Looking for a Muonic Force in the Muon Anomalies

Anders Eller Thomsen

Flavor at the Crossroads,
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UNIVERSITÄT
BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Muon Anomalies

—New physics in $b \to s\mu^+\mu^-$ and $(g-2)_\mu$?

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

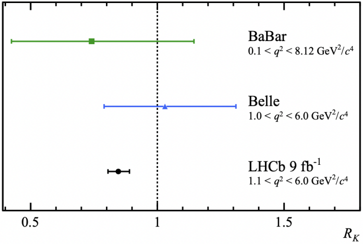
$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

- LHCb measurements of $R_K^{[1.1,6]}$, $R_{K^*}^{[1.1,6]}$, and $R_{K^*}^{[0.045,1.1]}$ deviate from SM by 3.1σ, 2.5σ, and 2.3σ, respectively
- Average ATLAS, CMS, and LHCb $B_s \to \mu^+\mu^-$ branching ratio deviate from SM by 2σ

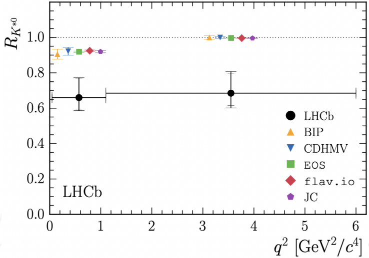
Altmannshofer, Stangl [2103.13370]

- 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: tentative global 4.3σ significance for the NP hypothesis

Lancierini *et al.* [2104.05631]



Aaij *et al.* [2103.11769]



Aaij *et al.* [1705.05802]

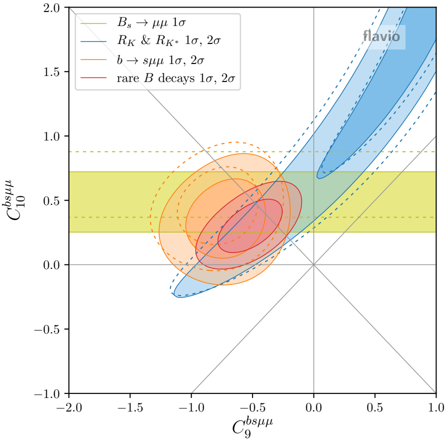
New physics in $b \to s\mu^+\mu^-$

At low-energies a good fit involves (LEFT)

$$\mathcal{L} \supset \frac{4G_F e^2 V_{tb}V_{ts}^*}{\sqrt{2}(4\pi)^2}(\bar{b}\gamma_\nu s)_\mathrm{L}(\bar{\mu}\gamma^\nu(C_9 + C_{10}\gamma_5)\mu)$$

In the unbroken phase of the SM (SMEFT), a left-handed current works well:

$$\mathcal{L}_\mathrm{SMEFT} \supset \frac{-1}{(40\,\mathrm{TeV})^2}(\bar{q}_3\gamma_\nu q_2)_\mathrm{L}(\bar{\ell}_2\gamma^\nu \ell_2)_\mathrm{L}$$



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Analyses from Algueró *et al.* [2104.08921], Ciuchini *et al.* [2011.01212], Hurth *et al.* [2104.10058], largely agree but in some cases favor C_9 over $C_9 - C_{10}$.

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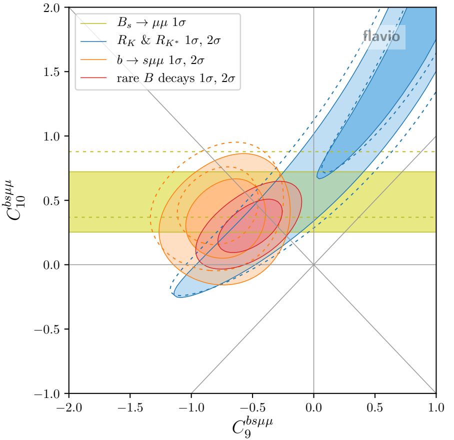
Loop models are also viable

Tree-level mediators:

- Z' neutral vector boson
  UV completion required
- U_1 (U_3) vector LQ
  UV completion required
- *S_3 scalar triplet LQ*
  single-field extension is possible

Flavor structure needed to avoid, e.g., FCNC bounds. MFV does not work. $\mathrm{U}(2)^5$ seems like a good candidate.



