Muon Anomalies: $R_{K^{(*)}}$ and $(g-2)_\mu$

Anders Eller Thomsen

b
UNIVERSITÄT
BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Moriond EW, 12–19 March 2022

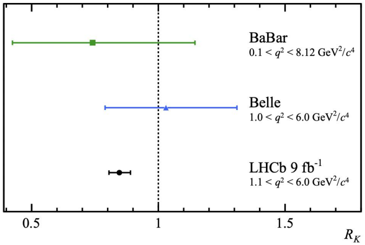
Muon Anomalies

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

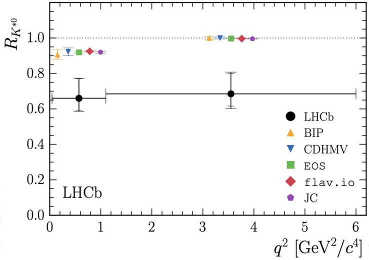
$b \to s\ell^+\ell^-$ anomalies

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

- 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 NP hypothesis
  Lancierini *et al.* [2104.05631]



Aaij *et al.* [2103.11769]



Aaij *et al.* [1705.05802]

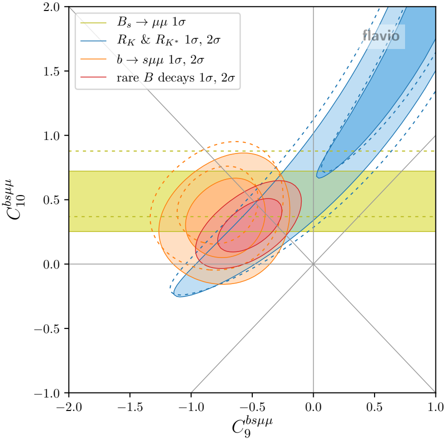
New physics in $b \to s\ell^+\ell^-$

At low-energies a good fit involves (LEFT)

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

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

$$\mathcal{L}_{\mathrm{SMEFT}} \supset C(\overline{q}_3\gamma_\nu q_2)_{\mathrm{L}} (\overline{\ell}_2\gamma^\nu \ell_2)_{\mathrm{L}}$$



Altmannshofer, Stangl [2103.13370]

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 $C_9 - C_{10}$.

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

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:

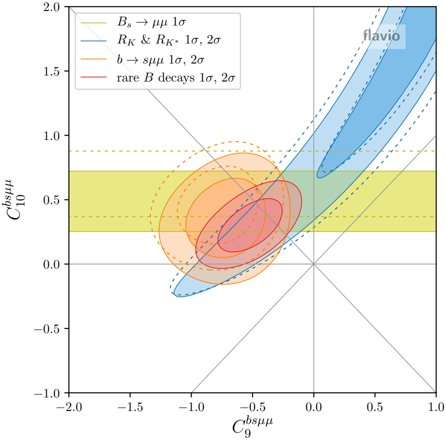
$$\mathcal{L}_\mathrm{SMEFT} \supset C(\bar{q}_3\gamma_\nu q_2)_\mathrm{L}(\bar{\ell}_2\gamma^\nu \ell_2)_\mathrm{L}$$

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

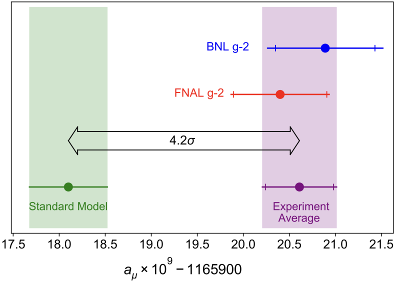
Flavor structure needed to avoid, e.g., FCNC bounds. MFV does not work. $\mathrm{U}(2)^5$ seems like a good candidate.



