Muonic Forces and Lepton Flavor Non-Universality

Anders Eller Thomsen

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

b
UNIVERSITÄT
BERN

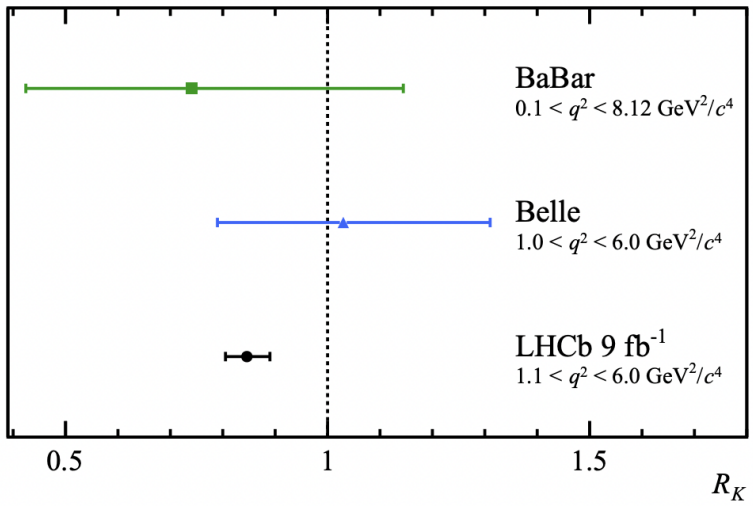
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

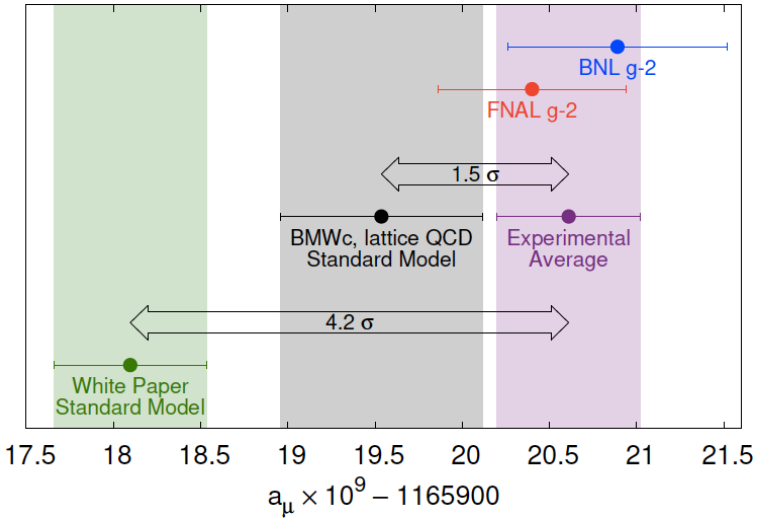
Implications of LHCb measurements and future prospects,
CERN 19–21 October 2022

Selection Rules

Muonic Forces

TeV-scale new physics?





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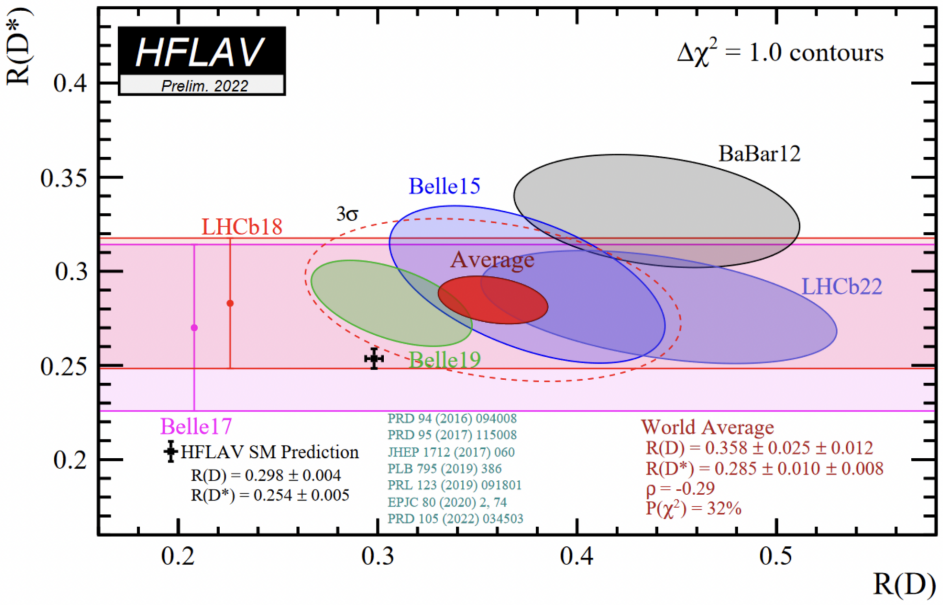

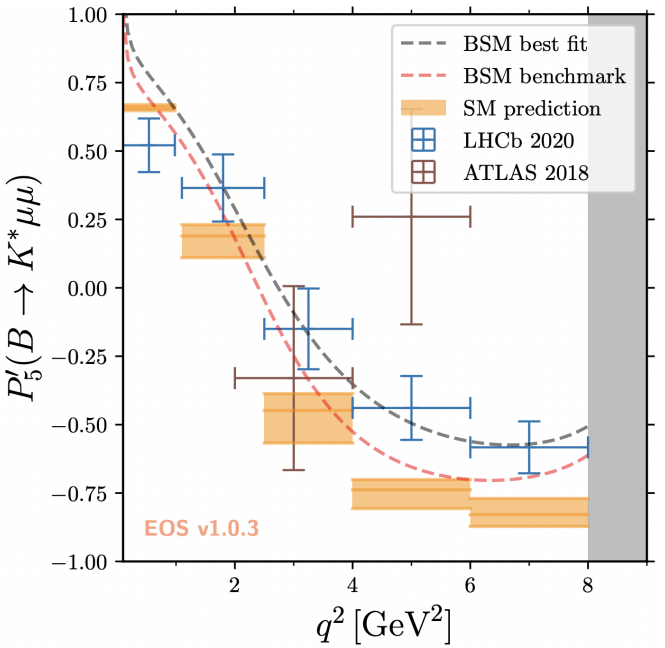

Gubernari *et al.* [2206.03797]

Selection rules in the SM

The Standard Model sans Higgs

Symmetries: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \times$ Poincaré

Matter fields: $q_i,\ u_i,\ d_i,\ \ell_i,\ e_i,\ H$

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Explicit breaking by the Higgs couplings

$$\mathcal{L}_\mathrm{yuk} = -\bar{q} y_u \tilde{H} u - \bar{q} y_d H d - \bar{\ell} y_e H e \ + \ \mathrm{H.c.}$$

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

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Consequences:

- Conservation of B number
- Conservation of LF

Exceptions:

- Non-perturbative violation of $B + L$
- Neutrino oscillations

Constraints on LFV in the lepton dipole

- Many BSM models can account for the $(g-2)_\mu$ discrepancy: VL leptons, 2HDM, MSSM, *light vector bosons*, *leptoquarks*,...

