

Looking for a Muonic Force in the Muon Anomalies

Anders Eller Thomsen

Based on work with A. Greljo, Y. Soreq, P. Stangl, and J. Zupan

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FOR FUNDAMENTAL PHYSICS

*International Workshop on Deep-Inelastic Scattering and
Related Subjects,
Santiago de Compostela 5 May 2022*

The flavor puzzle

Quark sector:

$$y_{u,d} \sim \begin{pmatrix} \square & & \\ & \square & \\ & & \blacksquare \end{pmatrix}$$

$$V_{\text{CKM}} \sim \begin{pmatrix} \blacksquare & \square & \\ \square & \blacksquare & \\ & & \blacksquare \end{pmatrix}$$

Lepton sector:

$$y_e \sim \begin{pmatrix} \square & & \\ & \square & \\ & & \blacksquare \end{pmatrix}$$

Not visible in colliders

$$V_{\text{PMNS}} \sim \begin{pmatrix} \blacksquare & \square & \\ \square & \square & \\ \square & \square & \square \end{pmatrix}$$

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- Is there structure to the flavor sector?
- How does potential new physics couple to flavor?
- Can this give hints towards an underlying model of flavor?

$b \rightarrow sl^+l^-$ anomalies

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

- 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

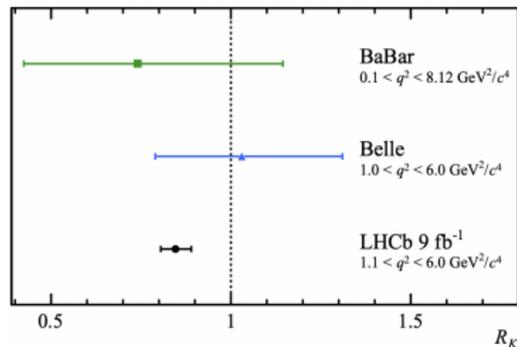
- Average ATLAS, CMS, and LHCb $B_s \rightarrow \mu^+\mu^-$ branching ratio deviate from SM by 2σ

Altmannshofer, Stangl [2103.13370]

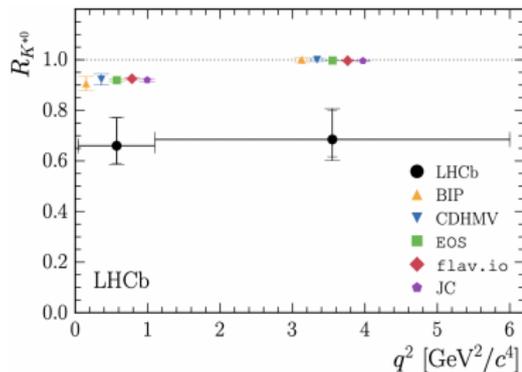
- Angular observables in $B \rightarrow K^*\mu^+\mu^-$ and branching ratios in $B \rightarrow K^{(*)}\mu^+\mu^-$ and $B_s \rightarrow \phi\mu^+\mu^-$

- 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]

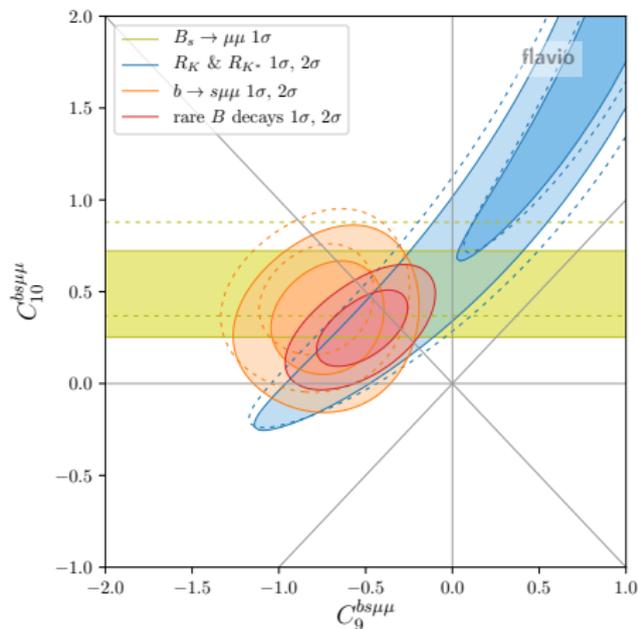
New physics in $b \rightarrow s\mu^+\mu^-$?

At low energies, a good fit involves (LEFT)

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

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

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



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 $C_9 - C_{10}$.

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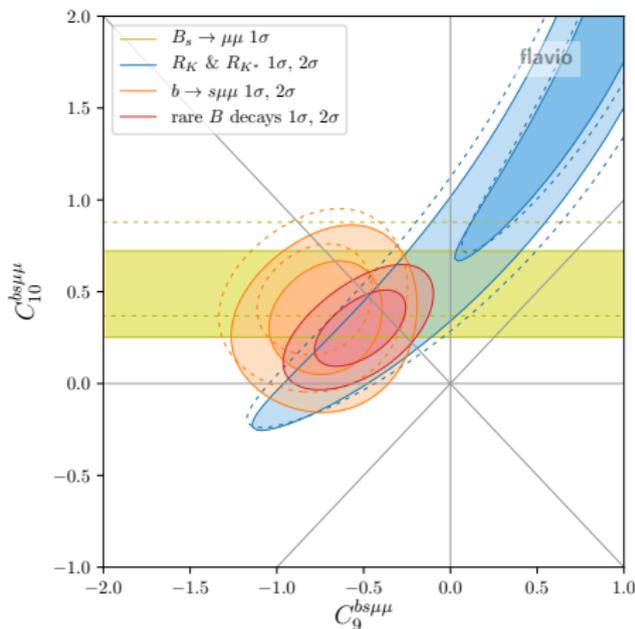
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Loop models are also viable