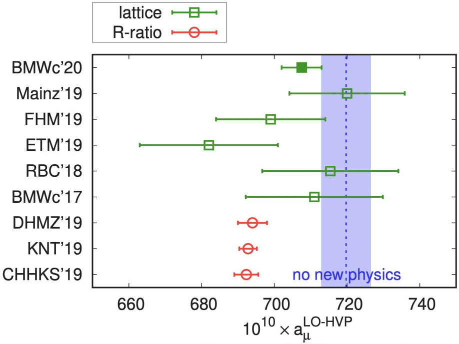
Altmannshofer, Stangl [2103.13370]

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 $C_9 - C_{10}$.

$(g-2)_\mu$ 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 $(g-2)_\mu$, $-\frac{e\,v}{(4\pi)^2} C_{e\gamma}^{ij}\, \bar{e}_{\mathrm{L}}^i \sigma^{\mu\nu} e_{\mathrm{R}}^j F_{\mu\nu}$, gives

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

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

Mass basis

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

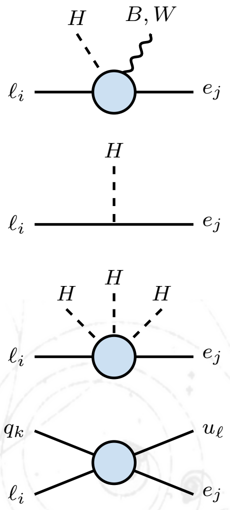
$$|C^{ij}_{e\gamma}| \sim \frac{1}{(14\,\mathrm{TeV})^2} \begin{pmatrix} \lesssim 10^{-1} & \lesssim 2\cdot 10^{-5} & \lesssim 1/4 \\ & 1 & \lesssim 1/4 \\ & & \lesssim 2\cdot 10^{5} \end{pmatrix}$$

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 to the dipole under RG

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 $(g-2)_\mu$, $-\frac{e\,v}{(4\pi)^2} C_{e\gamma}^{ij}\, \bar{e}_{\mathrm{L}}^i \sigma^{\mu\nu} e_{\mathrm{R}}^j F_{\mu\nu}$, gives

Mass basis

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

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

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

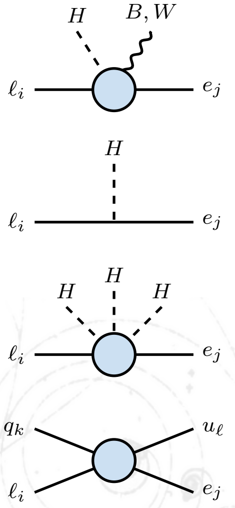
Also very strong CP constraints from EDM ($\lesssim 10^{-8}$)

- Alignment between all SMEFT operators is required

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

- No charged LFV if NP satisfies SM accidental symmetries

SMEFT operators

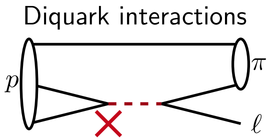


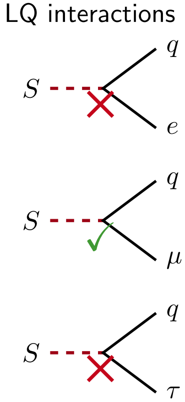
Contributes to the dipole under RG

A Muonic Force

—Are we seeing signs of a new symmetry?

Introducing the muoquarks

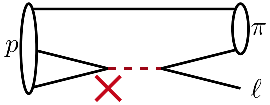




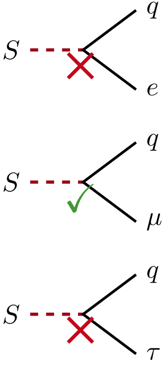
Scalar LQ explanations of the anomalies, should exhibit a fairly