- EFT fit to $(g-2)_\mu$, $-\frac{e\,v}{(4\pi)^2} C^{ij}_{e\gamma}\, \bar{e}^i_{\rm L} \sigma^{\mu\nu} e^j_{\rm R} F_{\mu\nu}$, gives

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

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

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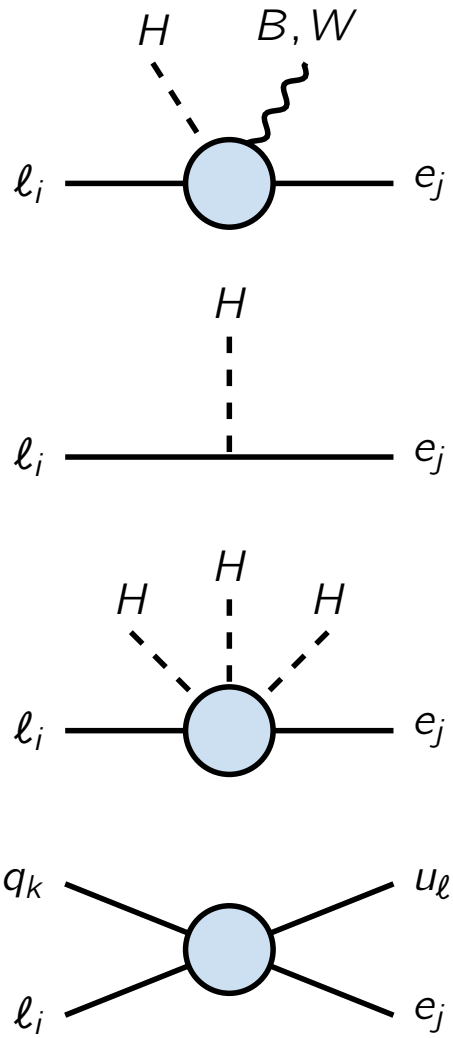
- Alignment between all SMEFT operators is required

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

SMEFT operators



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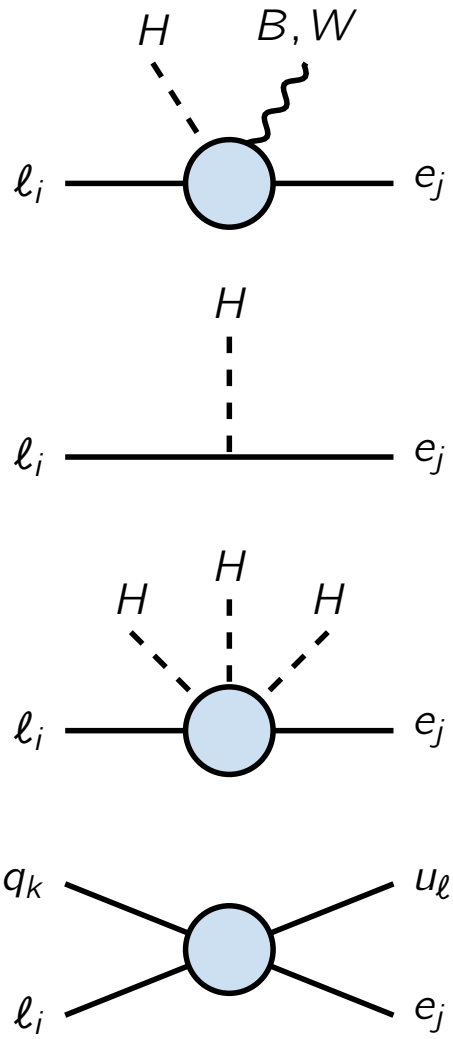
- No charged LFV in NP if it satisfies SM accidental symmetries

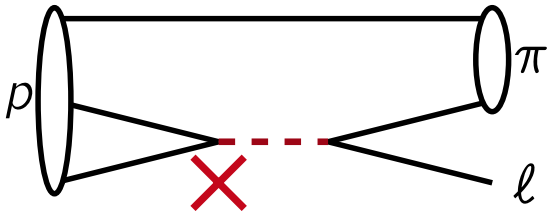
SMEFT operators



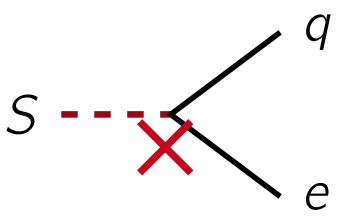
Contributes under the RG

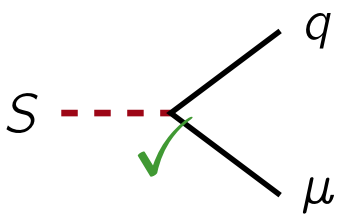
Muonic forces

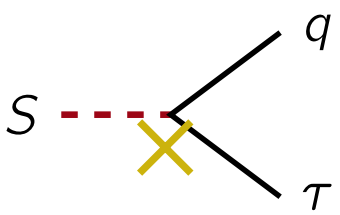
Diquark interactions



LQ interactions







Problem: TeV-scale scalar LQ interactions are strongly constrained

Muonic forces

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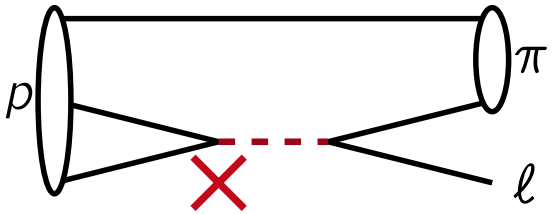

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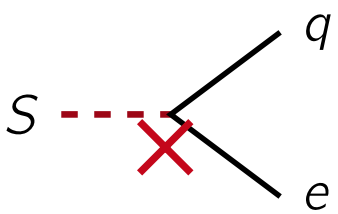
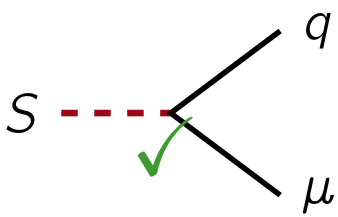
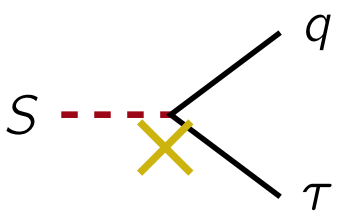


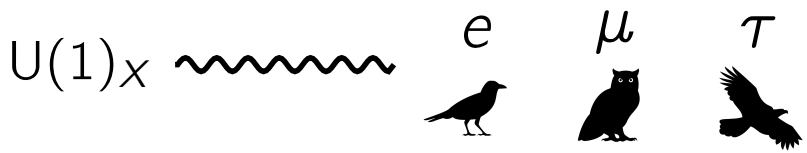




Problem: TeV-scale scalar LQ interactions are strongly constrained

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]; Crivellin *et al.* [2203.10111]; Greljo, Stangl, AET, Zupan [2203.13731]



Approximate recovery of SM accidental symmetries:

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

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

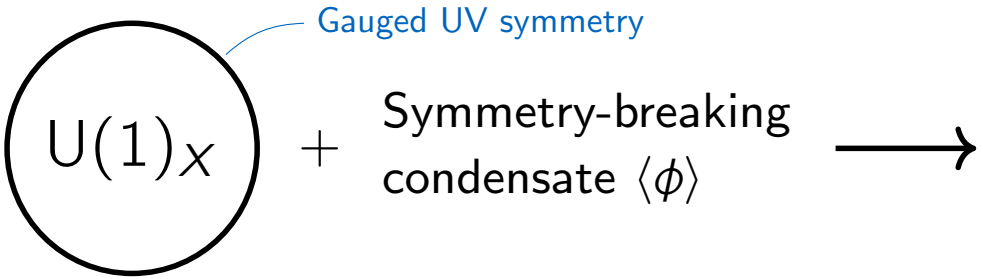
$O(500)$ quark-universal anomaly-free models with integer charge ratios ≤ 10 in SM+$3\nu_{\mathrm{R}}$

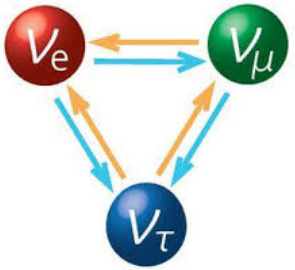
Greljo, Soreq, Stangl, AET, Zupan [2107.07518]; Allanach, Davighi, Melville [1812.04602]

