$(g-2)_\mu$ and scalar leptoquark(s)

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In collaboration with

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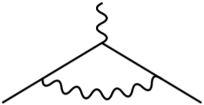
INFN

Università degli Studi di Padova

Introduction

Long-standing discrepancy [$\approx 3.6\,\sigma$] in $(g-2)_\mu$:

$$a_\mu^{\text{exp}} = 116592089(63) \times 10^{-11}$$
$$a_\mu^{\text{SM}} = 116591820(36) \times 10^{-11}$$



[Brookhaven, 2006]
[Keshavarzi et al., '18], [Davier et al. '19]

$\Rightarrow$ Signal of new bosons coupled to muons?

$\Rightarrow$ New results by *Muon* $g-2$ at Fermilab will be soon released!

This talk: (i) Brief overview

(ii) Single-leptoquark solutions

(iii) Leptoquark mixing for $(g-2)_\mu$

Brief overview

Introduction: The anomalous magnetic moment

- Dirac equation predicts for a lepton $\ell = e, \mu, \tau$:

$$\vec{\mu}_\ell = g_\ell \, \frac{e}{2m_\ell} \, \vec{s} \,, \qquad\qquad g_\ell = 2$$

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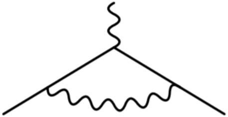
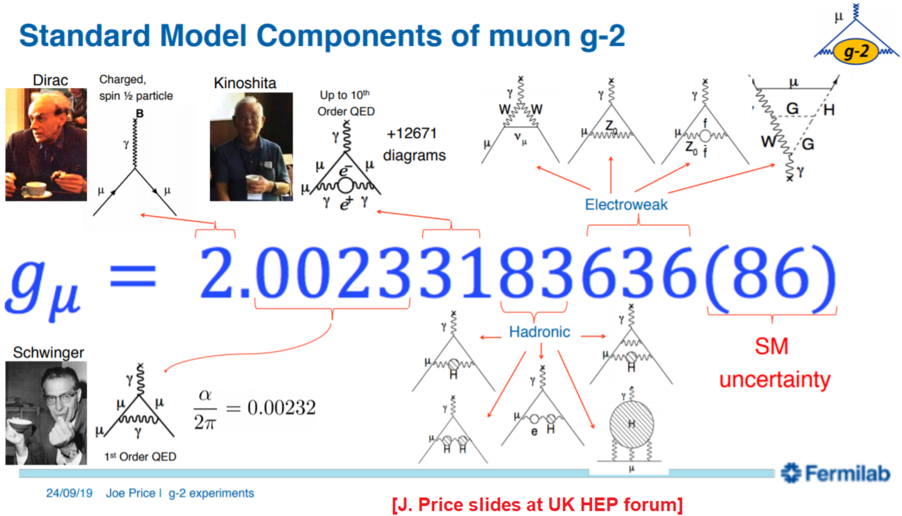


- Study the lepton-photon vertex:

$$\bar{u}(p')\Gamma_\mu u(p) = \bar{u}(p')\Big[\gamma_\mu \mathcal{F}_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_\ell}\mathcal{F}_2(q^2) + \dots\Big]u(p)$$

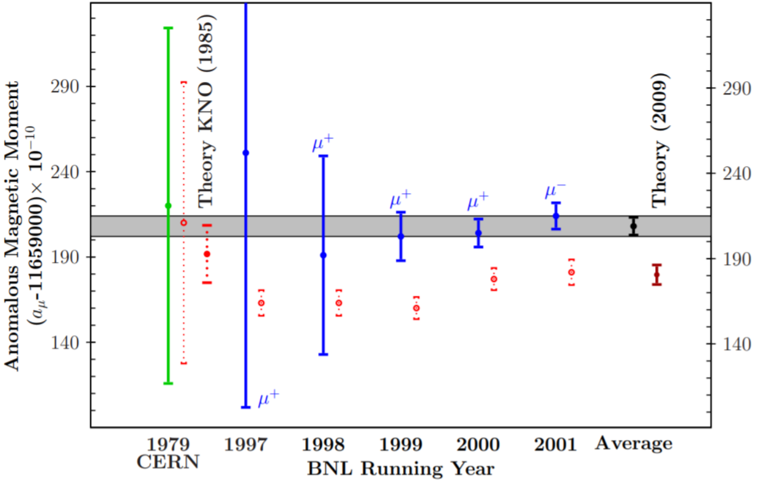
$$\mathcal{F}_1(0) = 1 \qquad\qquad \mathcal{F}_2(0) = a_\ell \propto \frac{\alpha_{\text{em}}}{\pi} + \dots \approx 10^{-3}$$