Introducing the muoquarks

Diquark interactions



LQ interactions



Scalar LQ explanations of the anomalies, should exhibit a fairly

Solution: *Gauged lepton-flavored* $\mathrm{U}(1)_X$

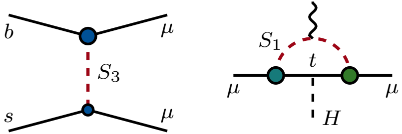
- Robust enough to preserve $\tau_p \gtrsim 10^{34}\,\mathrm{yr}$ after the breaking of $\mathrm{U}(1)_X$ to allow for neutrino masses
  Hambye, Heeck [1712.04871]; Davighi, Kirk, Nardechia [2007.15016]; Greljo, Stangl, AET [2103.13991]; Greljo, Soreq, Stangl, AET, Zupan [2107.07518]; Heeck, Thapa [2202.08854]
- Remnant symmetry $Z_{9(18)} \subset \mathrm{U}(1)_X$ symmetry can even guarantee exact p stability Davighi, Greljo, AET [2202.05275]
- Approximate recovery of SM accidental symmetries:

$$\mathrm{U}(1)_B \times \mathrm{U}(1)_{L_e} \times \mathrm{U}(1)_{L_\mu} \times \mathrm{U}(1)_{L_\tau}$$
$$S \sim (-\tfrac{1}{3},\, 0,\, -1,\, 0)$$

- $\sim$500 anomaly-free models with integer charge ratios ≤ 10 in SM+3ν_{R}.
  Examples: $X = L_\mu - L_\tau$, $X = B - 3L_\mu$, and many, many others

The Nightmare Scenario!

Muoquark (LQ) mediated anomalies
Crivellin, Müller, Ota [1703.09226]; Gherardi, Marzocca, Venturini [2008.09548]

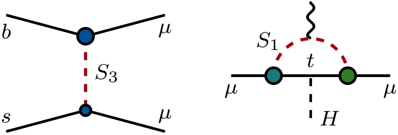


with couplings respecting lepton-flavored $\mathrm{U}(1)_X$

- 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
  Gherardi, Marzocca, Venturini [2003.12525]
- *Global fit* with `smelli` (also using `wilson` and `flavio`)

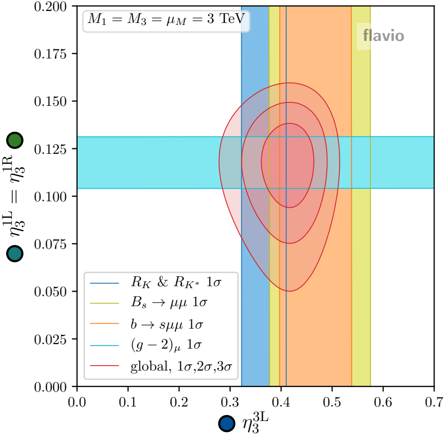
The Nightmare Scenario!

Muoquark (LQ) mediated anomalies
Crivellin, Müller, Ota [1703.09226]; Gherardi, Marzocca, Venturini [2008.09548]



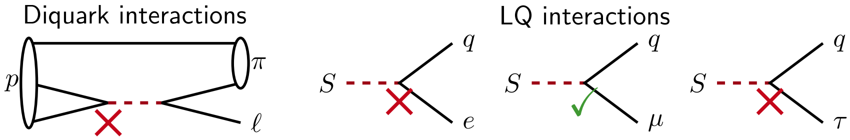
with couplings respecting lepton-flavored $\mathrm{U}(1)_X$

- 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
  Gherardi, Marzocca, Venturini [2003.12525]
- *Global fit* with `smelli` (also using `wilson` and `flavio`)



Greljo, Stangl, AET [2103.13991]

Do we need two muoquarks?

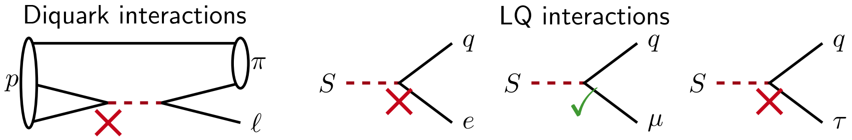


Solution: *Gauged lepton-flavored* $\mathrm{U}(1)_X$.