Tree-level mediators:

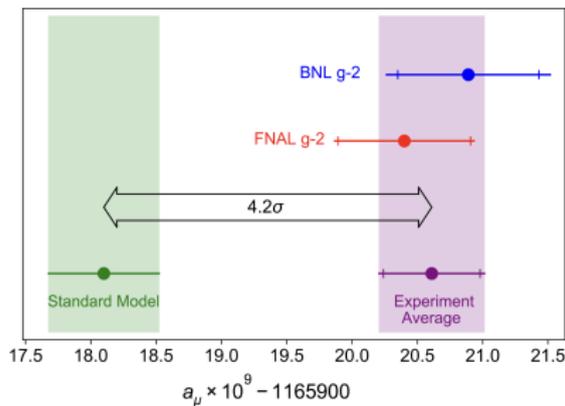
- Z' neutral vector boson
UV completion required
- U_1 (U_3) vector LQ
UV completion required
- S_3 scalar triplet LQ
single-field extension is possible



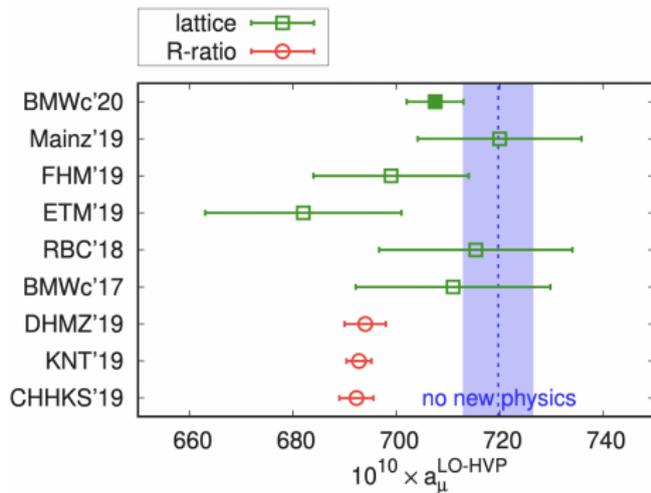
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$(g - 2)_\mu$ anomaly



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. Tension 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,...
- EFT fit to $(g - 2)_\mu$, $-\frac{e\nu}{(4\pi)^2} C_{e\gamma}^{ij} \bar{e}_L^i \sigma^{\mu\nu} e_R^j F_{\mu\nu}$, gives

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

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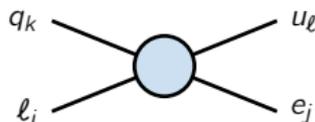
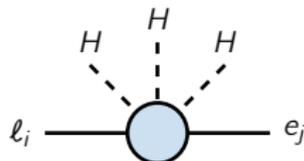
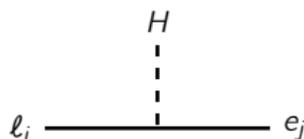
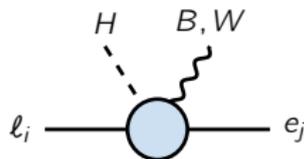
Mass basis BR($\mu \rightarrow e\gamma$) < 10^{-12}

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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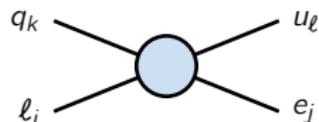
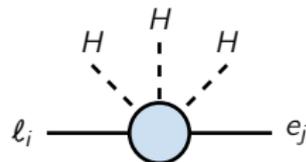
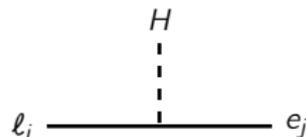
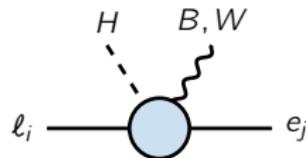
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Mass basis
 $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$
 Also very strong CP constraints from EDM ($\lesssim 10^{-8}$)
 $BR(\mu \rightarrow e\gamma) < 10^{-12}$

- Alignment between all SMEFT operators is required
Isidori, Pagès, Wilsch [2111.13724]; Calibbi et al. [2104.03296]
- No charged LFV in NP if it satisfies SM accidental symmetries

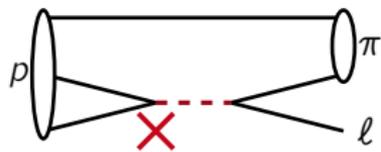
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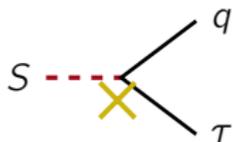
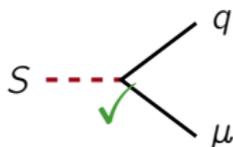
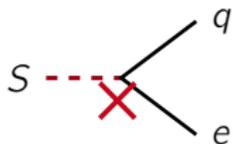
Introducing muoquarks

Diquark interactions



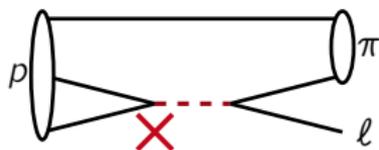
Scalar LQ explanations of the anomalies can only have a particular set of interactions