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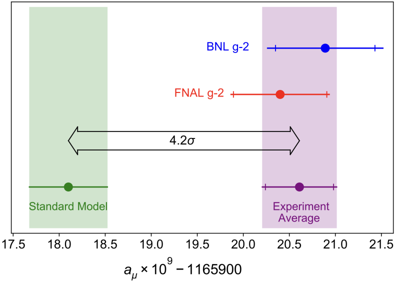
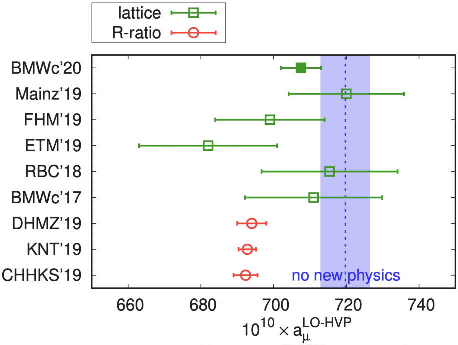
$(g-2)_\mu$ anomaly



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. Potential disagreement between Lattice results (BMWc) and the data-driven approach (R-ratio) used in SM prediction.

New physics in $(g-2)_\mu$

- Many types of NP can account for the discrepancy: VL leptons, 2HDM, MSSM, *light vector bosons*, *leptoquarks*,...
- NP scale can be up to order 10 TeV with chiral enhancement
- EFT fit to $(g-2)_\mu$, $-\frac{e\,v}{(4\pi)^2} C^{ij}_{e\gamma}\, \bar{e}^i_{\mathrm{L}} \sigma^{\mu\nu} e^j_{\mathrm{R}} F_{\mu\nu}$, gives

$$|C^{ij}_{e\gamma}| \sim \frac{1}{(14\,\mathrm{TeV})^2} \begin{pmatrix} \lesssim 10^{-1} & \lesssim 2\cdot 10^{-5} & \lesssim 1/4 \\ & 1 & \lesssim 1/4 \\ & & \lesssim 2\cdot 10^{5} \end{pmatrix}$$

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Mass basis

$\mathrm{BR}(\mu \to e\gamma) < 10^{-12}$

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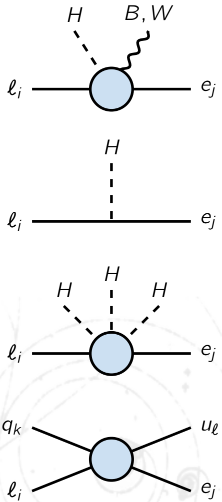
Also very strong CP constraints from EDM ($\lesssim 10^{-8}$)

- Alignment between all SMEFT operators is required

Isidori, Pagès, Wilsch [2111.13724]; Calibbi et al. [2104.03296]

SMEFT operators



Contributes under the RG

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

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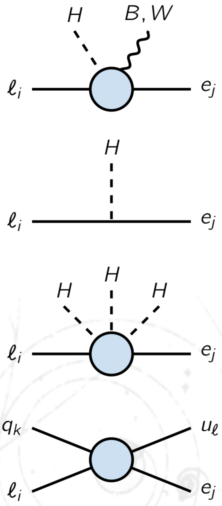
- No charged LFV in NP if it satisfies SM accidental symmetries

SMEFT operators



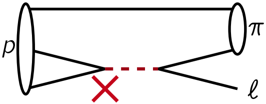
Contributes under the RG

A Muonic Force

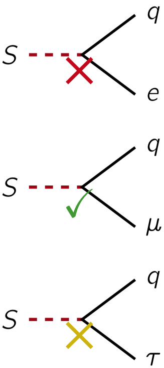
—Are we seeing signs of a new symmetry?

Introducing the muoquarks

Diquark interactions



LQ interactions



Scalar LQ explanations of the anomalies can only have a particular set of interactions

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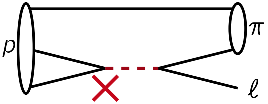

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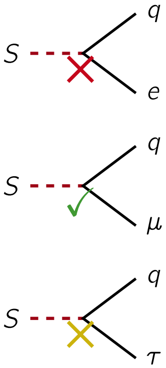
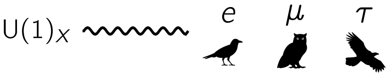


Scalar LQ explanations of the anomalies can only have a particular set of interactions