Scenarios:

- S_3 muoquark for $b \to s\mu\mu$ and S_1 muoquark for $(g-2)_\mu$

Do we need two muoquarks?



Solution: *Gauged lepton-flavored* $\mathrm{U}(1)_X$.

Scenarios:

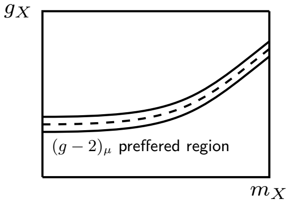
- S_3 muoquark for $b \to s\mu\mu$ and S_1 muoquark for $(g-2)_\mu$
- S_3 muoquark for $b \to s\mu\mu$ and X_μ vector boson of $\mathrm{U}(1)_X$ for $(g-2)_\mu$. Are there $\mathrm{U}(1)_X$ groups that allow for this scenario?

$$\mathcal{L} \supset -\tfrac{1}{4}X_{\mu\nu}^2 + \tfrac{1}{2}\varepsilon\, X_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}m_X^2 X_\mu^2 + g_X X^\mu \sum_f x_f \overline{f}\gamma_\mu f$$

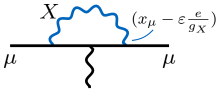
Charges of SM (chiral) fermions

kinetix mixing parameter

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

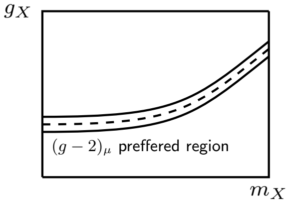


x_f: charge of fermion f
ε: kinetic mixing of X and γ

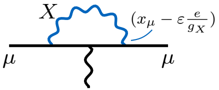


Baek *et al.* [hep-ph/0104141];
Ma, Roy, Roy [hep-ph/0110146];
many more...

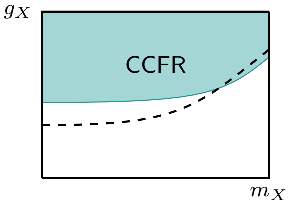
Addressing $(g-2)_\mu$ with the muonic force

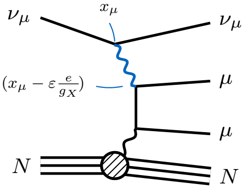


x_f: charge of fermion f
ε: kinetic mixing of X and γ



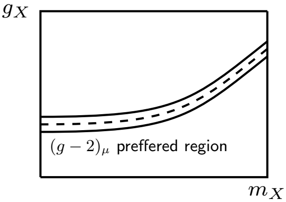
Baek *et al.* [hep-ph/0104141];
Ma, Roy, Roy [hep-ph/0110146];
many more...



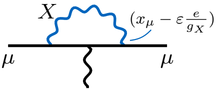


CCFR colaboration '91;
Altmannshofer *et al.* [1406.2332];
Altmannshofer *et al.* [1902.06765];
Ballett *et al.* [1902.08579]

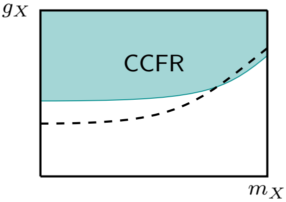
Addressing $(g-2)_\mu$ with the muonic force

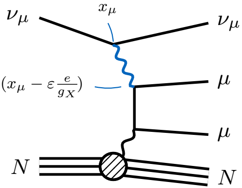


x_f: charge of fermion f
ε: kinetic mixing of X and γ

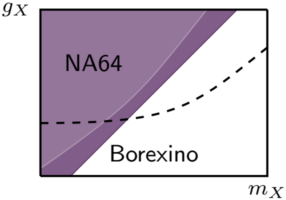


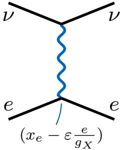
Baek *et al.* [hep-ph/0104141];
Ma, Roy, Roy [hep-ph/0110146];
many more...