LQ interactions

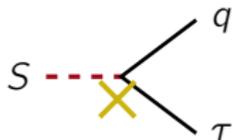
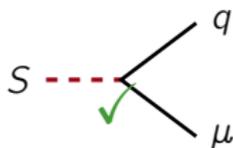
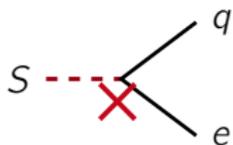


Introducing muoquarks

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LQ interactions



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

Solution: *Lepton-flavored gauged* $U(1)_X$

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:

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

$$S \sim \left(-\frac{1}{3}, 0, -1, 0\right)$$

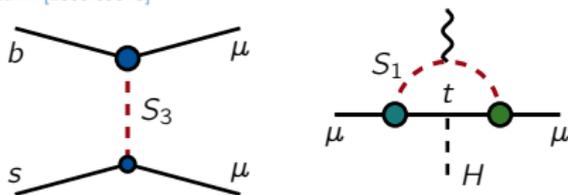
~500 quark-universal anomaly-free models with integer charge ratios ≤ 10 in SM+ $3\nu_R$. [Allanach, Davighi, Melville \[1812.04602\]](#)

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

An explanation with two muoquarks

Muoquark (LQ) mediated anomalies:

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



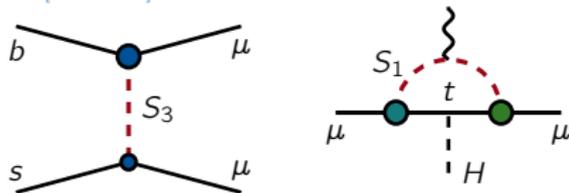
Couplings respecting lepton-flavored $U(1)_X$

- Direct searches give only modest constraints: $M_{1,3} \gtrsim 1.7 \text{ TeV}$
ATLAS collaboration [2006.05872]
- Decoupling limit ($\frac{v_X \rightarrow \infty}{g_X \rightarrow 0}$) ensures NP contribution exclusively from $S_{1,3}$
- Approximate $U(2)$ flavor symmetry
Kagan *et al.* [0903.1794]; Barbieri *et al.* [1105.2296]
- Existing 1-loop $S_{1,3}$ matching results
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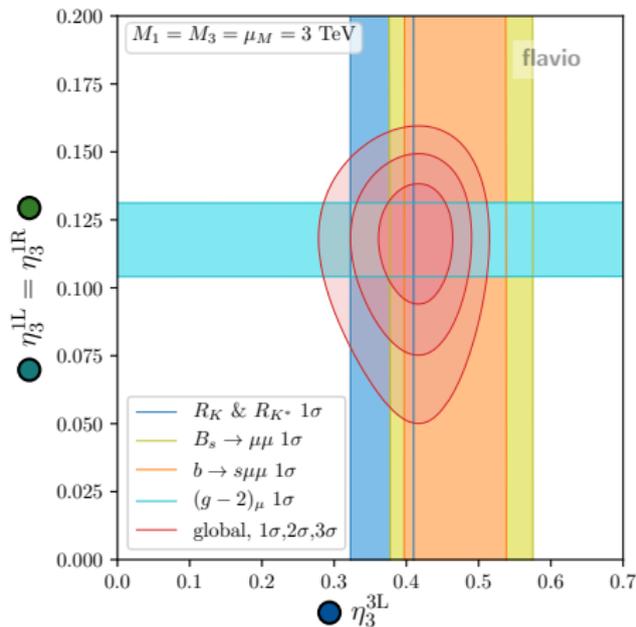
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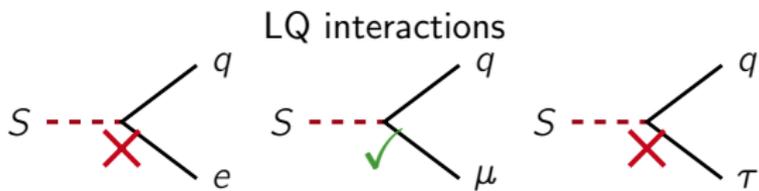
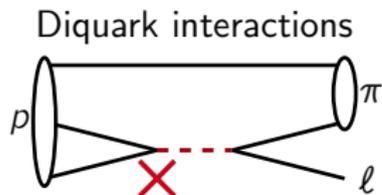
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Greljo, Stangl, AET [2103.13991]

Do we need two muoquarks?

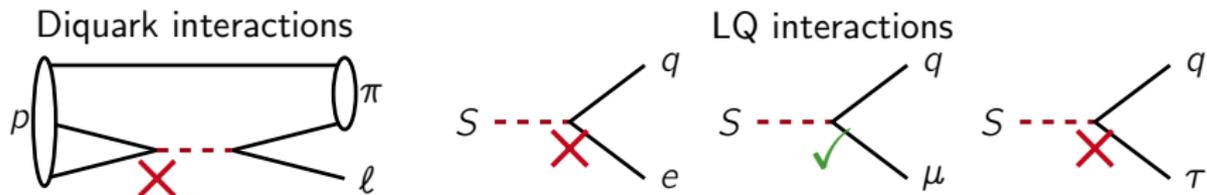


Solution: *Gauged lepton-flavored* $U(1)_X$

Scenarios:

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

Do we need two muoquarks?