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

IR protection from muonic forces

Observations indicate that the muonic force must be broken





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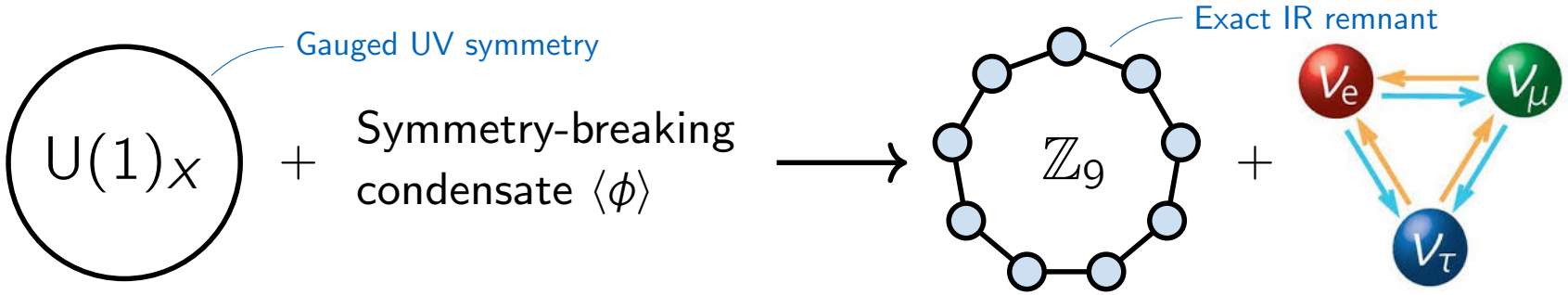

A non-trivial, remnant $\mathbb{Z}_9$ symmetry appear for *some* $U(1)_X$ groups of the type

Davighi, Greljo, AET [2202.05275]

$$X = 3m(B-L) - n(2L_\mu - L_e - L_\tau), \quad \text{e.g., } X = B - 3L_\mu$$

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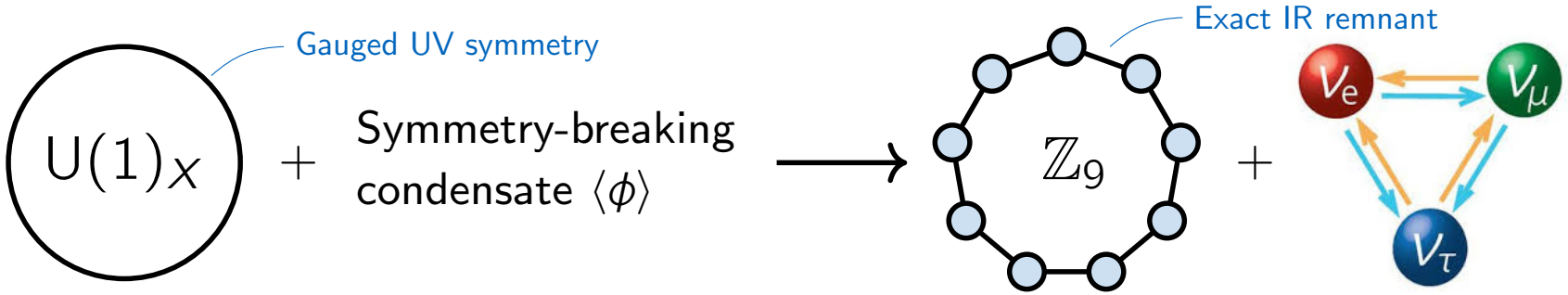

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- **Exact proton stability!**
  $\Delta B \equiv 0 \pmod 3$ quarks are the only charged SM particles under $\mathbb{Z}_9$
- Accidental LF conservation: LFV is higher order in the UV EFT expansion
  $\mathrm{Br}(\mu \to e\gamma) \sim (\langle\phi\rangle/\Lambda_{\rm UV})^{k\geq 2}$ $\Lambda_{\rm UV}$ is the scale of EFT operators with ϕ

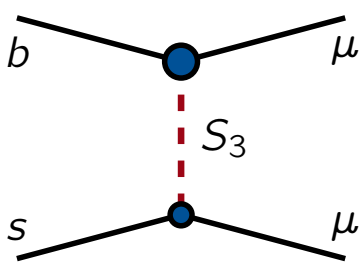
Phenomenology

Muonic Forces

Muoquark fit

Muoquark (LQ) mediated anomalies

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



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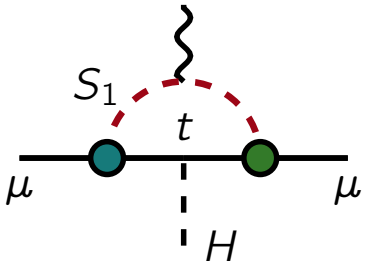

$(g-2)_\mu$

- Direct searches give only modest constraints: $M_{1,3} \gtrsim 1.7\,\text{TeV}$

  ATLAS collaboration [2006.05872] [2210.04517]

- Decoupling limit $\binom{v_X \to \infty}{g_X \to 0}$ ensures NP contribution exclusively from $S_{1,3}$
- Approximate U(2) flavor symmetry

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- *Global fit* with `smelli` (also using `wilson` and `flavio`)

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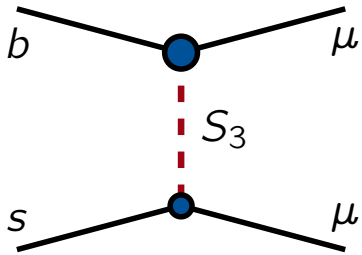

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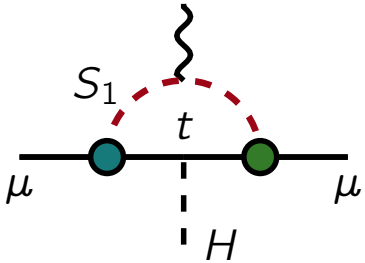

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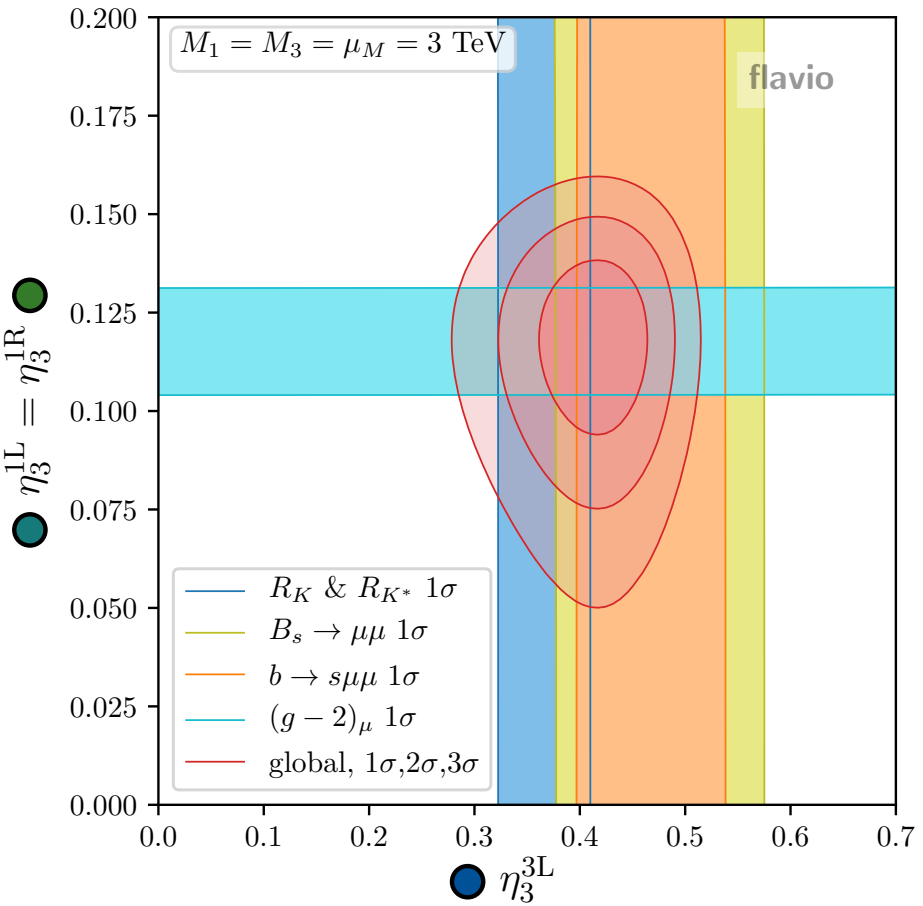
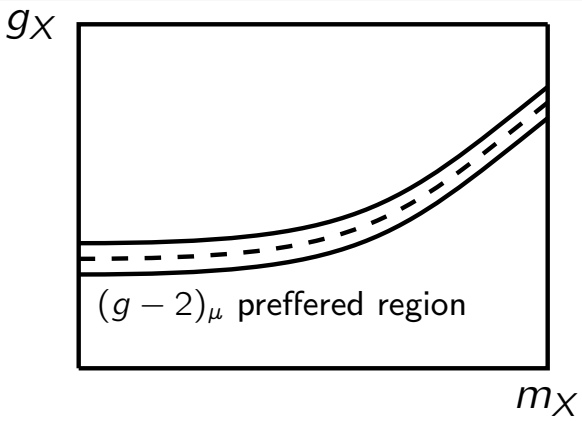
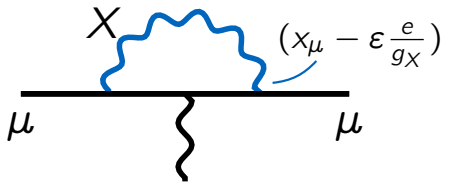