$\Rightarrow$ Pure quantum effect! Very sensitive probe of new physics



[J. Price slides at UK HEP forum]

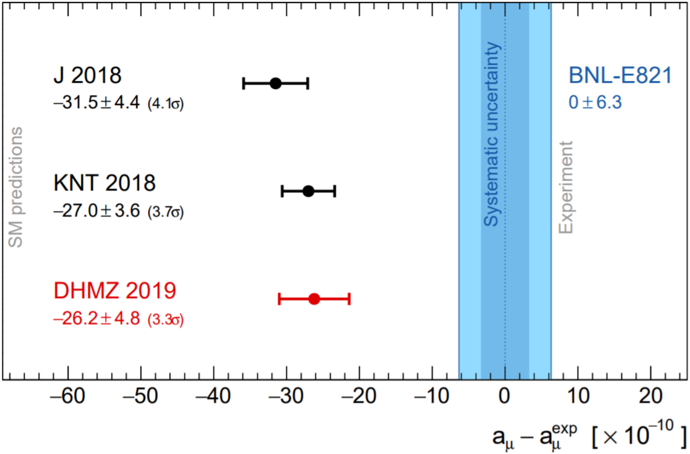
History plot:



[Jegerlehner, Nyffeler. '09]

$\Rightarrow$ BNL delivered 0.5ppm precision.

Current status

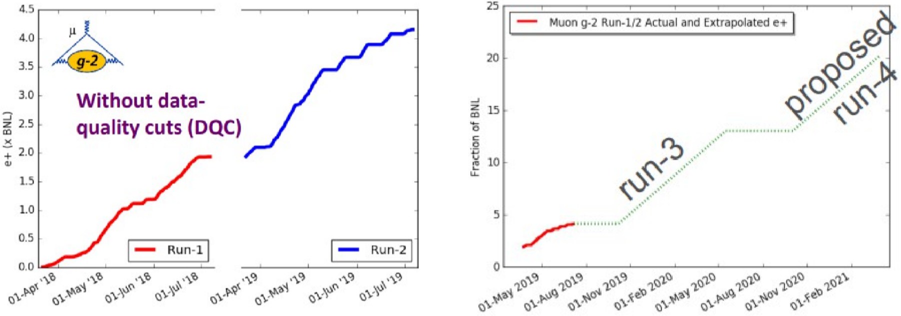


[Davier, Hoecker, Malaescu, Zhang.'19]

⇒ Fermilab aims to reduce the exp. error by $\approx \times 4$.

⇒ Effort to reduce the theory error, cf. "Muon $(g-2)$ Th. Initiative".

Fermilab data collected compared to BNL:



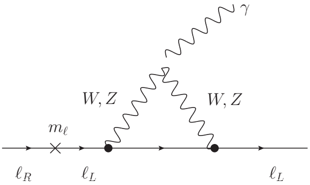
[D. Hertzog talk at "Muon $g-2$ Th. Initiative Workshop", '19]

$\Rightarrow$ News coming very soon!

$(g-2)_\mu$ and new physics: Leptoquarks

$(g-2)_\mu$ and new physics

- Current discrepancy is of similar size of SM electroweak loops:



Naive scaling:

$$\Delta a_\ell \propto \frac{m_\ell^2}{v^2}$$

[Giudice et al. '12]

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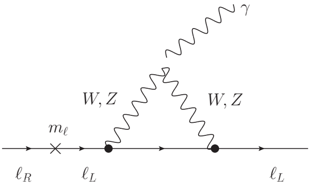

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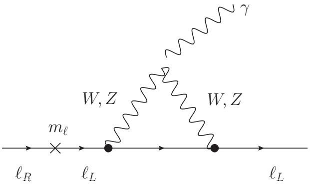

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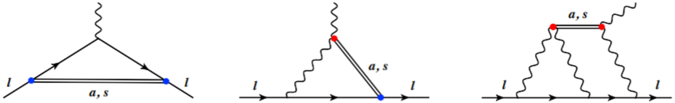
$\Rightarrow$ Either new physics is light, **and/or** an enhacement mechanism takes place (breaking the naive scaling).