Solution: *Gauged lepton-flavored* $U(1)_X$

Scenarios:

- S_3 muoquark for $b \rightarrow s\mu\mu$ and S_1 muoquark for $(g-2)_\mu$
- S_3 muoquark for $b \rightarrow s\mu\mu$ and X_μ vector boson of $U(1)_X$ for $(g-2)_\mu$

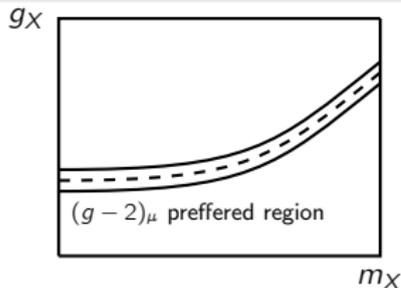
Which $U(1)_X$ groups allow for this scenario?

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

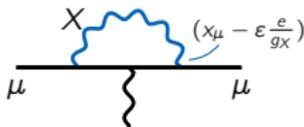
Charges of SM (chiral) fermions

kinetic mixing parameter

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

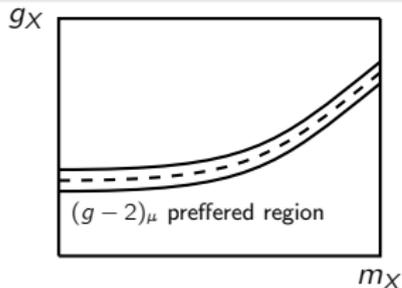


x_f : charge of fermion f
 ε : kinetic mixing of X and γ

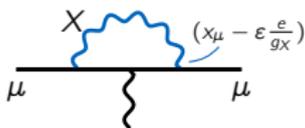


Baek *et al.* [[hep-ph/0104141](#)];
Ma, Roy, Roy [[hep-ph/0110146](#)];
many, many more...

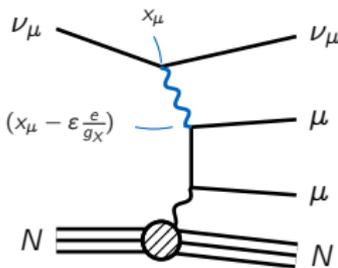
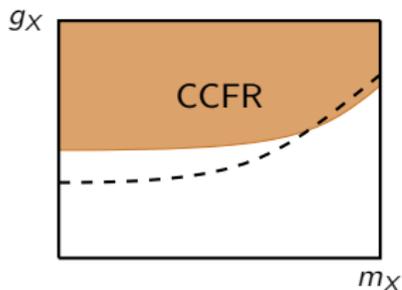
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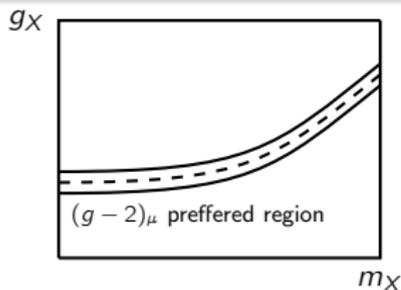


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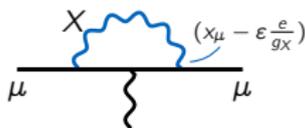