Solution: *Lepton-flavored gauged* $\mathrm{U}(1)_X$

Hambye, Heeck [1712.04871]; Davighi, Kirk, Nardechia [2007.15016]; Greljo, Stangl, AET [2103.13991]; Greljo, Soreq, Stangl, AET, Zupan [2107.07518]; Davighi, Greljo, AET [2202.05275]; Heeck, Thapa [2202.08854]



Approximate recovery of SM accidental symmetries:

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

$$S \sim (-\tfrac{1}{3},\, 0,\, -1,\; 0)$$

$\sim$500 quark-universal anomaly-free models with integer charge ratios ≤ 10 in SM+$3\nu_{\mathrm{R}}$. Allanach, Davighi, Melville [1812.04602]

Examples: $X = L_\mu - L_\tau$, $X = B - 3L_\mu$, and many, many others

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

Muoquarks

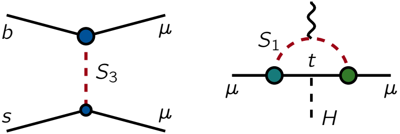
X-breaking
SM singlet

Muonic force

The Nightmare Scenario!

Muoquark (LQ) mediated anomalies

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



with couplings respecting lepton-flavored $\mathrm{U}(1)_X$

- Direct searches give only modest constraints: $M_{1,3} \gtrsim 1.7\,\mathrm{TeV}$
  ATLAS collaboration [2006.05872]
- Decoupling limit $\binom{v_X \to \infty}{g_X \to 0}$ 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
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- *Global fit* with `smelli` (also using `wilson` and `flavio`)

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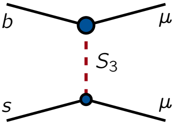

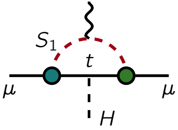

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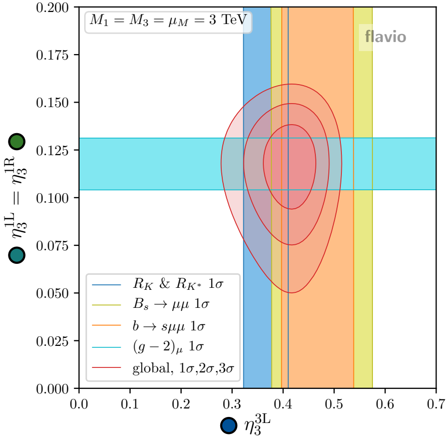
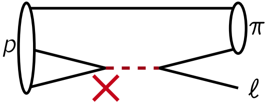


Greljo, Stangl, AET [2103.13991]

Do we need two muoquarks?

Diquark interactions



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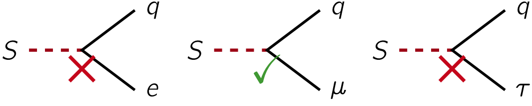

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Scenarios:

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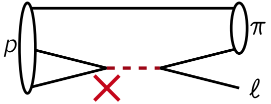

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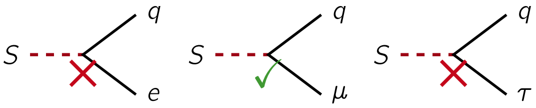

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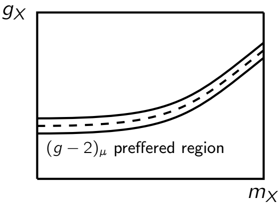
- S_3 muoquark for $b \to s\mu\mu$ and S_1 muoquark for $(g-2)_\mu$
- S_3 muoquark for $b \to s\mu\mu$ and X_μ vector boson of $\mathrm{U}(1)_X$ for $(g-2)_\mu$.

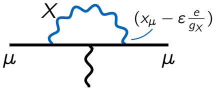
  Are there $\mathrm{U}(1)_X$ groups that allow for this scenario?

$$\mathcal{L} \supset -\tfrac{1}{4} X_{\mu\nu}^2 + \tfrac{1}{2} \underbrace{\varepsilon}_{\text{kinetix mixing parameter}} X_{\mu\nu} F^{\mu\nu} + \tfrac{1}{2} m_X^2 X_\mu^2 + g_X X^\mu \sum_f \overbrace{x_f}^{\text{Charges of SM (chiral) fermions}} \overline{f} \gamma_\mu f$$

Addressing $(g-2)_\mu$ with the muonic force



x_f: charge of fermion f
ε: kinetic mixing of X and γ



Baek *et al.* [hep-ph/0104141];
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many, many more...