- Popular solution: light (pseudo)scalar particles [Marciano et al. '16]



see also [Bauer et al. '19], [Cornella, Paradisi, **OS**. In preparation]

Leptoquarks and chiral enhancement

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (2.7 \pm 0.7) \times 10^{-9}$$

$$\mathcal{L} \supset \frac{c_{\mathrm{dip}}}{\Lambda^2}\, \overline{L}\, \sigma_{\mu\nu} \ell_R\, H\, F^{\mu\nu} + \mathrm{h.c.}$$

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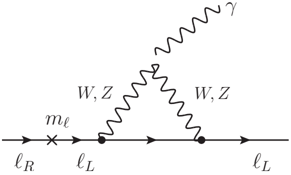

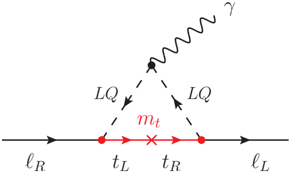

$\Rightarrow$ LQs should couple to $\overline{\mu_L}\, t_R\, S$ **and** $\overline{\mu_R}\, t_L\, S$.

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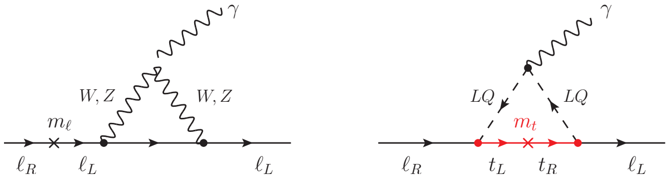

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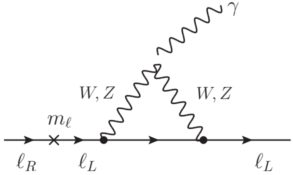

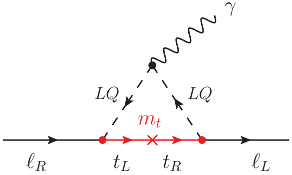

$\Rightarrow$ LQs should couple to $\overline{\mu_L}\, t_R\, S$ **and** $\overline{\mu_R}\, t_L\, S$.

$\Rightarrow$ Perturbativity implies that $m_{\text{LQ}} \lesssim 30$ TeV.

$\Rightarrow$ Only two models are viable: $S_1 = (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$ and $R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$.

[Cheung. '01]

Leptoquarks for $(g-2)_\mu$

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

- Are there other potentially large contributions in LQ models?
- What if more than one scalar LQ exist?

Leptoquark mixing for $(g-2)_\mu$

[Dorsner, Fajfer, **OS**. 1910.03877].

Why two scalar LQs?

⇒ Having more than one LQ is motivated by theory/phenomenology:

- $SU(5)$ unification possible with two light scalar LQs.

  cf. e.g. [Dorsner et. al. '18]

- Models for radiative neutrino masses.

  [Mahanta, '99], [Chua et al. '99]

- B-physics anomalies require more than one (scalar) LQ.

  [Angelescu, Becirevic, Faroughy, **OS**. '18]

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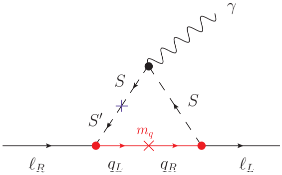
Leptoquark mixing

⇒ Scalar LQs can mix with the SM Higgs (cf. [Hirsch. '06]), inducing new contributions to dipoles!

[Dorsner, Fajfer, **OS**. 1910.03877].

$$\mathcal{L} \supset \xi\, HHSS' \quad \text{or} \quad g\, HSS'$$



⇒ Chirality enhancement induced by mixing of chiral LQs!

Viable scenarios

[Dorsner, Fajfer, **OS**. 1910.03877].

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	–
$\tilde{R}_2 - S_1$	H	–	d
$\tilde{R}_2 - S_3$	H	–	d

- Two new possibilities with non-chiral LQs – but stemming from different couplings: R_2-$\widetilde{R}_2$ and S_1-S_3.
- One entirely new scenario: $\widetilde{S}_1$-S_3.