CCFR collaboration '91;
 Altmannshofer *et al.* [[1406.2332](#)];
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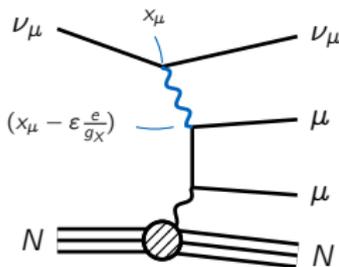
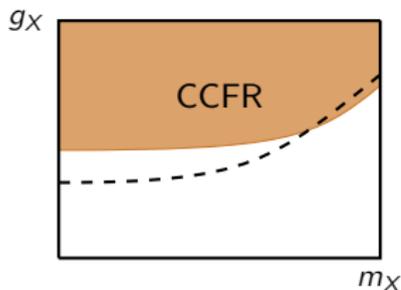
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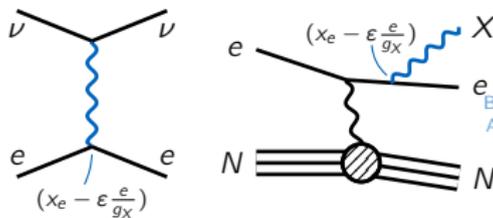
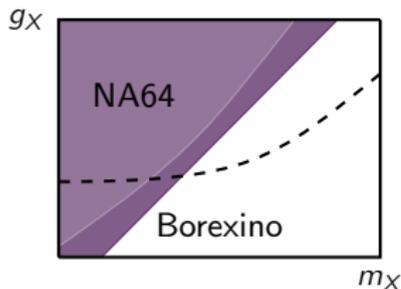
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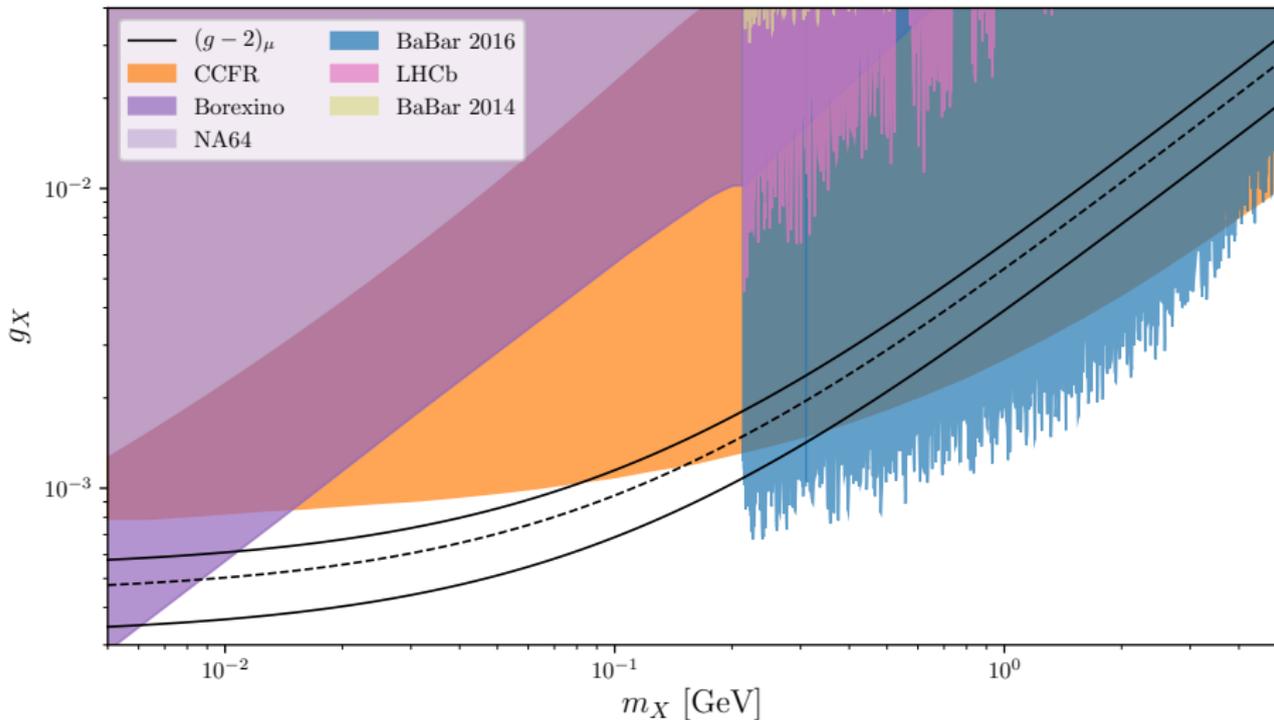
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Borexino collaboration [[1707.09279](#)];
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 Banerjee *et al.* [[1906.00176](#)]

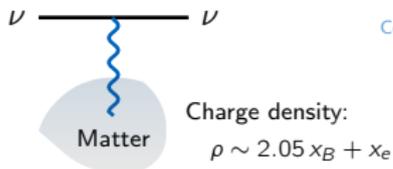
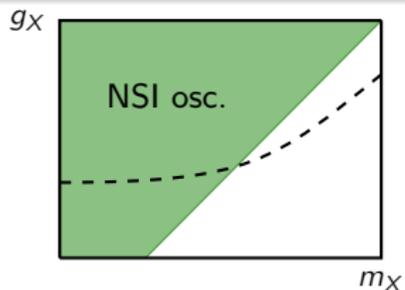
Light vector solution: $X \equiv L_\mu - L_\tau$

$L_\mu - L_\tau$, μ/τ -loop effective kinetic mixing



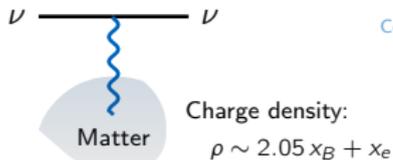
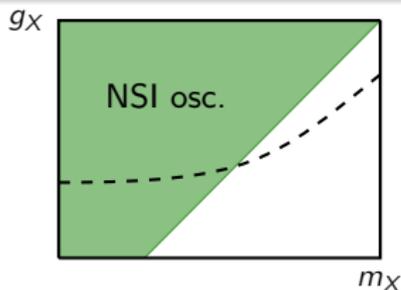
Grejo, Stangl, AET, Zupan [2203.13731]

Complementary constraints on a light X

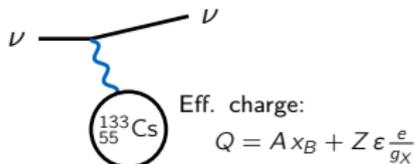
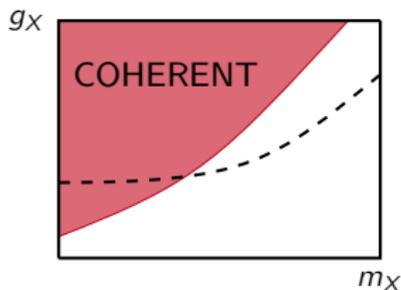


Coloma, Gonzalez-Garcia, Maltoni [2009.14220];
Esteban *et al.* [1805.04530];
Heeck *et al.* [1812.04067] Wolfenstein '78

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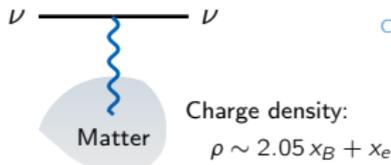
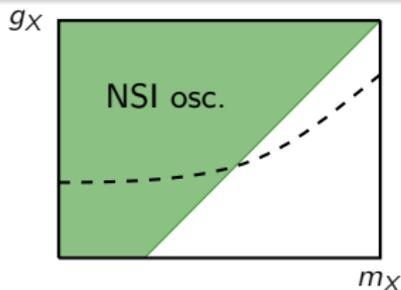