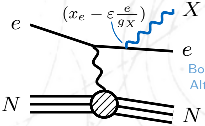




CCFR colaboration '91;
Altmannshofer *et al.* [1406.2332];
Altmannshofer *et al.* [1902.06765];
Ballett *et al.* [1902.08579]

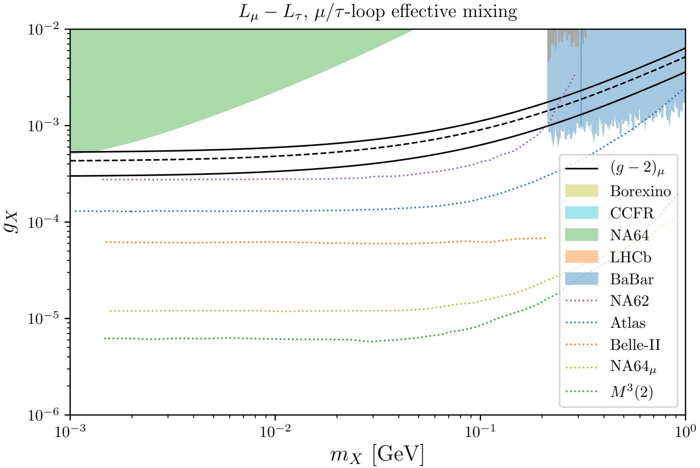






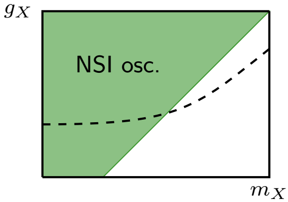
Borexino colaboration [1707.09279];
Altmannshofer *et al.* [1902.06765];
Banerjee *et al.* [1906.00176]

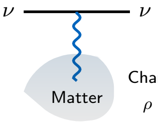
Light vector solution: $X = L_\mu - L_\tau$



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

Complementary constraints on a light X



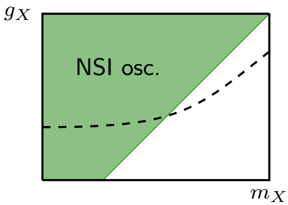


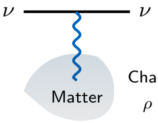
Charge density:

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

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

Complementary constraints on a light X

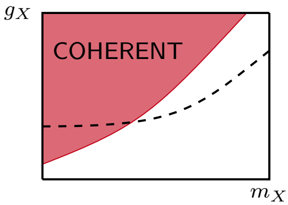


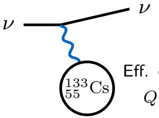


Charge density:

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

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



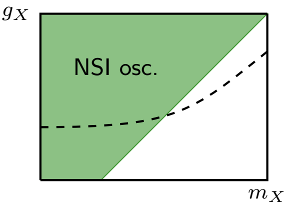


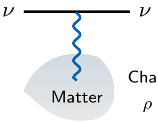
Eff. charge:

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

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

Complementary constraints on a light X

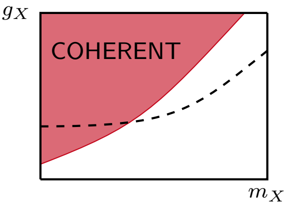


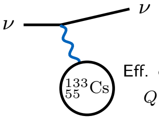


Charge density:

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

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

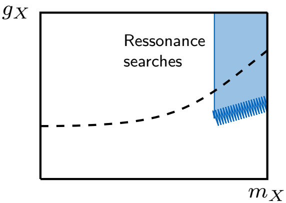


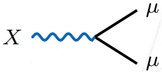


Eff. charge:

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

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

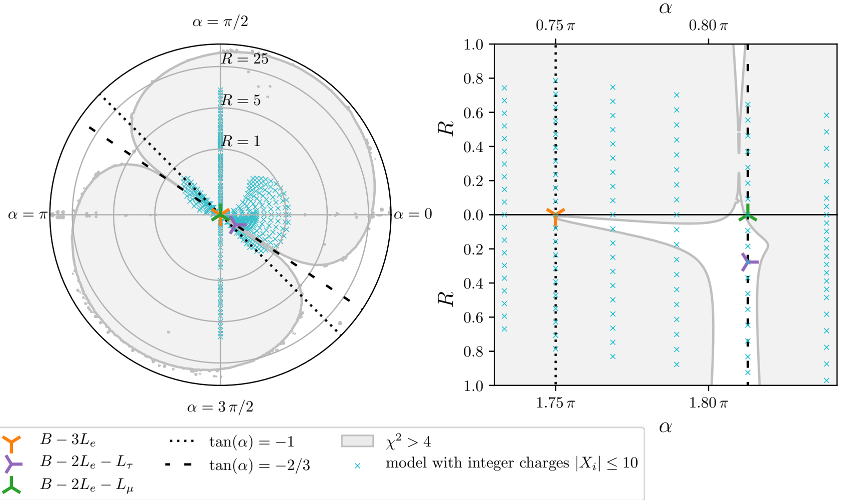




BaBar collaboration [1606.03501]; BaBar collaboration [1406.2980]; LHCb collaboration [1710.02867]; darkcast: Ilten *et al.* [1801.04847]

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

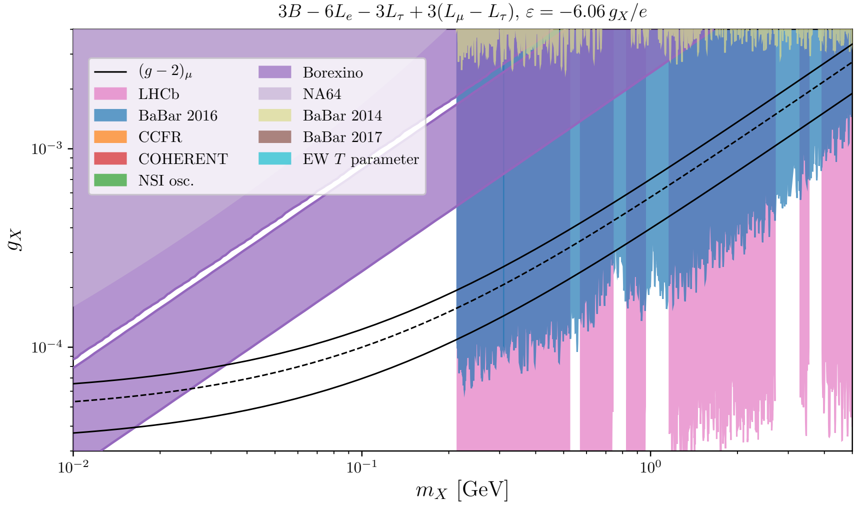
$$\sin(\alpha)(L_e - L_\mu) + \cos(\alpha)(B/3 - L_\mu) + R\,(L_\mu - L_\tau)$$



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

Greljo, Stangl, AET, Zupan [WIP]

Allowed model with B charge



Greljo, Stangl, AET, Zupan [WIP]

Summary

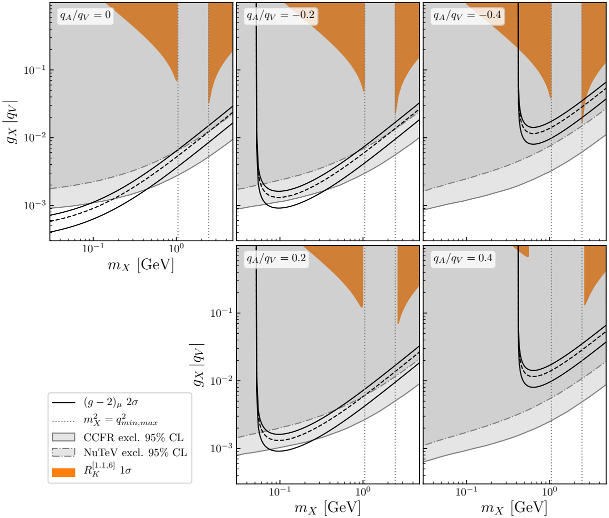
Model	Type A	Type B	Type C	(Type D)
$b \to s\mu\mu$	S_3	S_3	heavy X	light X
$(g-2)_\mu$	S_1/R_2	light X	S_1/R_2	
	✓	✓	?	✗

