
S \rightarrow t \mu, S \rightarrow b \mu
$$

for the second quark generation

$$
S \rightarrow j \mu \quad m_{S} \gtrsim 1530 \mathrm{GeV}
$$

Indirectly can be probed via high $\mathrm{p}_{\mathrm{T}}$ dilepton-tails at LHC Faroughy, Greljo and Kamenik, 2015

CMS-PAS-EX17-003
We use
$m_{S} \geq 1.6 \mathrm{TeV}$

ATLAS:1707.0242;1709.07242

## 1) top quark in the loop $\left(S_{1} \& S_{3}\right)$



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

$$
\begin{gathered}
\mathcal{L}_{S_{1} \& S_{3}}=y_{R}^{i j} \bar{u}_{R i}^{C} e_{R j} S_{1}^{(1 / 3)}-y_{L}^{i j} \bar{d}_{L i}^{C} \nu_{L j} S_{3}^{(1 / 3)}-\sqrt{2} y_{L}^{i j} \bar{d}_{L i}^{C} e_{L j} S_{3}^{(4 / 3)} \\
+\sqrt{2}\left(V^{*} y_{L}\right)^{i j} \bar{u}_{L i}^{C} \nu_{L j} S_{3}^{(-2 / 3)}-\left(V^{*} y_{L}\right)^{i j} \bar{u}_{L i}^{C} e_{L j} S_{3}^{(1 / 3)}+\text { h.c. } \\
\mathcal{L}_{\operatorname{mix}}^{S_{1} \& S_{3}}=\xi H^{\dagger}\left(\vec{\tau} \cdot \overrightarrow{S_{3}}\right) H S_{1}^{*}+\text { h.c. }
\end{gathered}
$$

Parameters in our study $\quad\left\{m_{S_{3}}, m_{S_{1}}, \xi, y_{L}^{b \mu}, y_{R}^{t \mu}\right\}$


## 2) b quark in the loop

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

2/3 charge states mix

$$
\mathcal{L}_{\widetilde{R}_{2}}=-y_{L}^{i j} \bar{d}_{R i} \widetilde{R}_{2} i \tau_{2} L_{j}+\text { h.c. }
$$

$$
\mathcal{L}_{R_{2}}=y_{R}^{i j} \bar{Q}_{i} e_{R j} R_{2}+\text { h.c. }
$$

$$
\mathcal{L}_{\text {mix }}^{\widetilde{R}_{2} \& R_{2}}=-\xi\left(R_{2}^{\dagger} H\right)\left(\widetilde{R}_{2}^{T} i \tau_{2} H\right)+\text { h.c. }
$$

T parameter allows mass splitting $\leq 50 \mathrm{GeV}$ (Keith and Ma, 1997; Froggatt et al, 1992)
$\underset{\text { (considered by Košnik, 2012) }}{\text { Mixing of }} R_{2}^{\&} \tilde{R}_{2}$
Mixing of $R_{2} \& \tilde{R}_{2}$
(considered by Košnik, 2012)
$\mu \mathrm{b}$ coupling contributes only!
It


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

$$
S_{3}=(\overline{3}, 3,4 / 3) \& \tilde{S}_{1}=(3,1,4 / 3)
$$

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

$$
\mathcal{L}_{\widetilde{S}_{1}}=y_{R}^{i j} \bar{d}_{R i}^{C} e_{R j} \widetilde{S}_{1}+\text { h.c. } \quad \mathcal{L}_{S_{3}}=y_{L}^{i j} \bar{Q}_{i}^{C} i \tau_{2}\left(\vec{\tau} \cdot \vec{S}_{3}\right) L_{j}+\text { h.c. }
$$

$$
\mathcal{L}_{\text {mix }}^{\widetilde{S}_{1} \& S_{3}}=\xi H^{T} i \tau_{2}\left(\vec{\tau} \cdot \vec{S}_{3}\right) H \widetilde{S}_{1}^{*}+\text { h.c. }
$$




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

## 3) Charm quark in the loop

$$
S_{1}=(\overline{3}, 1,1 / 3) \& S_{3}=(\overline{3}, 3,1 / 3) \quad \text { mixing }
$$