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Remainder of this talk: (i) How does it work? S_1-S_3 via top loops

(iii) Mixing scenarios with b-quark loops

How does it work?

Example: S_1-S_3 via top loops

• Take two scalars $S_a^{(Q)}$ and $S_b^{(Q)}$, from different EW multiplets, with same electric charge Q, and mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} m_{S_a}^2 & \Omega \\ \Omega & m_{S_b}^2 \end{pmatrix}$$

where Ω is the mixing term and $m_{S_{a,b}}$ are the masses prior to mixing.

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- **New mass eigenstates** with charge Q are:

$$\begin{pmatrix} S_+^{(Q)} \\ S_-^{(Q)} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S_a^{(Q)} \\ S_b^{(Q)} \end{pmatrix}, \qquad \tan 2\theta = \frac{2\,\Omega}{m_{S_a}^2 - m_{S_b}^2}$$

with

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

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$$m^2_{S_\pm^{(Q)}} = \frac{m_{S_a}^2 + m_{S_b}^2}{2} \pm \frac{1}{2}\sqrt{(m_{S_a}^2 - m_{S_b})^2 + 4\,\Omega^2}\,,$$

• Maximal mixing ($\theta = \pi/4$) can arise for $m_S \equiv m_{S_a} = m_{S_b}$:

$$\delta m_S^{(Q)} \equiv m_{S_+}^{(Q)} - m_S \simeq m_S - m_{S_-}^{(Q)} \qquad (m_{S_{a,b}} \gg \Omega)$$

Example: $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ & $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$$\mathcal{L}_{S_1} = y_R^{ij}\, \overline{u_{Ri}^C} e_{Rj}\, S_1 + \text{h.c.}\,,$$

$$\mathcal{L}_{S_3} = y_L^{ij}\, \overline{Q_i^C} i\tau_2 (\vec{\tau} \cdot \vec{S}_3) L_j + \text{h.c.}\,,$$

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$$\mathcal{L}_{S_3} = y_L^{ij}\, \overline{Q_i^C} i\tau_2 (\vec{\tau}\cdot\vec{S}_3) L_j + \text{h.c.}\,,$$

These states can mix via the SM Higgs:

$$\mathcal{L}_{\text{mix}} \supset \xi\, H^\dagger (\vec{\tau}\cdot\vec{S}_3) H S_1^* + \text{h.c.} \qquad \Longrightarrow \qquad \mathcal{M}^2_{S^{(1/3)}} = \begin{pmatrix} m^2_{S_3} & -\frac{\xi v^2}{2} \\ -\frac{\xi v^2}{2} & m^2_{S_1} \end{pmatrix}$$

Mass eigenstates:

$$\begin{pmatrix} S_+^{(1/3)} \\ S_-^{(1/3)} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S_3^{(1/3)} \\ S_1^{(1/3)} \end{pmatrix}.$$

$\Rightarrow$ Both mass-eigenstates have couplings with $\overline{u_L^C}\, e_L$ and $\overline{u_R^C}\, e_R$.

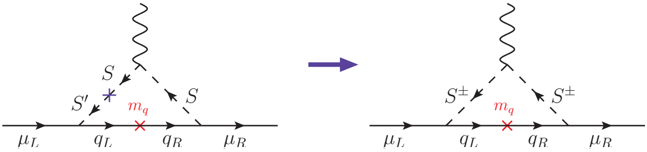
Example: $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ & $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ $\quad (g-2)_\mu$

Yukawa choice:

$$\mathcal{L}_{S_1} = y_R^{ij}\, \overline{u_{Ri}^C} e_{Rj}\, S_1 + \text{h.c.}\,,$$

$$\mathcal{L}_{S_3} = y_L^{ij}\, \overline{Q_i^C} i\tau_2 (\vec{\tau}\cdot\vec{S}_3) L_j + \text{h.c.}\,,$$

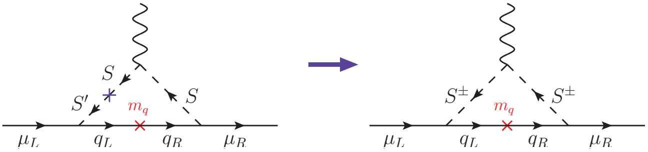
with $y^L_{t\mu} \neq 0$ and $y^R_{t\mu} \neq 0$.