- 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
- 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]

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

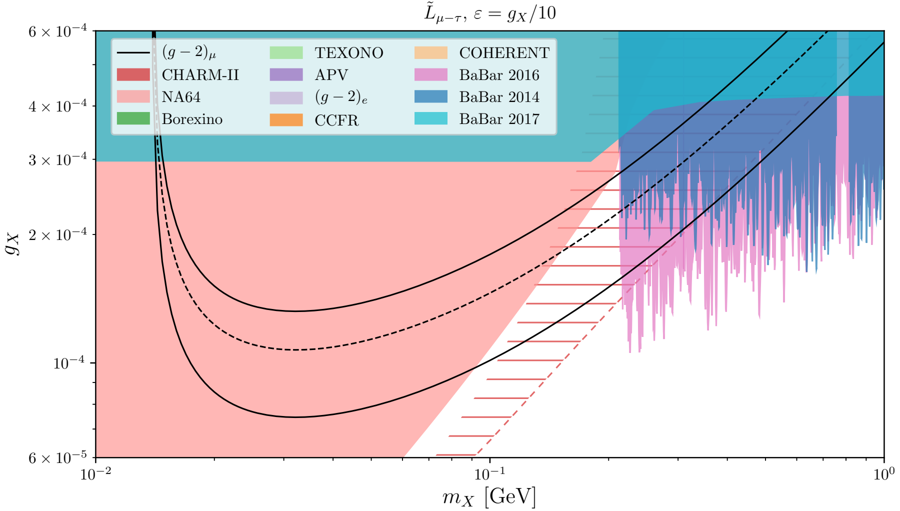
TeV — Muoquarks

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

IR

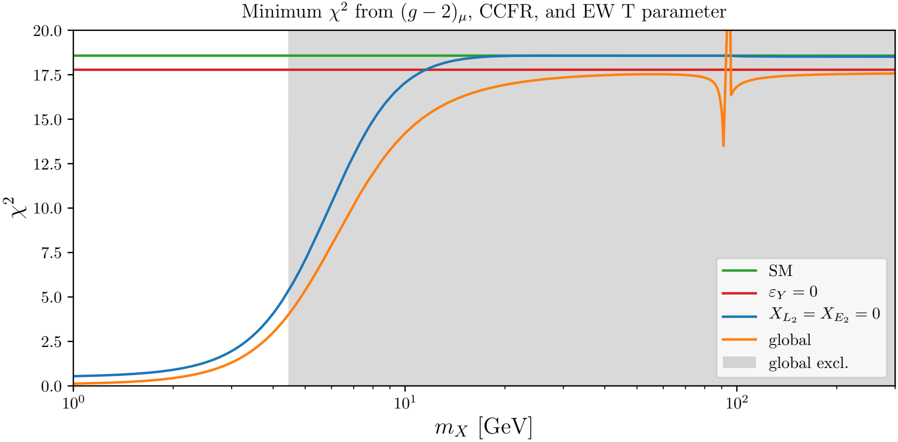
Davighi, Greljo, AET [2202.05275]

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



Greljo, Stangl, AET, Zupan [WIP]

High energy vector boson mediator



Greljo, Stangl, AET, Zupan [WIP]

The $B - 3L_\mu$ model

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-3L_\mu}$
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 through H)

Muoquarks (S_3, S_1)

X-breaking SM singlet (Φ)

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