Addressing the Muon Anomalies with Muon-Flavored Leptoquarks

Anders Eller Thomsen
with A. Greljo & P. Stangl [2103.13991]

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b
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$b \to s\ell^+\ell^-$ anomalies

- LHCb measurements of $R_K^{[1,6]}$, $R_{K^*}^{[1.1,6]}$, and $R_{K^*}^{[0.045,1.1]}$ deviate from SM at 3.1σ, 2.5σ, and 2.3σ, respectively

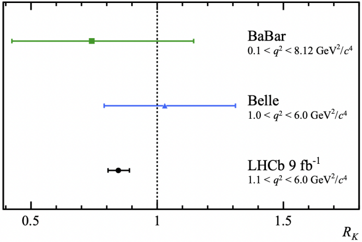
$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

- Average ATLAS, CMS, and LHCb $B_s \to \mu^+\mu^-$ branching ratio deviate from SM by 2σ

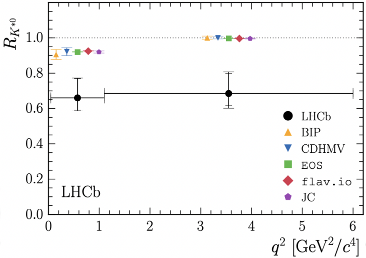
Altmannshofer, Stangl [2103.13370]

- Angular observables in $B \to K^*\mu^+\mu^-$ and branching ratios in $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$
- Consistent picture emerges in the EFT (primarily a left-handed current): global 3.9σ significance for NP hypothesis

Lancierini *et al.* [2104.05631]



Aaij *et al.* [2103.11769]



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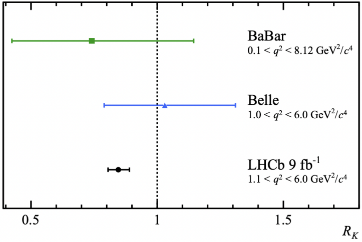
B anomalies? No, muon anomalies!



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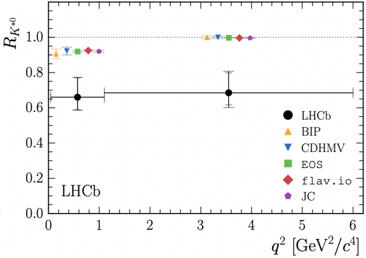

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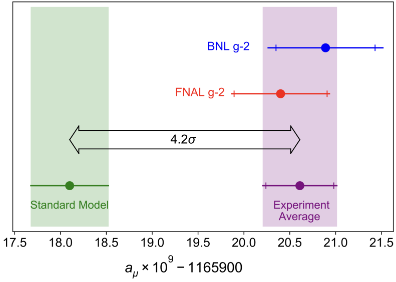
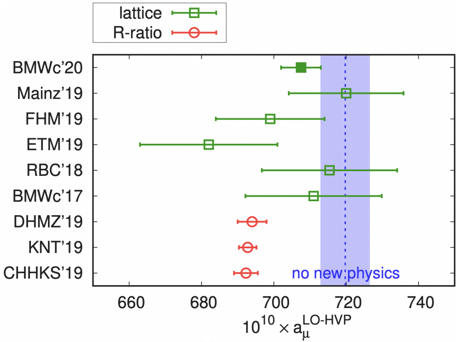
$(g-2)_\mu$ anomaly





Abi *et al.* [2104.03281]

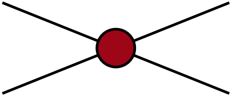
Borsany *et al.* [2002.12347]

- First measurement of the Fermilab Muon g-2 Experiment is compatible with the Brookhaven experiment. Combined 4.2σ discrepancy with the Muon g-2 Theory Initiative. Aoyama *et al.* [2006.04822]
- HVP is the dominant error of the SM prediction. Lattice results (BMWc) in potential disagreement with the data-driven calculations (R-ratio) used in SM prediction.

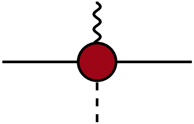
Muon anomalies in $\mathcal{L}_6$

Effective description of the anomalies with dimension-6 operators:

$$b \to s\ell^+\ell^- : \quad \frac{V_{ts}}{(10\,\mathrm{TeV})^2}(\bar{b}_\mathrm{L}\gamma_\mu s_\mathrm{L})(\overline{\mu}_\mathrm{L}\gamma^\mu \mu_\mathrm{L})$$



$$(g-2)_\mu : \quad \frac{1}{(10\,\mathrm{TeV})^2}\frac{g'}{(4\pi)^2}B_{\mu\nu}H(\bar{\ell}_2\sigma^{\mu\nu}\mu)$$