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

Example: $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ & $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ $(g-2)_\mu$

- **Chirality-enhanced** contribution:



$$\delta a_\mu \propto \frac{m_\mu^2}{m_S^2}(\dots) + m_\mu m_t \, y_L^{b\mu} \, y_R^{t\mu\,*} \left[\frac{\mathcal{G}_{1/3}(x_t^+)}{m_{S_+}^2} - \frac{\mathcal{G}_{1/3}(x_t^-)}{m_{S_-}^2} \right]$$

with $x_t^\pm = m_t^2/m_{S_\pm}^2$.

- For **maximal mixing** ($\theta = \pi/4$), this contribution reads

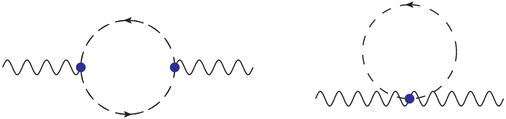
$$\delta a_\mu \propto \frac{m_\mu m_t}{m_S^2} \frac{\delta m_S}{m_S} y_R^{b\mu} y_L^{t\mu}$$

$\Rightarrow$ Crucial: How do we fix δm_S?

T-parameter:

$$\Delta T = -\frac{N_c}{4\pi c_w^2 s_w^2} \frac{1}{m_Z^2} \left[\cos^2\theta \, F(m_{S_3}, m_{S_-}) + \sin^2\theta \, F(m_{S_3}, m_{S_+}) \right],$$

with $F(m,m) = 0$.



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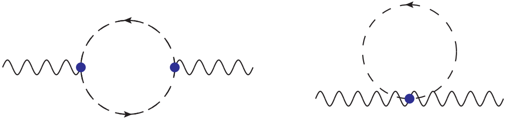


Expanding on δm_S for maximal mixing ($\theta = \pi/4$):

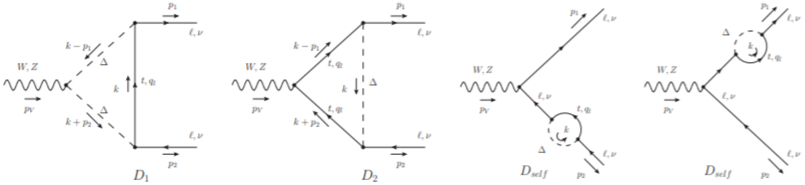
$$\Delta T = \frac{N_c}{3\pi c_w^2 s_w^2}\frac{\delta m_S^2}{m_Z^2} + \dots$$

$\Delta T^{\text{exp}} = 0.05(12) \quad \Rightarrow \quad |\delta m_S| \lesssim 40$ GeV [Gfitter. '12]

LQs modify the Z-couplings to leptons at one-loop:

$$\delta\mathcal{L}_{\mathrm{eff}}^{Z} = \frac{g}{\cos\theta_W} \sum_{i,j} \bar{\ell}_i \gamma^\mu \left[g_{\ell_L}^{ij} \, P_L + g_{\ell_R}^{ij} \, P_R \right] \ell_j \, Z_\mu$$

$$g_{\ell_{L(R)}}^{ij} = \delta_{ij} \, g_{\ell_{L(R)}}^{\mathrm{SM}} + \delta g_{\ell_{L(R)}}^{ij}$$

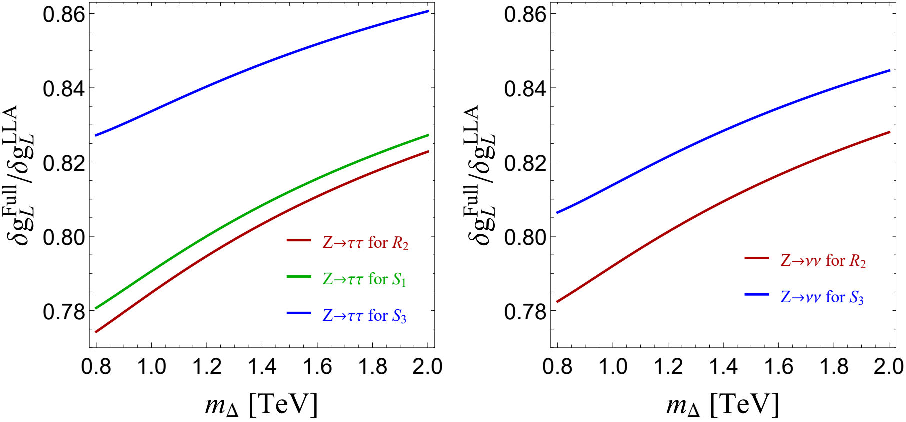


$\Rightarrow$ Complete one-loop computation: [Arnan, Becirevic, Mescia, **OS**. '19]