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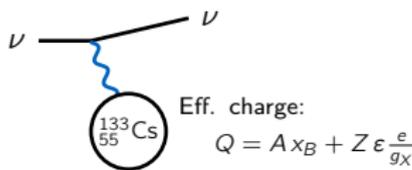
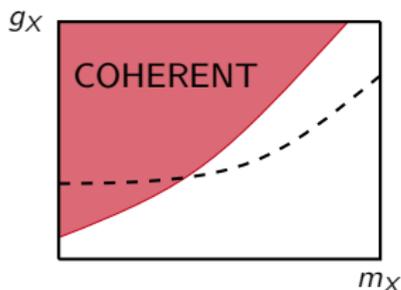


Denton, Gehrlein [2008.06062];
Esteban et al. [1805.04530];
COHERENT collaboration [1708.01294];
Freedman '74; Drukier, Stodolsky '84

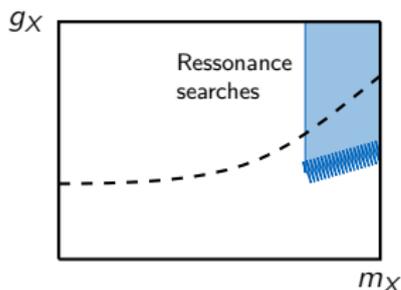
Complementary constraints on a light X



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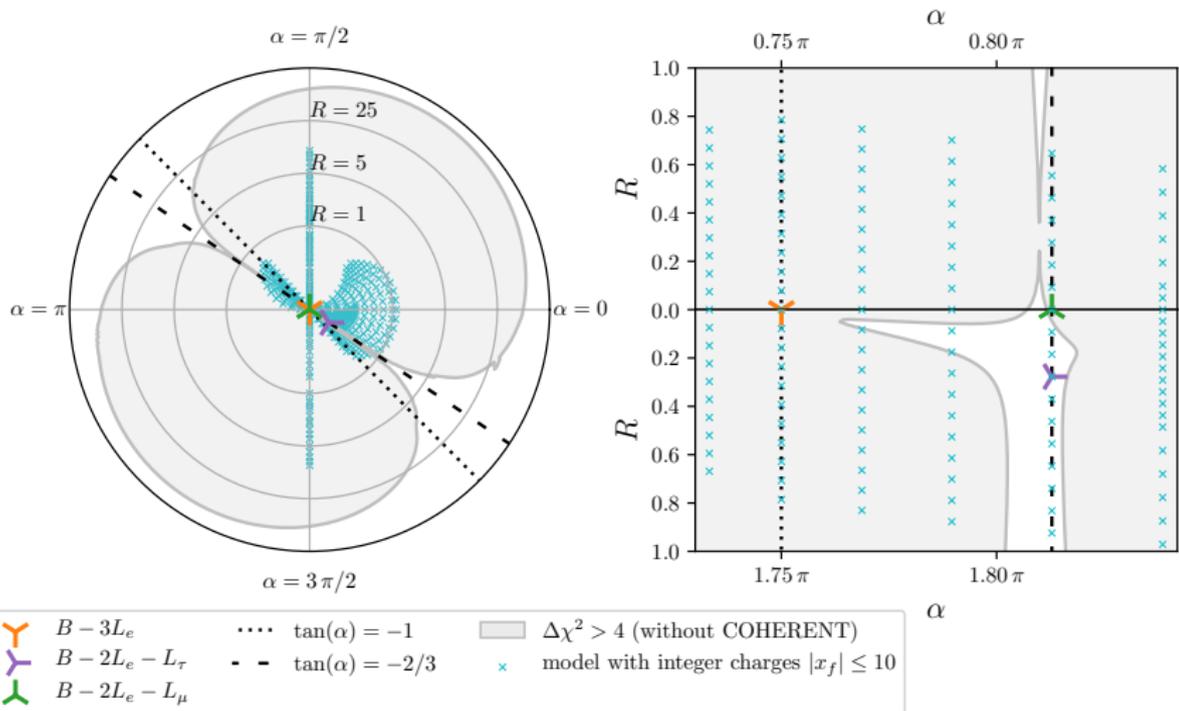
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BaBar collaboration [1606.03501];
 BaBar collaboration [1406.2980];
 LHCb collaboration [1710.02867];
 darkcast: Ilten *et al.* [1801.04847]