Greljo, Stangl, AET [2103.13991]

Addressing $(g-2)_\mu$ with a 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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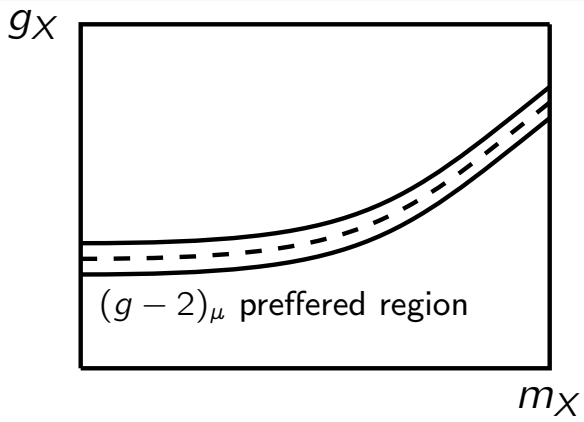

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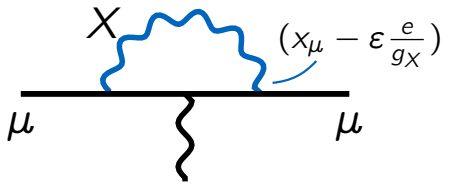

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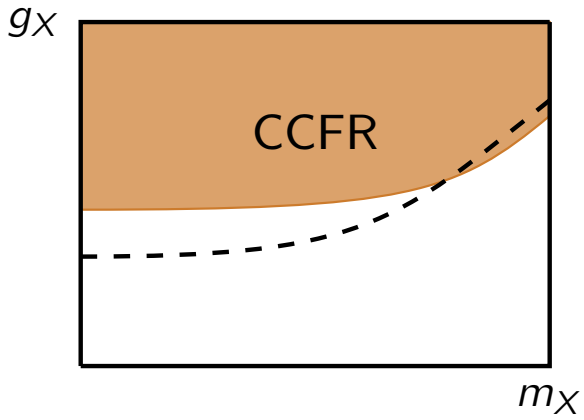

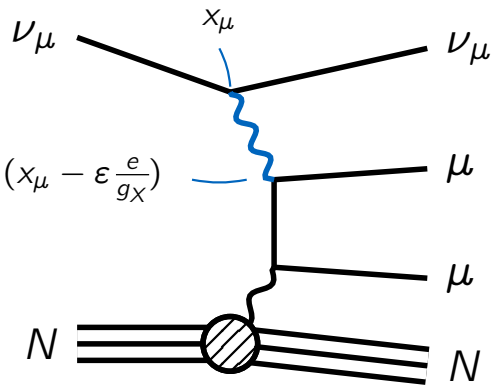

CCFR colaboration '91;
Altmannshofer *et al.* [1406.2332];
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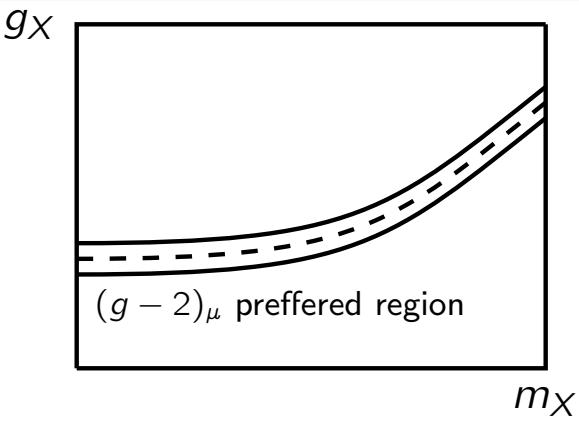

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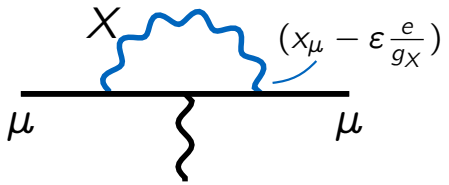

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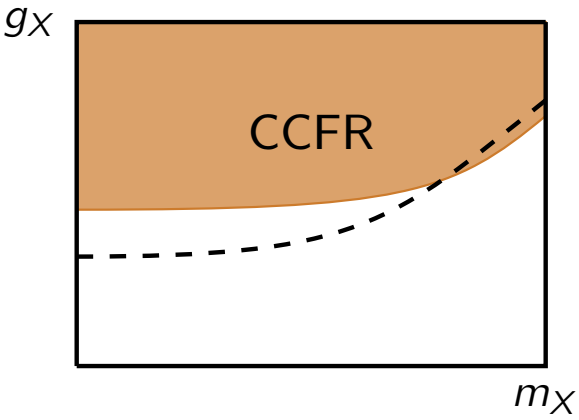