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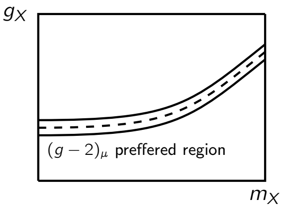

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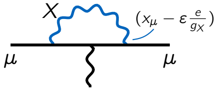

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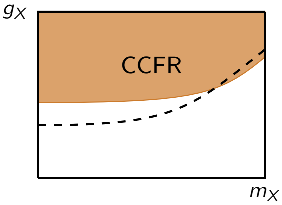

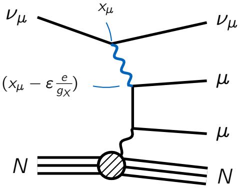

CCFR colaboration '91;
Altmannshofer *et al.* [1406.2332];
Altmannshofer *et al.* [1902.06765];
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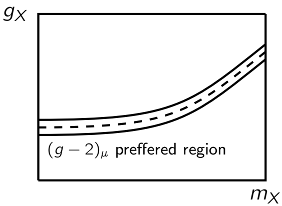

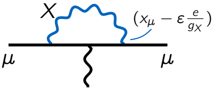

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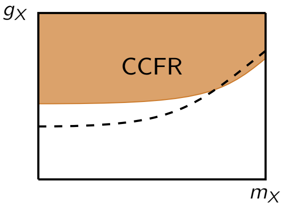

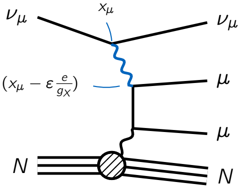

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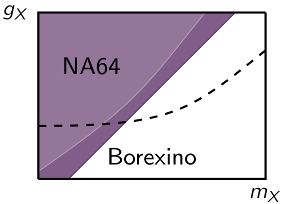
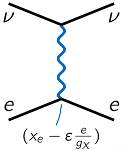
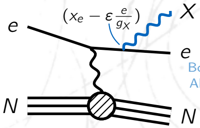
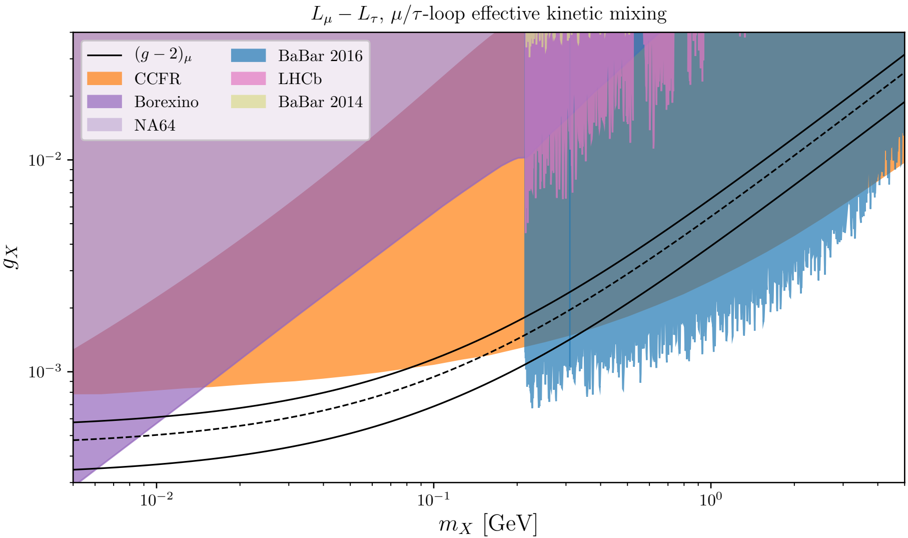






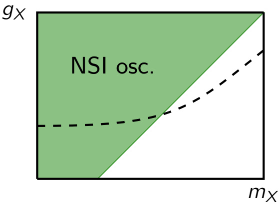
Borexino colaboration [1707.09279];
Altmannshofer *et al.* [1902.06765];
Banerjee *et al.* [1906.00176]

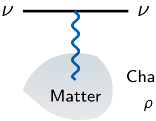
Light vector solution: $X = L_\mu - L_\tau$



Greljo, Stangl, AET, Zupan [2203.13731]