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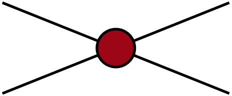

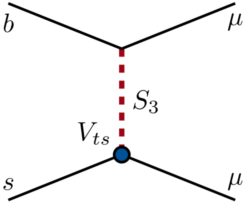

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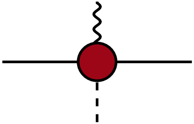

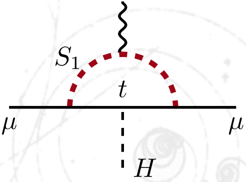

Crivellin, Müller, Ota [1703.09226]
Gherardi, Marzocca, Venturini [2008.09548]

What we do *not* see

Accidental symmetries of $\mathcal{L}_{\mathrm{SM}}$:

$$\mathrm{U}(1)_B \times \mathrm{U}(1)_{L_e} \times \mathrm{U}(1)_{L_\mu} \times \mathrm{U}(1)_{L_\tau}$$

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$$\mathcal{L}_{\mathrm{eff}} \supset \frac{e\,v}{(4\pi)^2 \Lambda_{ij}^2}(\bar{\ell}_i \sigma_{\mu\nu} P_{\mathrm{R}} \ell_j) F^{\mu\nu} \qquad \begin{cases} \Lambda_{\mu\tau} > 30\,\mathrm{TeV} \\ \Lambda_{e\mu} > 3 \cdot 10^4\,\mathrm{TeV} \end{cases}$$

Best fit of Δa_μ is $\Lambda_{\mu\mu} = 14\,\mathrm{TeV}$

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No B violation, no LFV, but indications of LFUV

The problem with leptoquarks

TeV scale scalar leptoquarks

$$\mathcal{L} \supset y(LQ)S + z(QQ)S^*$$

Pati-Salam type vector LQs do not have di-quark couplings and are great candidates for combined explanations of B anomalies.

lead to violation of SM accidental symmetries:

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B violation is so problematic that even a dimension-5 contribution $z \sim v/M_{\mathrm{Pl}}$ is excluded. Arnold, Formal, Wise [1304.6119] Assad, Formal, Grinstein [1708.06350]

$\implies$ Global symmetries might not be sufficiently robust

Leptoquarks with a $\mathrm{U}(1)_X$ symmetry

Impose a local $\mathrm{U}(1)_X$ symmetry to rescue scalar leptoquarks

examples in Hambye, Heck [1712.04871], Davighi, Kirk, Nardecchia [2007.15016]

Need to have:

- Lepton-flavor-specific charges —
  allowing QL_iS for $i = \mu$ but not for $i = e, \tau$
- An S charge to forbid QQS^* coupling
- A remnant (approximate) LF symmetry

Comprehensive study in Greljo, Soreq, Stangl, AET, Zupan [2107.07518]

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Leptoquark $\longrightarrow$ Muoquark

The $B - 3L_\mu$ model

Fields	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{B-3L_\mu}$
q_L	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/3$
u_R	$\mathbf{3}$		$2/3$	$1/3$
d_R	$\mathbf{3}$		$-1/3$	$1/3$
ℓ_L		$\mathbf{2}$	$-1/2$	$\{0, -3, 0\}$
e_R			-1	$\{0, -3, 0\}$
ν_R			0	$\{0, -3, 0\}$
H		$\mathbf{2}$	$1/2$	0
S_3	$\bar{\mathbf{3}}$	$\mathbf{3}$	$1/3$	$8/3$
S_1	$\bar{\mathbf{3}}$		$1/3$	$8/3$
Φ			0	3