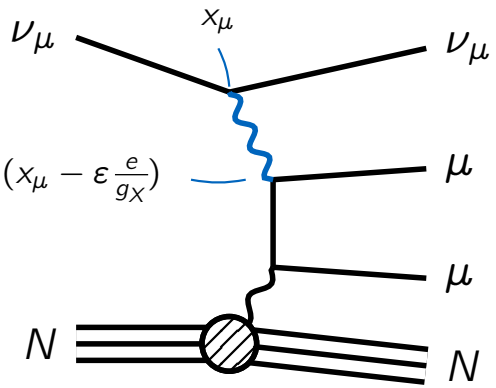

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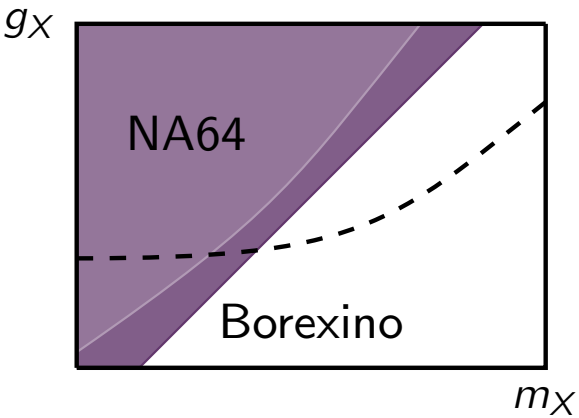
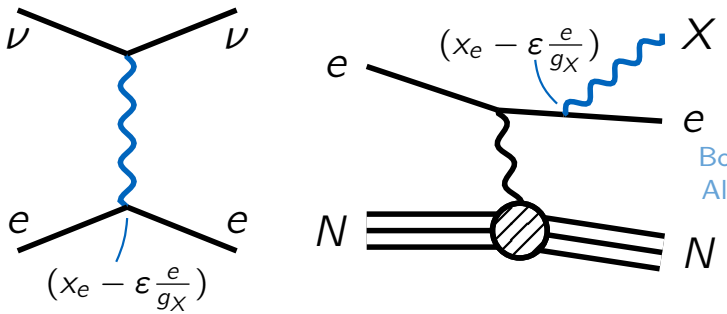
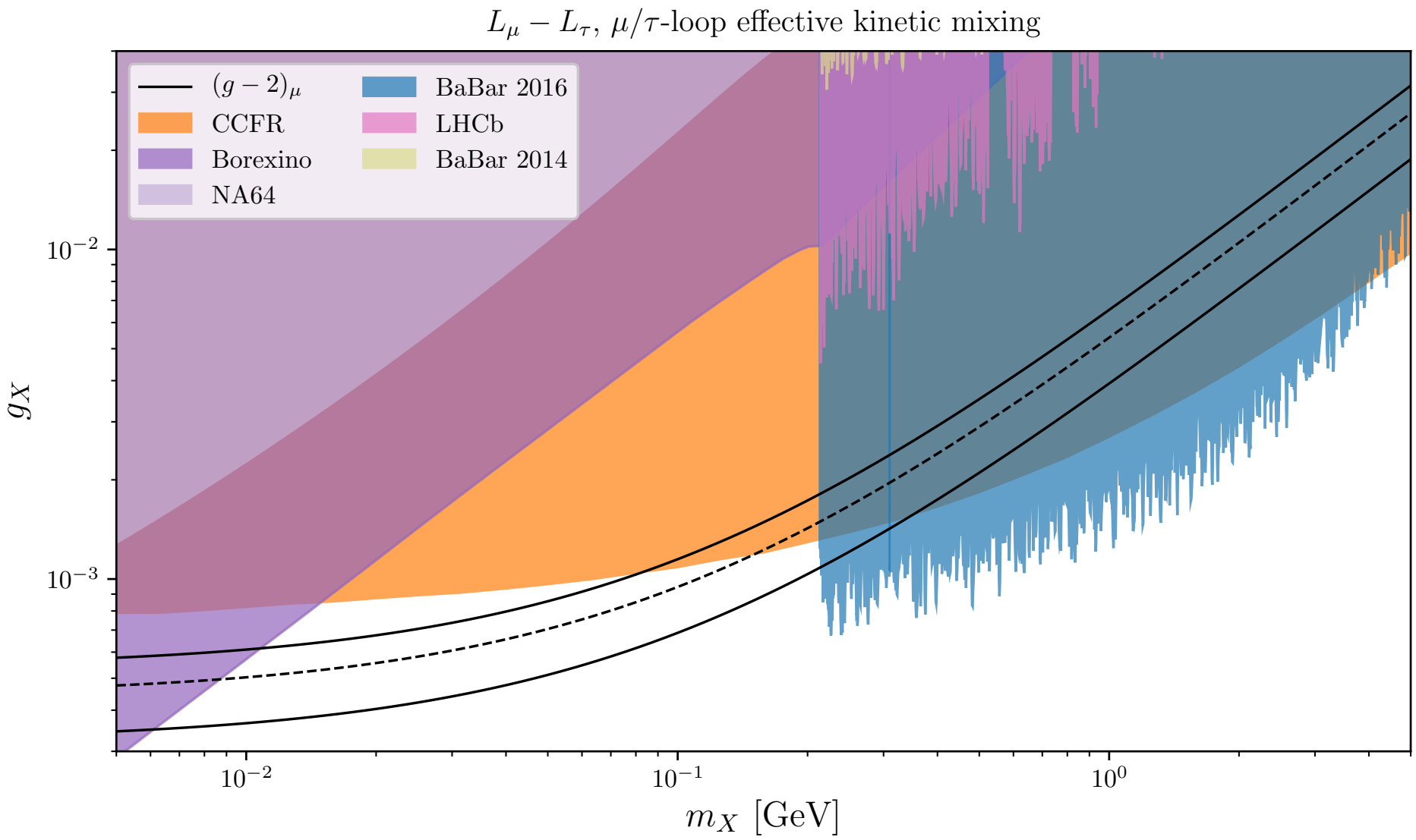




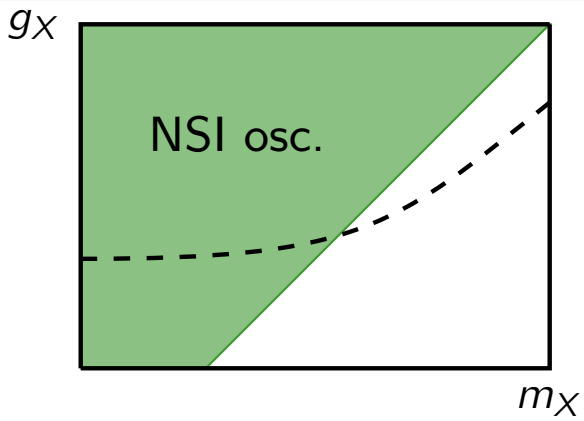
Borexino colaboration [1707.09279];
Altmannshofer *et al.* [1902.06765];
Banerjee *et al.* [1906.00176]

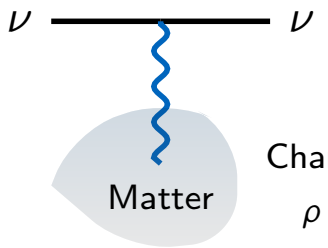
Light vector solution: $X = L_\mu - L_\tau$



Greljo, Stangl, AET, Zupan [2203.13731]

Complementary constraints on a light X



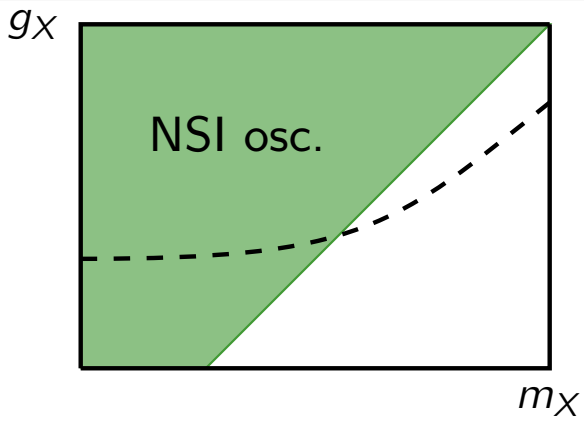


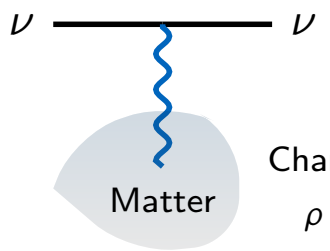
Charge density:

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

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

Complementary constraints on a light X





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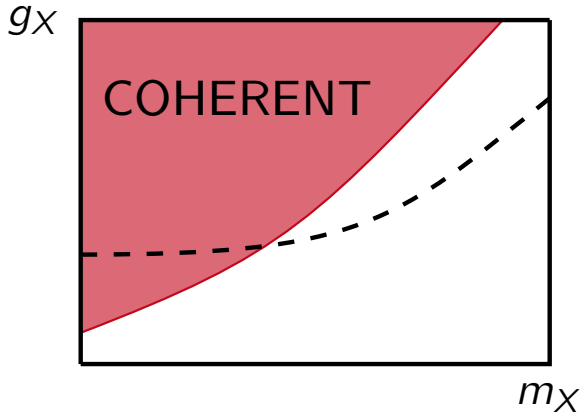
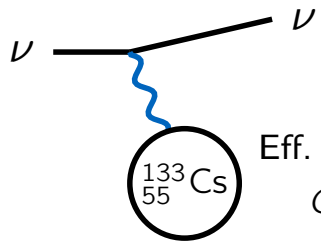