Complementary constraints on a light X



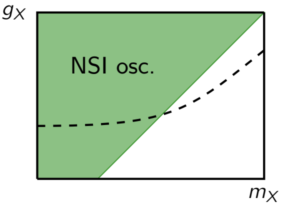


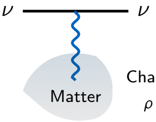
Coloma, Gonzalez-Garcia, Maltoni [2009.14220];
Esteban *et al.* [1805.04530];
Heeck *et al.* [1812.04067] Wolfenstein '78

Charge density:

$\rho \sim 2.05\, x_B + x_e$

Complementary constraints on a light X

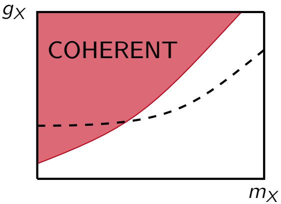


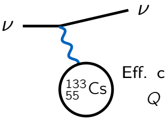


Charge density:

$$\rho \sim 2.05\, x_B + x_e$$

Coloma, Gonzalez-Garcia, Maltoni [2009.14220];
Esteban *et al.* [1805.04530];
Heeck *et al.* [1812.04067] Wolfenstein '78





Eff. charge:

$$Q = A\, x_B + Z\, \varepsilon \frac{e}{g_X}$$

Denton, Gehrlein [2008.06062];
Esteban *et al.* [1805.04530];
COHERENT collaboration [1708.01294];
Freedman '74; Drukier, Stodolsky '84

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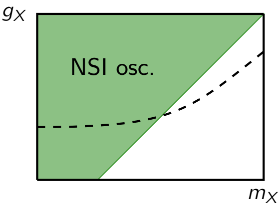

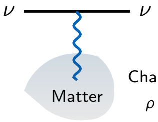

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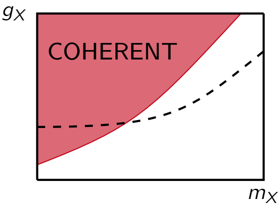

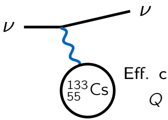

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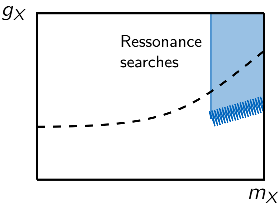
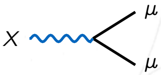
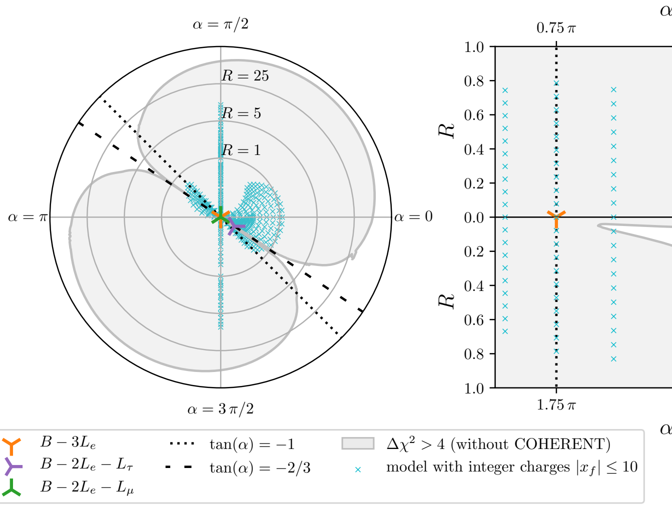




BaBar collaboration [1606.03501];
BaBar collaboration [1406.2980];
LHCb collaboration [1710.02867];
`darkcast`: Ilten *et al.* [1801.04847]