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

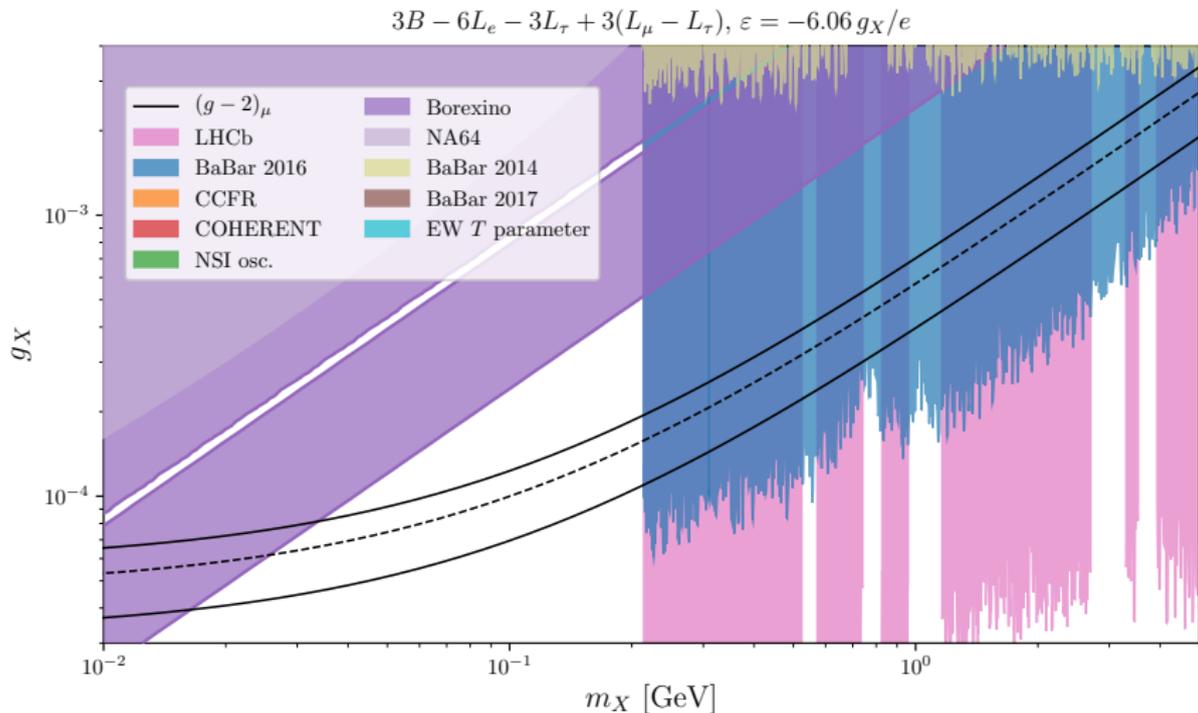
$$\sin(\alpha)(L_e - L_\mu) + \cos(\alpha)(B/3 - L_\mu) + R(L_\mu - L_\tau)$$



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

Greljo, Stangl, AET, Zupan [2203.13731]

Allowed model with B charge



Grejlo, Stangl, AET, Zupan [2203.13731]

Summary

Model	Type A	Type B	Type C	(Type D)
$b \rightarrow s\mu\mu$	S_3	S_3	heavy X	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* new 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 elusive