Yukawas and flavor

$Z \to \ell\ell$ and $Z \to \nu\bar{\nu}$

[Arnan, Becirevic, Mescia, **OS**. '19]



⇒ To compare with leading-log approximation (LLA). cf. [Feruglio et al. '16]

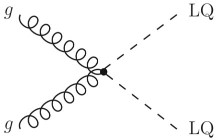
⇒ $\mathcal{O}(20\%)$ corrections due to external momenta ($\propto x_Z \log x_t$) not considered before. cf. e.g. [Neubert et al. '15], [Buttazo et al. '17] + many more

LHC constraints

$U_1 = (3, 1, 2/3)$

- LQ pair-production via QCD:

[CMS-PAS-EXO-17-003]

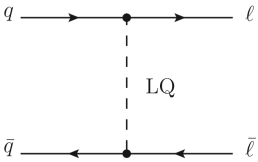


$m_S \gtrsim 1.6$ TeV

[*conservative choice;* $q\mu$ *final state*]

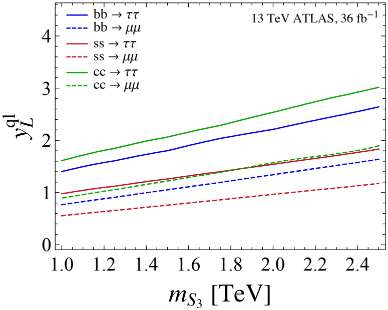
- Di-lepton tails at high-pT:

[ATLAS. 1707.02424,1709.07242]



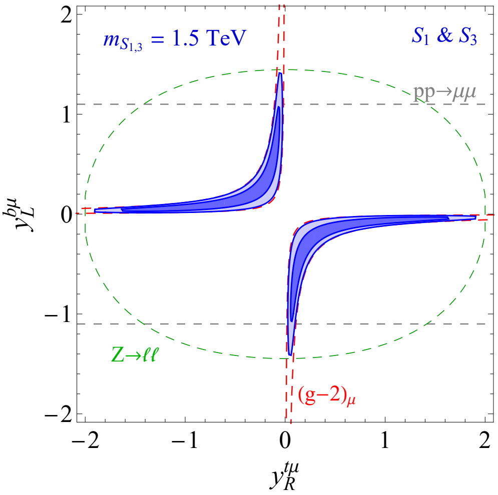
[Angelescu, Becirevic, Faroughy, OS. '18]

[see also Faroughy et al. '15]



Combining everything

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

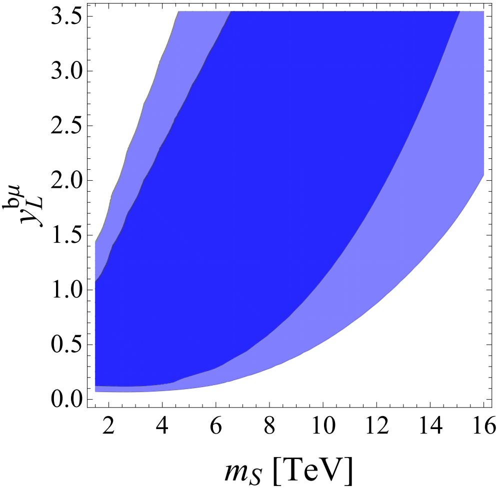


Benchmark:

- Maximal mixing ($\theta = \pi/4$).
- $\delta m_S = 40$ GeV (EWPT).

How heavy can the LQs be?