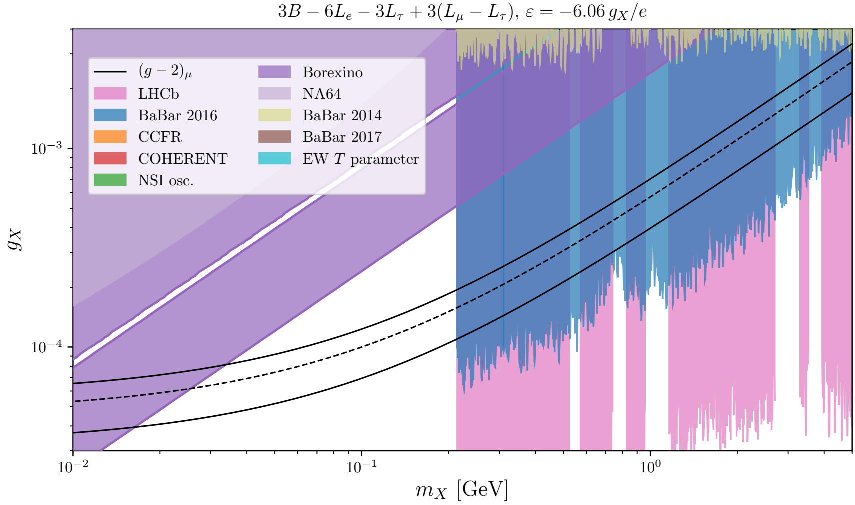
Vector-like $U(1)_X$ solutions to $(g-2)_\mu$

$$\sin(\alpha)(L_e - L_\mu) + \cos(\alpha)(B/3 - L_\mu) + R\,(L_\mu - L_\tau)$$



Light, quark-universal X solutions to $(g-2)_\mu$ in the space of vector-like $U(1)_X$ at $m_X = 200\,\text{MeV}$. Includes NSI osc., NA64, and Borexino bounds. Greljo, Stangl, AET, Zupan [2203.13731]

Allowed model with B charge



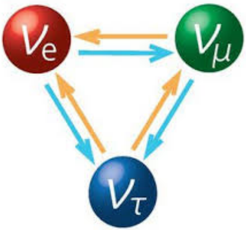
Greljo, Stangl, AET, Zupan [2203.13731]

Proton Stability

—Quality of the broken symmetry

Why break the lepton-flavored $\mathrm{U}(1)_X$

- *LFV is observed in nature!* PMNS matrix is filled with $\mathcal{O}(1)$ elements.
- Neutrino mixing implies the breaking of lepton any flavored $\mathrm{U}(1)_X$



- Current bounds on the proton lifetime is $\tau_p \gtrsim 10^{34}$ yr, but effective B-violation from further new physics is generically suppressed only by $(v_X/\Lambda_{\text{UV}})^n$, which needs to make up 10^{-20}

If $\mathrm{U}(1)_X$ is broken, how good is our protection against proton decay? At dimension 5? 6?...

How good is the symmetry?

The class of vector-like, lepton-flavored,
quark-universal symmetries

$$X = 3m(B - L) - n\,(2L_\mu - L_e - L_\tau)$$

with $[e]_X = [\tau]_X \neq [\mu]_X$.

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Fields	$\mathrm{U}(1)_X$
$q_i,\ u_i,\ d_i$	m
$\ell_{1,3},\ e_{1,3},\ \nu_{1,3}$	$n - 3m$
$\ell_2,\ e_2,\ \nu_2$	$-2n - 3m$
H	0
$S_3,\ S_1$	$2m + 2n$

$$\mathcal{L} \supset -\,y_e^{ij}\bar{\ell}_i e_j H - y_\nu^{ij}\bar{\ell}_i \nu_j H^*$$

$$y_{e,\nu} \sim \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

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$$\begin{aligned}\mathcal{L} \supset &- y_e^{ij}\bar{\ell}_i e_j H - y_\nu^{ij}\bar{\ell}_i \nu_j H^* \\ &- \bar{\nu}^{i\,c}\nu^j(\xi_{e\tau}^{ij}\phi_{e\tau} + \xi_\mu^{ij}\phi_\mu)\end{aligned}$$

Fields	$\mathrm{U}(1)_X$
$q_i,\ u_i,\ d_i$	m
$\ell_{1,3},\ e_{1,3},\ \nu_{1,3}$	$n-3m$
$\ell_2,\ e_2,\ \nu_2$	$-2n-3m$
H	0
$S_3,\ S_1$	$2m+2n$
$\phi_{e\tau}$	$6m-2n$
ϕ_μ	$6m+n$

$$y_{e,\nu} \sim \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \qquad \frac{M_\nu}{v_X} \sim \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

Sufficient for realistic neutrino masses and mixings with a type-I seesaw for $v_X \lesssim 10^{11}$ TeV

e.g. Asai [1907.04042]