Backup

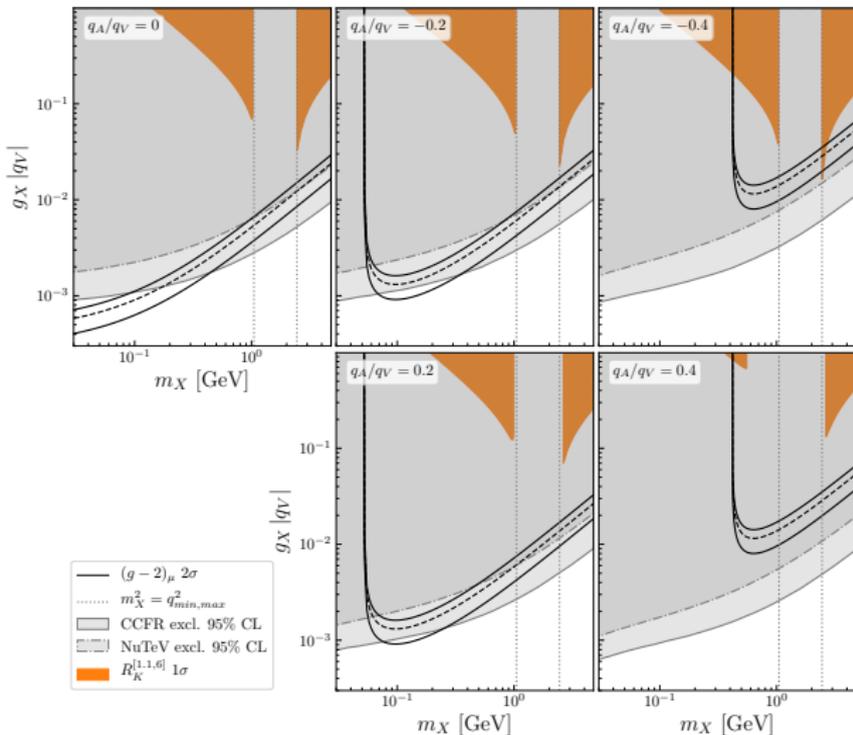
The $B - 3L_\mu$ model

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

Muonic force

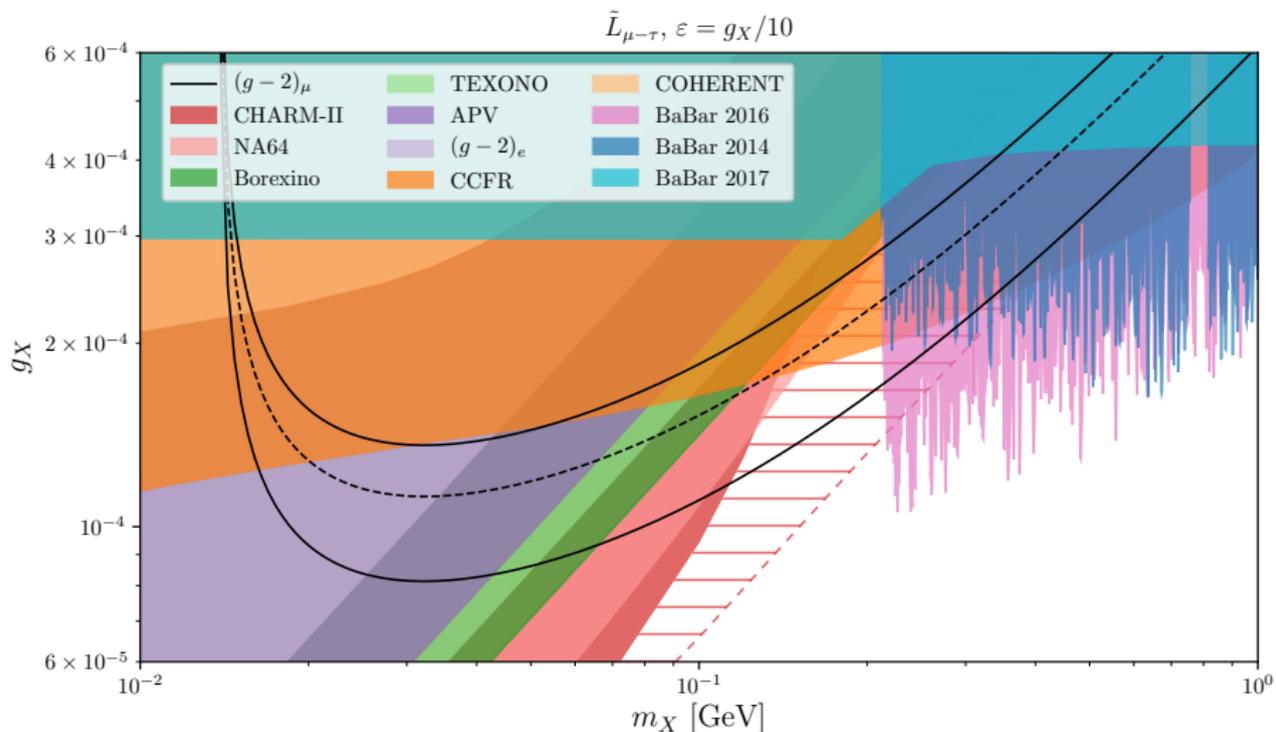
A single mediator seems unlikely

- 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 $\text{BR}(B \rightarrow K\nu\nu)$.
- $B \rightarrow K\nu\nu$ bound might be looser for $m_X > 2.5$ GeV
[Crivellin et al. \[2202.12900\]](#)
- Using kinetic mixing to relax CCFR bound, EW precision excludes $m_X \gtrsim 5$ GeV



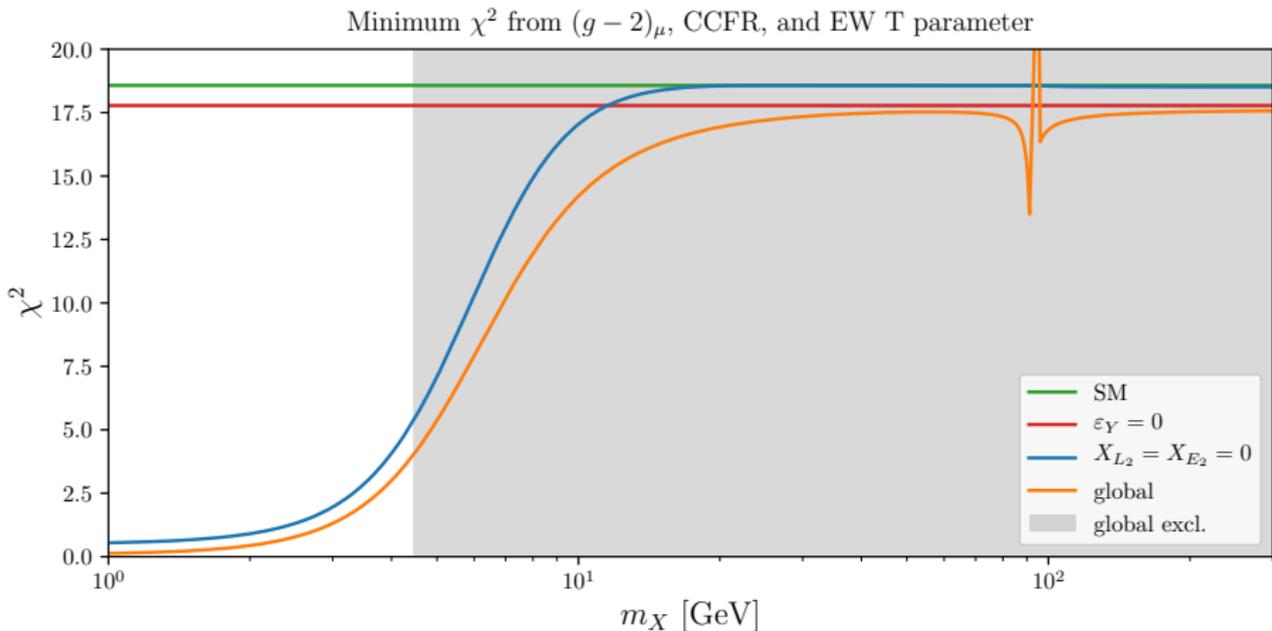
Greljo, Soreq, Stangl, AET, Zupan [2107.07518]

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



Grejjo, Stangl, AET, Zupan [WIP]

High energy vector boson mediator



Greljo, Stangl, AET, Zupan [WIP]