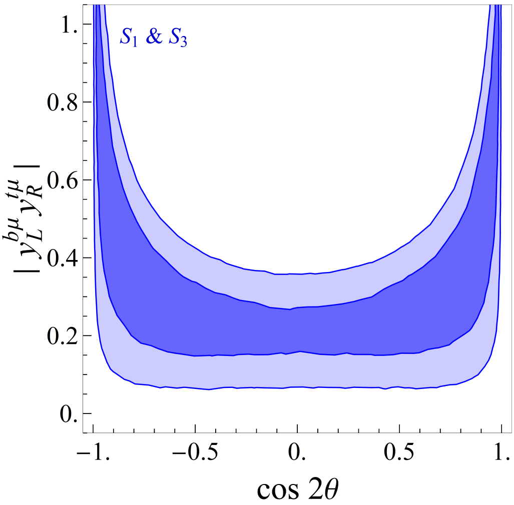
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ & $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$



$\Rightarrow$ Yukawa perturbativity ($\lesssim \sqrt{4\pi}$) $\Rightarrow$ $m_S \lesssim 15$ TeV.

Maximal mixing or not?

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



⇒ It does not change much...

Other possibilities: b-quark loops

Reminder:

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

Other possibilities - I

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

- Yukawa choice:

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

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

with $y_{b\mu}^L \neq 0$ and $y_{b\mu}^R \neq 0$.

Other possibilities - I $\qquad R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$ & $\widetilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$

- Yukawa choice:

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

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

with $y^L_{b\mu} \neq 0$ and $y^R_{b\mu} \neq 0$.

- Mixing with SM Higgs: see also [Kosnik. '12]

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

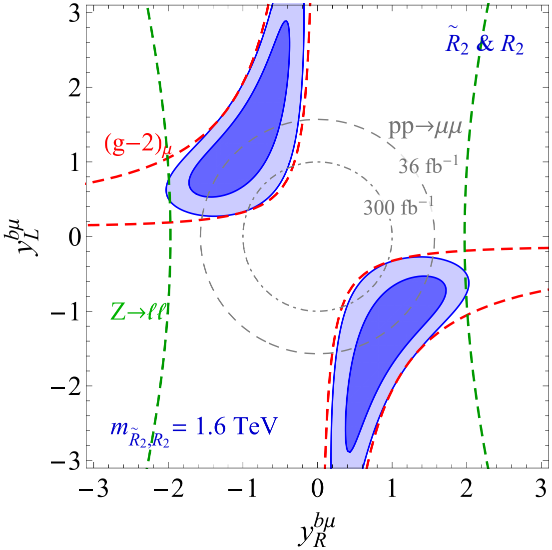
$\Rightarrow$ Mixing of $Q = 2/3$ components of doublets.

$\Rightarrow$ EWPT gives $\delta m_S \lesssim 50$ GeV for maximal mixing.

$\Rightarrow$ Diquark couplings forbidden by gauge invariance.

Other possibilities - I

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



Other possibilities - II

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

- Yukawa choice:

$$\mathcal{L}_{\widetilde{S}_1} = y_R^{ij}\, \bar{d}_{Ri}^{C}\, e_{Rj}\, \widetilde{S}_1 + \text{h.c.}\,,$$

$$\mathcal{L}_{S_3} = y_L^{ij}\, \bar{Q}_i^{C}\, i\tau_2(\vec{\tau}\cdot\vec{S}_3)L_j + \text{h.c.}\,,$$

with $y_{b\mu}^L \neq 0$ and $y_{b\mu}^R \neq 0$.

- Yukawa choice:

$$\mathcal{L}_{\widetilde{S}_1} = y_R^{ij}\, \bar{d}_{Ri}^{C}\, e_{Rj}\, \widetilde{S}_1 + \text{h.c.}\,,$$

$$\mathcal{L}_{S_3} = y_L^{ij}\, \bar{Q}_i^{C}\, i\tau_2 (\vec{\tau} \cdot \vec{S}_3) L_j + \text{h.c.}\,,$$

with $y_{b\mu}^{L} \neq 0$ and $y_{b\mu}^{R} \neq 0$.