Remnant symmetry

The scalar condensate breaks $\mathrm{U}(1)_X \to \Gamma$ in the IR:

$$\Gamma = \left\{ e^{i\alpha} : \; e^{i\alpha[\phi]_X} \phi = \phi \right\} \cong \mathbb{Z}_k , \qquad k = \mathrm{gcd}([\phi_{e\tau}]_X , \, [\phi_\mu]_X)$$

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Diquark operators are banned by Γ *iff*

Davighi, Greljo, AET [2202.05275]

$$\begin{gathered} (m, \, n) = \big(3a + r, \, 9b + 3r\big), \quad \text{for} \quad r \in \{1, \, 2\}, \\ (a, \, b) \in \mathbb{Z}^2, \quad \text{and} \quad \mathrm{gcd}\big(3a + r, \, b - a\big) = 1 \end{gathered} \qquad \Gamma \cong \begin{cases} \mathbb{Z}_9, & \text{for } b + r \in 2\mathbb{Z} + 1 \\ \mathbb{Z}_{18}, & \text{for } b + r \in 2\mathbb{Z} \end{cases}$$

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$b + r \pmod 2$	Γ	ℓ	q	S	$qS\ell$	qS^*q
0	$\mathbb{Z}_{18}$	$9(b-a)$	$3a+r$	$6a+8r$	0	$12r$
1	$\mathbb{Z}_9$	0	$3a+r$	$6a+8r$	0	$3r$

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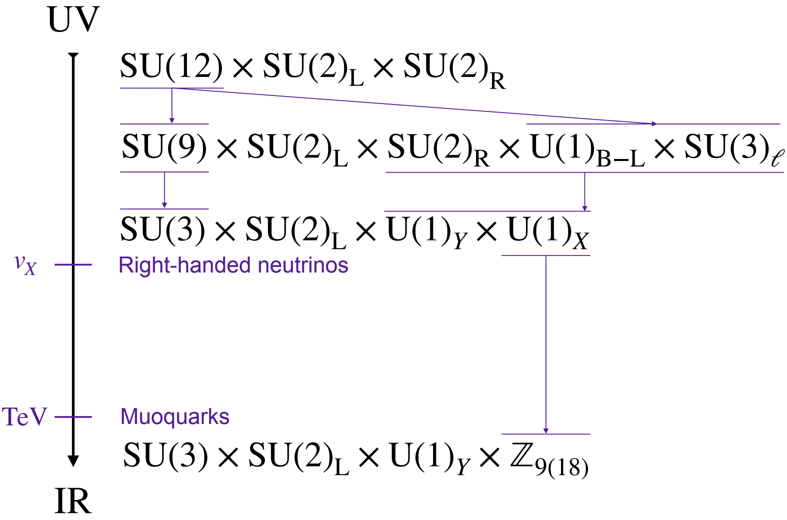
Exact Proton Stability to all orders in EFT

$$\Delta B \equiv 0 \qquad \text{mod } 3$$

Unification of lepton-flavored $\mathrm{U}(1)_X$



UV

$$\mathrm{SU}(12) \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$$

$$\mathrm{SU}(9) \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{SU}(3)_\ell$$

$$\mathrm{SU}(3) \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X$$

v_X Right-handed neutrinos

TeV Muoquarks

$$\mathrm{SU}(3) \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \times \mathbb{Z}_{9(18)}$$

IR

Davighi, Greljo, AET [2202.05275]

Summary

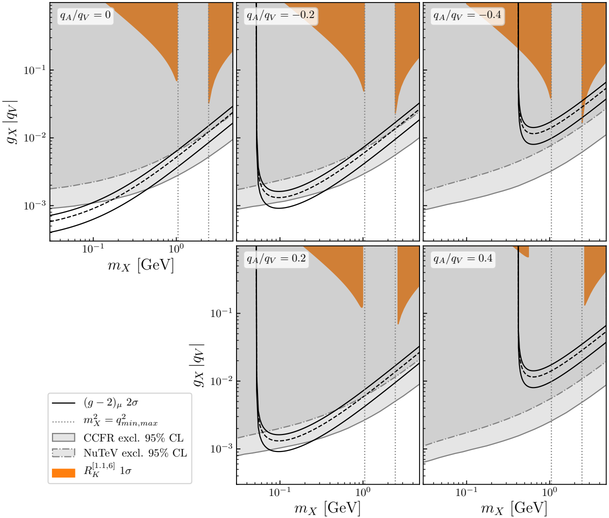
Model	Type A	Type B	Type C	(Type D)
$b \to s\mu\mu$ $(g-2)_\mu$	S_3 S_1/R_2	S_3 light X	heavy X S_1/R_2	X
	✓	✓	?	✗

- Lepton-flavored gauge symmetries provide a good organizing principle for scalar-Leptoquark explanations of the muon anomalies
- Kinetic mixing between X and γ opens up *one* direction in models of light X solutions to $(g-2)_\mu$ with charged quarks
- Lepton-flavored symmetry groups opens for new exciting mechanisms for exact proton stability
- We have to be prepared for the possibility (Type A) that new physics in the anomalies can be very elusive!