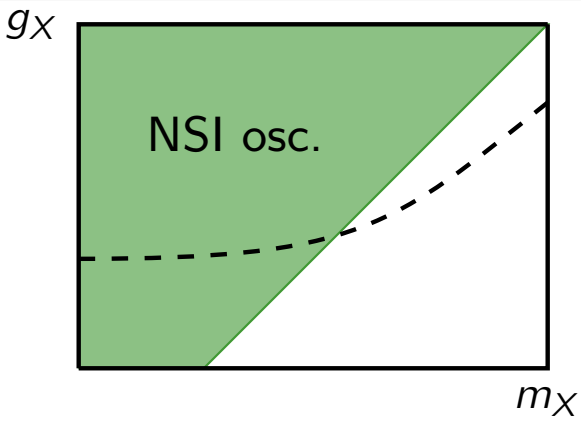


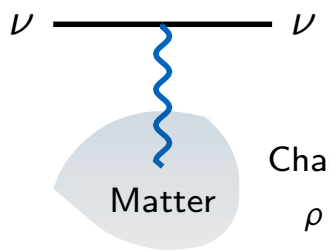
Eff. charge:

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

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

Complementary constraints on a light X





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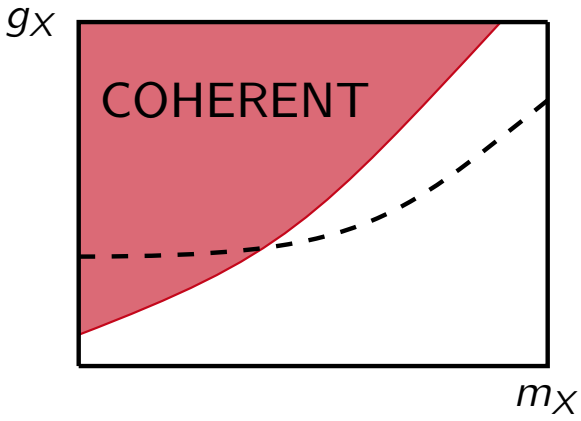

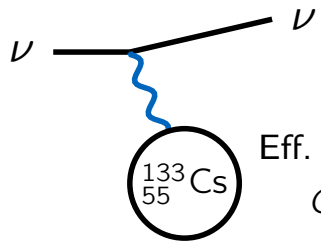

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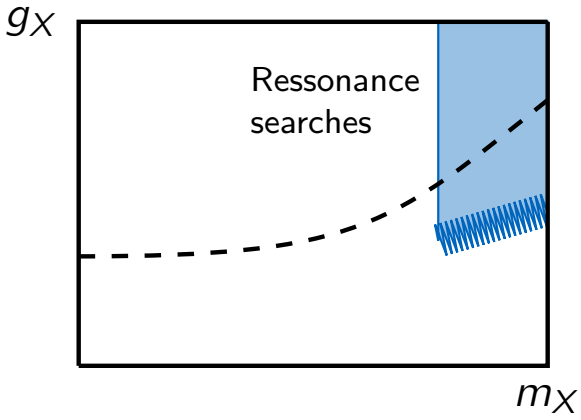
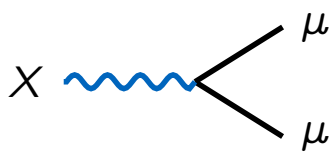
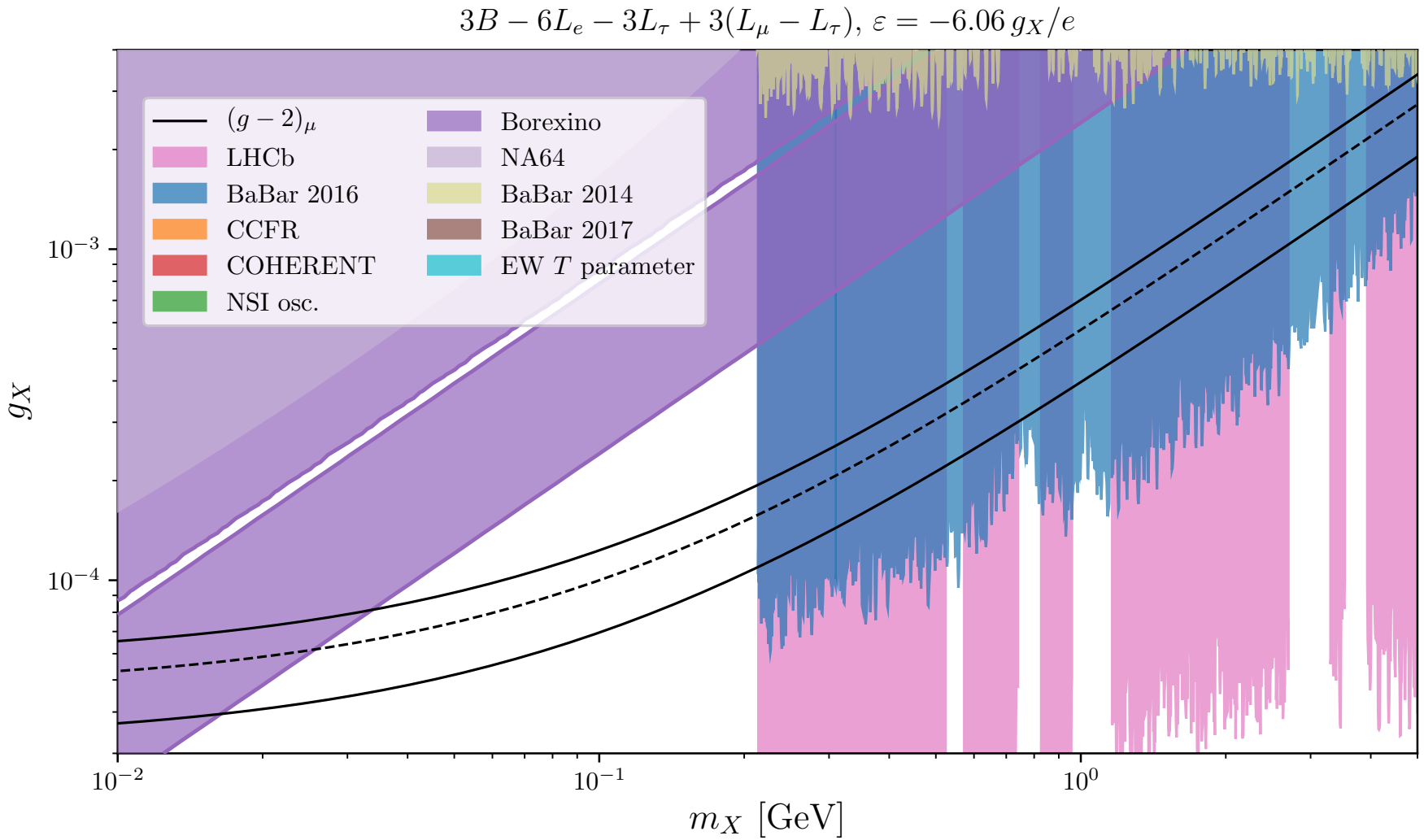




BaBar collaboration [1606.03501];
BaBar collaboration [1406.2980];
LHCb collaboration [1710.02867];
`darkcast`: Ilten *et al.* [1801.04847]

Allowed model with B charge

There are 6 allowed models with Baryon number charge and integer charge ratios less than 10. Qualitatively these all look the same:



Greljo, Stangl, AET, Zupan [2203.13731]