Chiral enhancement not significant $\left(m_{c} \ll m_{t}\right)$

$$
\delta a_{\mu} \approx-3 \times 10^{-9}\left(\frac{\xi}{1.9}\right)\left(\frac{\operatorname{Re}\left(y_{L}^{s \mu} y_{R}^{c \mu}\right)}{1.5}\right)\left(\frac{1 \mathrm{TeV}}{m_{S}}\right)^{4}
$$

for the maximal $\xi<1.9 m_{S} \approx 1 \mathrm{TeV}$
from T-parameter in agreement with LHC data and perturbative limit

Strong constraints from

$$
\begin{gathered}
B R\left(D^{0} \rightarrow \mu \mu\right)<6.2 \times 10^{-9} \\
\frac{\left|y_{L}^{s \mu} y_{R}^{c \mu}\right|}{m_{S}^{2}} \lesssim 0.12 \mathrm{TeV}^{-2}
\end{gathered}
$$

This allows only a marginal improvement of $a_{\mu}$ !

## Electron anomalous magnetic moment

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

opposite sign of $\mathrm{a}_{\mu}$
Is it possible to explain both using the same NP model? LQs?

For example $\mathrm{S}_{1}$ (single LQ solution) can have both chiralities $\quad S_{1}(\overline{3}, 1,1 / 3)$
$\Delta a_{e}=-\frac{3 m_{e}^{2}}{8 \pi^{2} M^{2}}\left[\frac{m_{t}}{m_{e}} \operatorname{Re}\left(V_{t b}^{*} y_{31}^{L}\left(y_{31}^{R}\right)^{*}\right)\left(\frac{7}{6}+\frac{2}{3} \ln x_{t}\right)-\frac{1}{12}\left(\left|y_{31}^{R}\right|^{2}+\left|y_{31}^{L}\right|^{2}\right)\right]$,
$\Delta a_{\mu}=-\frac{3 m_{\mu}^{2}}{8 \pi^{2} M^{2}}\left[\frac{m_{t}}{m_{\mu}} \operatorname{Re}\left(V_{t b}^{*} y_{32}^{L}\left(y_{32}^{R}\right)^{*}\right)\left(\frac{7}{6}+\frac{2}{3} \ln x_{t}\right)-\frac{1}{12}\left(\left|y_{32}^{R}\right|^{2}+\left|y_{32}^{L}\right|^{2}\right)\right]$

However, MEG experimental bound

$$
B R(\mu \rightarrow e \gamma)<4.2 \times 10^{-13}
$$

Bennet et al., 2016

$$
\begin{aligned}
& x=y_{31}^{R} / y_{32}^{R} \quad B R(\mu \rightarrow e \gamma)=\frac{\tau_{\mu} \alpha m_{\mu}^{3}}{16}\left(\frac{\Delta a_{e}^{2}}{m_{e}^{2}} \frac{1}{x^{2}}+\frac{\Delta a_{\mu}^{2}}{m_{\mu}^{2}} x^{2}\right) \\
& (B R(\mu \rightarrow e \gamma))^{\mathrm{min}}=\frac{\tau_{\mu} \alpha m_{\mu}^{3}}{8} \frac{\left|\Delta a_{e} \Delta a_{\mu}\right|}{m_{e} m_{\mu}}=1.6 \times 10^{-4} \text { independent on LQ mass! }
\end{aligned}
$$

This cannot satisfy experimental bound!
Dorsner, SF, Saad 2006.1164

Single LQ scenario $S_{1}$ and $R_{2}$ top loops for both ( $\mu$ and e) and top loops ( $\mu$ ) and charm loops (e)

LQ mixing
$S_{1} \& S_{3}$, top for both
$S_{1} \& S_{3}$, top loops ( $\mu$ ) and charm loops (e)

$$
\mathrm{R}_{2} \& \tilde{\mathrm{R}}_{2}
$$

Top for $\mu$, bottom for e

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

The only solution is either $\mathrm{S}_{1}$ for $a_{e}$ and $\mathrm{R}_{2}$ for $a_{\mu}$ or vice versa!

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

- Fermilab measurement will help to understand whether is $(\mathrm{g}-2)_{\mu} \mathrm{SM}$;
- Two light scalar LQ can resolve existing discrepancy $\left(S_{1} \& S_{3}\right.$, top in the loop);
- We showed that mixing of two scalar LQs might generate couplings of $\mu$ with quark having both chiralities and resolved the $(g-2)_{\mu}$ discrepancy;
- $(g-2)_{\mu}$ and (g-2) cannot be explained either by single LQ or by LQ mixing due to the bound from $\mu \rightarrow e \gamma$.