Backup

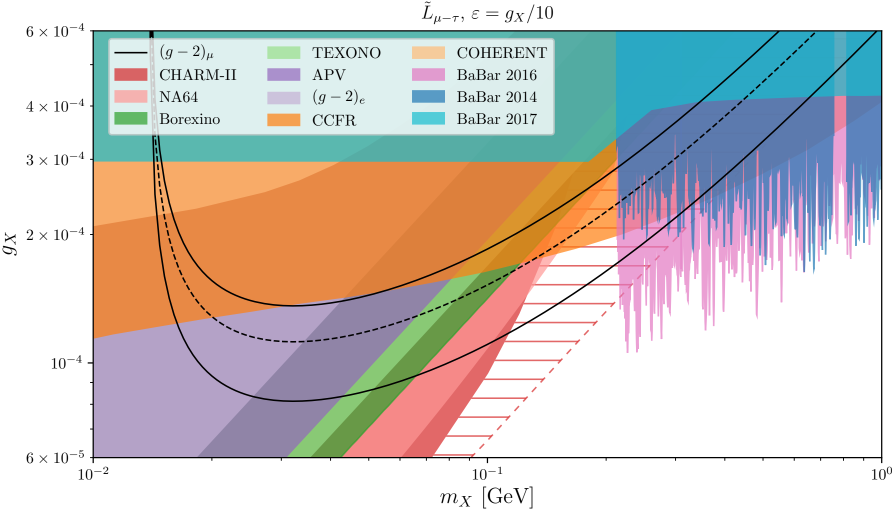
A single mediator seems unlikely

- Float X-couplings in b–s current, and muon vector and axial charges q_V, q_A. Assume $\varepsilon = 0$.
- Upper bound on b–s couplings to X from $\mathrm{BR}(B \to K\nu\nu)$.
- $B \to K\nu\nu$ bound might be looser for $m_X > 2.5\,\mathrm{GeV}$
  Crivellin *et al.* [2202.12900]
- Using kinetic mixing to relax CCFR bound, EW precision excludes $m_X \gtrsim 5\,\mathrm{GeV}$



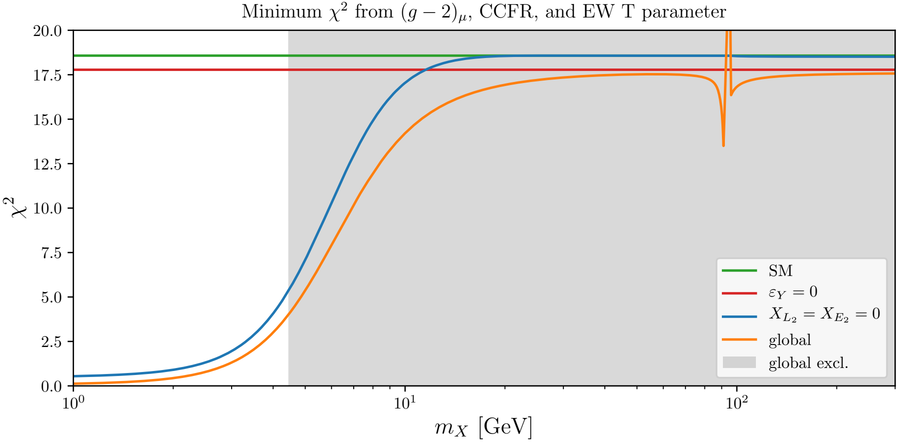
Greljo, Soreq, Stangl, AET, Zupan [2107.07518]

Addressing $(g-2)_\mu$ with the muonic force.



Greljo, Stangl, AET, Zupan [WIP]

High energy vector boson mediator



Greljo, Stangl, AET, Zupan [WIP]