Summary

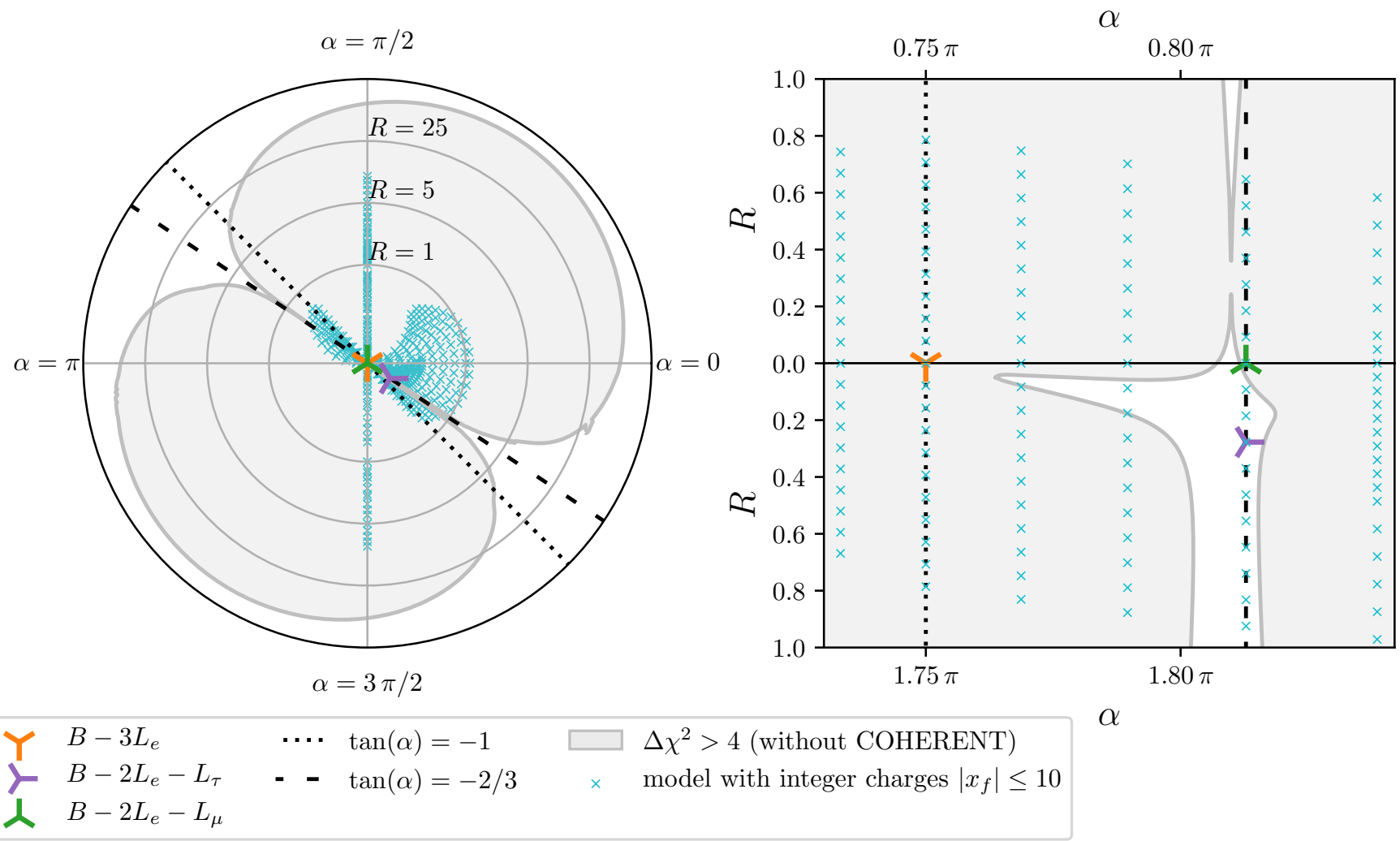
- Muonic (lepton-flavored) forces provide a robust organizing principle for ensuring SM selection rules in BSM models
- Muonic forces easily allow LQ explanations of the anomalies
- A muonic force mediator is very constrained as an explanation for the $(g-2)_\mu$ anomaly ($L_\mu - L_\tau$ is the best solution)

Thank You!

Backup

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]

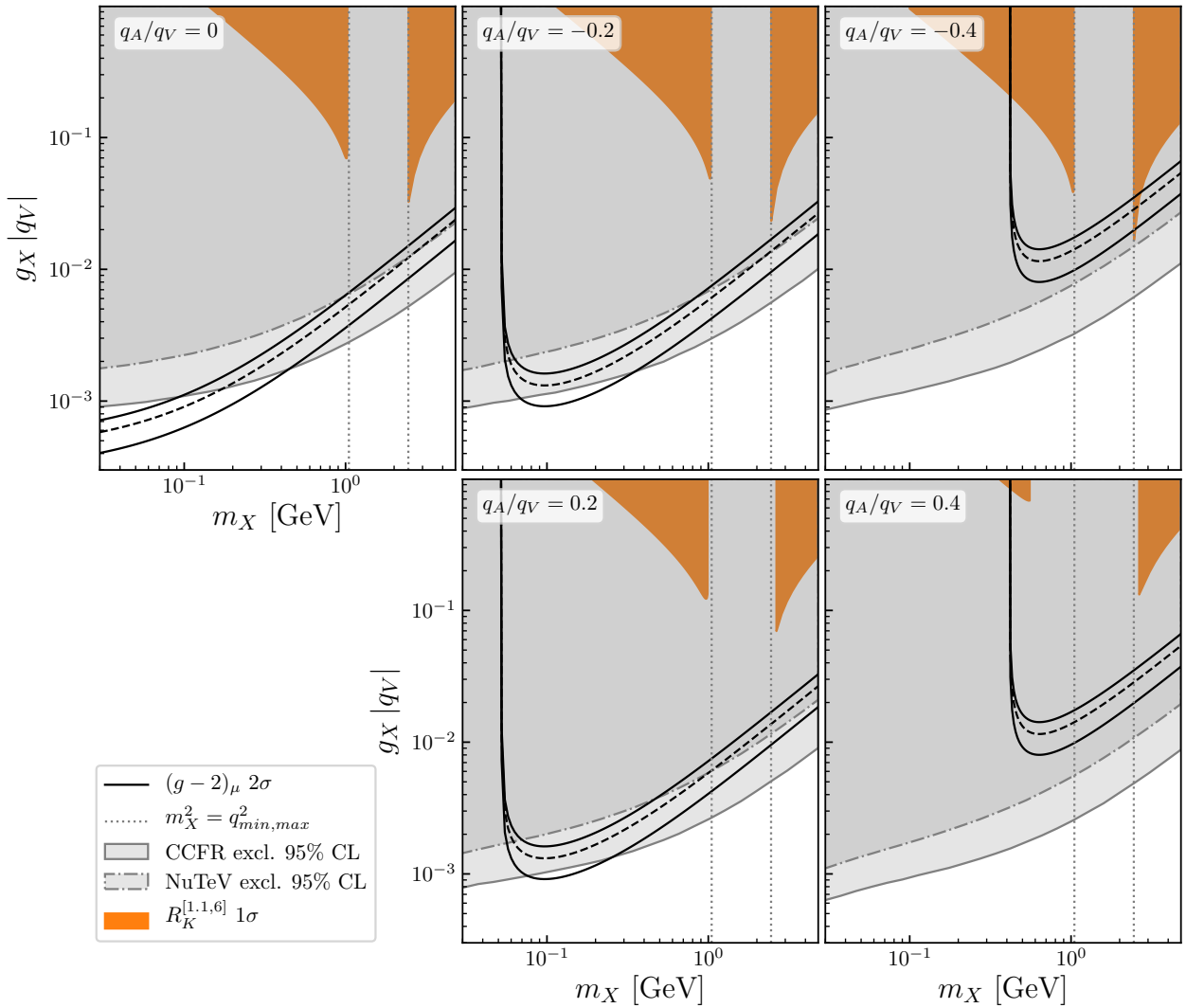
The $B - 3L_\mu$ model

	Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-3L_\mu}$
SM	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
Muoquarks	S_3	$\bar{\mathbf{3}}$	$\mathbf{3}$	$1/3$	$8/3$
	S_1	$\bar{\mathbf{3}}$		$1/3$	$8/3$
X-breaking SM singlet	Φ			0	3