SM: q_L, u_R, d_R, ℓ_L, e_R, ν_R, H

Muoquarks: S_3, S_1

Φ: X-breaking SM singlet

$\mathrm{U}(1)_{B-3L_\mu}$: Muonic force

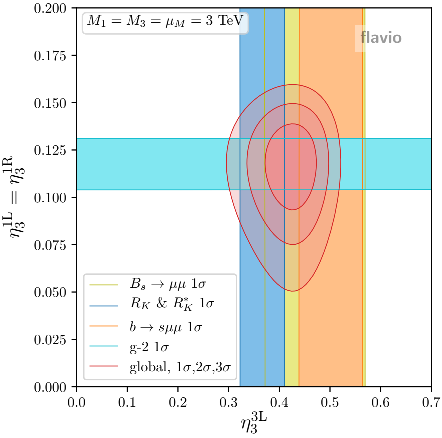
Combined explanation of the anomalies

Anomalies due to the interactions

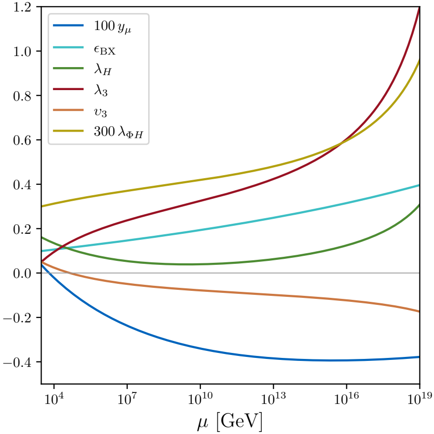
$$\mathcal{L}_{\mathrm{yuk}} \supset -\eta_i^{3\mathrm{L}}\, \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2\, S_3 \\ - \eta_i^{1\mathrm{L}} \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2 S_1 - \eta_i^{1\mathrm{R}} \overline{u}_{\mathrm{R}}^{c\,i} \mu_{\mathrm{R}} S_1$$

- Decoupling limit $\binom{v_\Phi \to \infty}{g_X \to 0}$ ensures NP contribution exclusively from $S_{1,3}$
- Approximate $\mathrm{U}(2)$ flavor symmetry
  Kagan *et al.* [0903.1794]; Barbieri *et al.* [1105.2296]
- Existing 1-loop $S_{1,3}$ matching results
  Gherardi, Marzocca, Venturini [2003.12525]
- Global fit with `smelli` (also using `wilson` and `flavio`)

Best fit favored with $\Delta\chi^2 \simeq 62$ over the SM



Radiative stability



y_u is the muon-Higgs Yukawa; ϵ_{BX} the B_μ–X_μ kinetic mixing; λ_H the Higgs self coupling; λ_3 and υ_3 two S_3 self couplings; $\lambda_{\Phi H}$ the Higgs–Φ portal coupling.

- There are no Landau poles before M_{Pl}
- Large radiative corrections to y_μ:

$$\delta y_\mu = -\frac{3}{(4\pi)^2}\left(1 + \ln\frac{\mu_M^2}{M_1^2}\right)\eta_t^{1\mathrm{L}*} y_t \eta_t^{1\mathrm{R}}$$

- Sizable corrections to the Higgs mass:

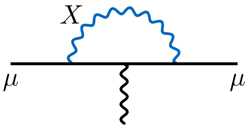
$$\delta\mu_H^2 = -\frac{9(\lambda_{H3} + \kappa_{H3})}{(4\pi)^2} M_3^2 \left(1 + \ln\frac{\mu_M^2}{M_3^2}\right)$$

$$+\frac{3\lambda_{H1}}{(4\pi)^2} M_1^2 \left(1 + \ln\frac{\mu_M^2}{M_1^2}\right)$$

- Preferred muoquark masses
  $M_{1,3} \lesssim \text{few} \times \text{TeV}$ for finite naturalness

Light muon force

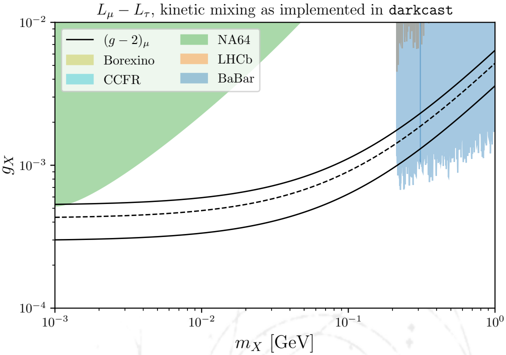
Light X_μ solution to $(g-2)_\mu$



Baek *et al.* [hep-ph/0104141];
Ma, Roy, Roy [hep-ph/0110146];
Altmannshofer *et al.* [1406.2332];
many more...

Minimal muoquark model:

- Lepton-flavored $\mathrm{U}(1)_X$
- S_3 muoquark for $b \to s\ell^+\ell^-$
- $\cancel{S_1} \to X_\mu$ mediator for $(g-2)_\mu$ viable for $10\,\mathrm{MeV} \lesssim m_X < 2m_\mu$



Greljo, Soreq, Stangl, AET, Zupan [2107.07518]

Conclusions and outlook

- Lepton-flavored gauge symmetries provide a good organizing principle for scalar-Leptoquark explanations of the muon anomalies
- Three variations of muoquark models

	Type A	Type B	Type C
$b \to s\mu\mu$	S_3	S_3	heavy X
$(g-2)_\mu$	S_1/R_2	light X	S_1/R_2

Examples in this talk

- Some $\mathrm{U}(1)_X$ groups allow for LQs coupling to taus: could address the $R_{D^{(*)}}$ anomaly
- The $\mathrm{U}(1)_X$ groups impose non-trivial structure in the neutrino sector: can lead to predictions for neutrino mixing parameters