- Mixing with SM Higgs:

$$\mathcal{L}_{\text{mix}}^{\widetilde{S}_1\,\&\,S_3} = \xi\, H^T\, i\tau_2 (\vec{\tau} \cdot \vec{S}_3) H \widetilde{S}_1^* + \text{h.c.}\,,$$

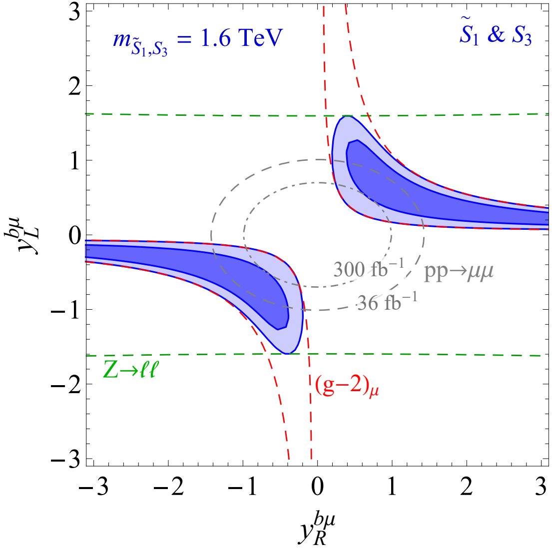
$\Rightarrow$ Mixing of $Q = 4/3$ components of doublets.

$\Rightarrow$ EWPT gives $\delta m_S \lesssim 50$ GeV for maximal mixing.

$\Rightarrow$ Entirely new scenario!

Other possibilities - II

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



Summary and perspectives

- $(g-2)_\mu$ remains one of the most precise tests of the SM validity.

  Clarification from Fermilab coming soon!

- We summarize the viable single LQ explanations to $(g-2)_\mu$.

  Top-quark chirality enhancement $\Rightarrow m_S \lesssim 30$ TeV

- We propose the mixing of two scalar LQs as a new mechanism for chirality enhancement and identify three new viable scenarios

  Complementarity between EWPT, LHC and flavor data

- Building a concrete model to simultaneously explain $(g-2)_\mu$ and the B-physics anomalies remains a very challenging task.

  Data-driven model building!

Thank you!

Back-up

Limits on LQ pair-production

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

Decays	LQs	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	S_1, R_2, S_3, U_1, U_3	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	R_2, S_3, U_1, U_3	850 (550) GeV	1550 (1290) GeV	12.9 fb^{-1} [49]
$t\bar{t}\,\tau\bar{\tau}$	S_1, R_2, S_3, U_3	900 (560) GeV	1440 (1220) GeV	35.9 fb^{-1} [50]
$jj\,\mu\bar{\mu}$	S_1, R_2, S_3, U_1, U_3	1530 (1275) GeV	2110 (1860) GeV	35.9 fb^{-1} [51]
$b\bar{b}\,\mu\bar{\mu}$	R_2, U_1, U_3	1400 (1160) GeV	1900 (1700) GeV	36.1 fb^{-1} [52]
$t\bar{t}\,\mu\bar{\mu}$	S_1, R_2, S_3, U_3	1420 (950) GeV	1780 (1560) GeV	36.1 fb^{-1} [53, 54]
$jj\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	980 (640) GeV	1790 (1500) GeV	35.9 fb^{-1} [55]
$b\bar{b}\,\nu\bar{\nu}$	S_1, R_2, S_3, U_3	1100 (800) GeV	1810 (1540) GeV	35.9 fb^{-1} [55]
$t\bar{t}\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	1020 (820) GeV	1780 (1530) GeV	35.9 fb^{-1} [55]

B-anomalies

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

[Angelescu, Becirevic, Faroughy, **OS**. '18]

$$\delta a_\mu = -\frac{N_c\, m_\mu^2}{8\pi^2} \Bigg\{ 2\,|y_L^{b\mu}|^2\, \frac{\mathcal{F}_{4/3}(x_b)}{m_{S_3}^2} + \Big[\sin^2\theta\,|y_R^{t\mu}|^2 + \cos^2\theta\,|y_L^{b\mu}|^2\Big] \frac{\mathcal{F}_{1/3}(x_t^-)}{m_{S_-}^2}$$

$$+ \Big[\cos^2\theta\,|y_R^{t\mu}|^2 + \sin^2\theta\,|y_L^{b\mu}|^2\Big] \frac{\mathcal{F}_{1/3}(x_t^+)}{m_{S_+}^2}$$

$$+ \frac{m_t}{m_\mu} \sin\theta\cos\theta\,\mathrm{Re}\big(y_L^{b\mu}\, y_R^{t\mu\,*}\big) \left[\frac{\mathcal{G}_{1/3}(x_t^+)}{m_{S_+}^2} - \frac{\mathcal{G}_{1/3}(x_t^-)}{m_{S_-}^2} \right] \Bigg\},$$