Muonic force

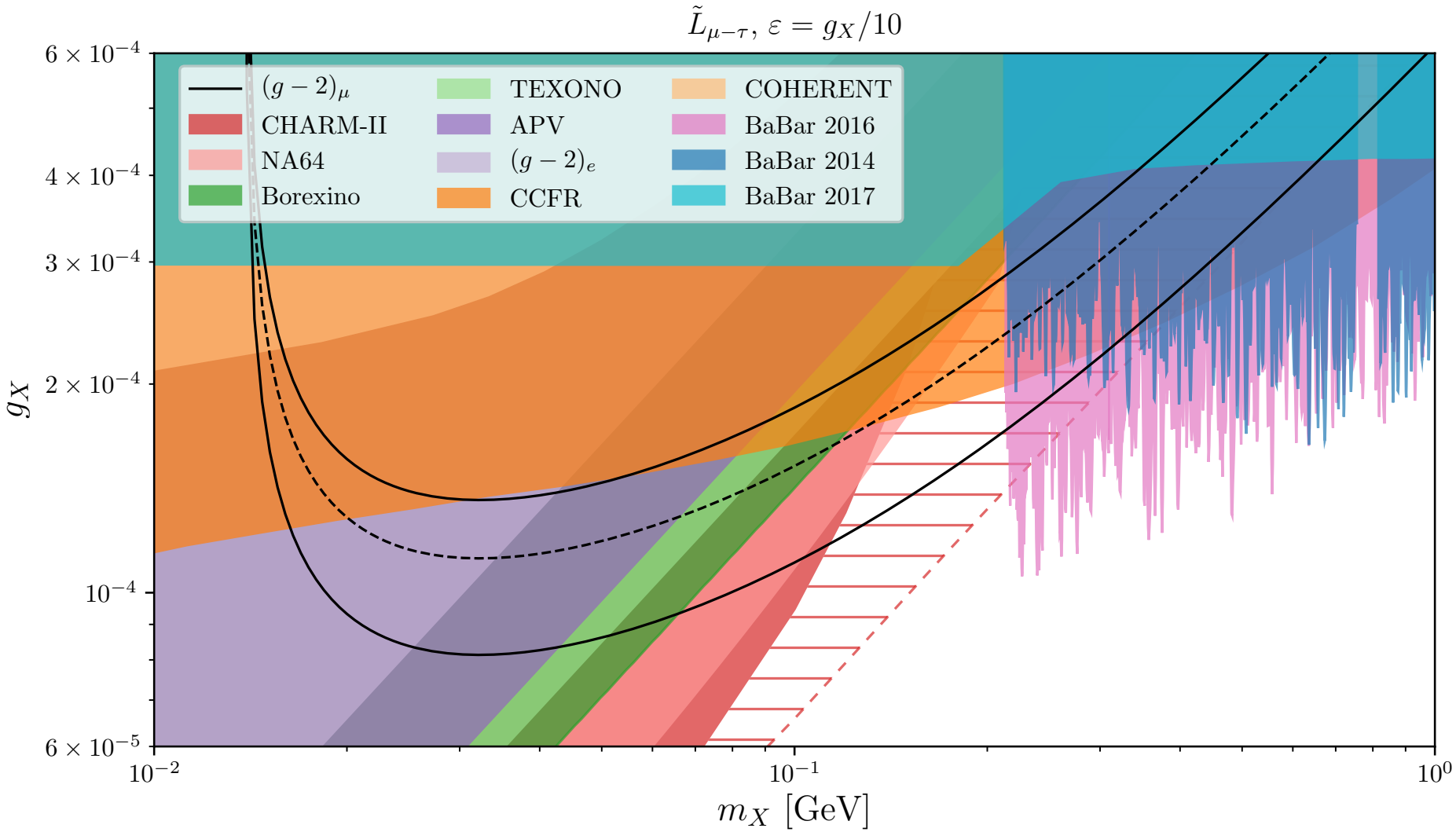
Light X_μ for $b \to s\ell\ell$ and $(g-2)_\mu$

- 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 $m_X \gtrsim 5\,\mathrm{GeV}$



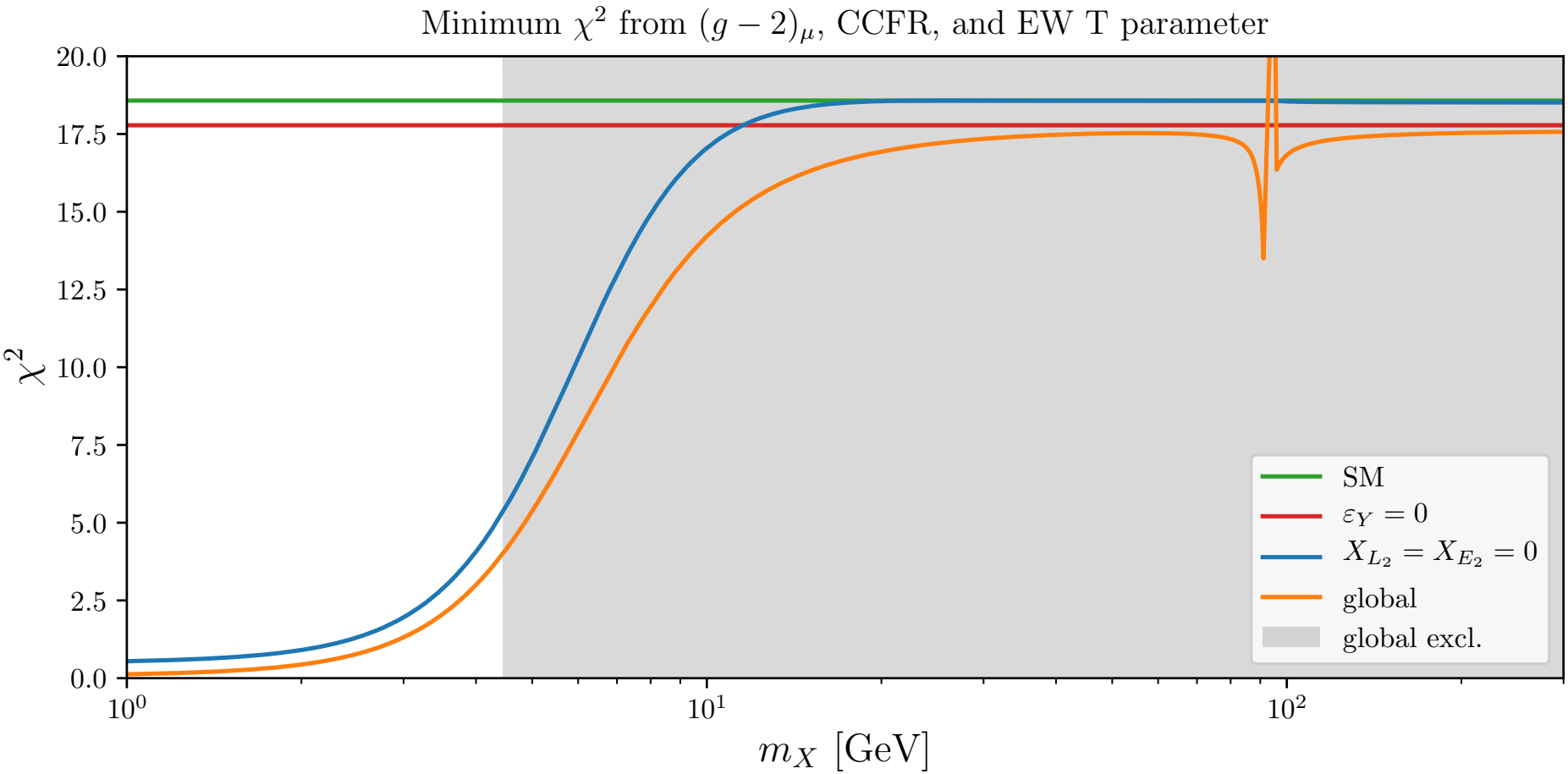
Greljo, Soreq, Stangl, AET, Zupan [2107.07518]

Chiral muonic force for $(g-2)_\mu$



Greljo, Stangl, AET, Zupan [WIP]

High energy vector boson mediator



Greljo, Stangl, AET, Zupan [WIP]