Exactly Stable Protons with a Muonic Force

Anders Eller Thomsen

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

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AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

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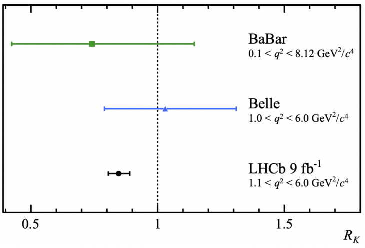
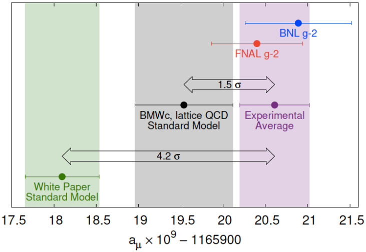
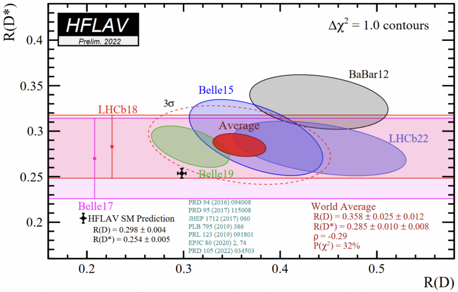
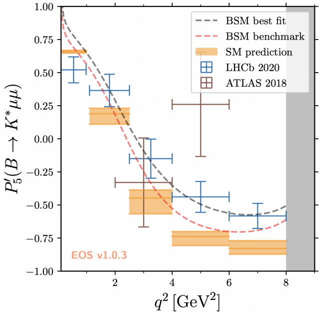
TeV-scale new physics?









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: $q_i,\; u_i,\; d_i,\; \ell_i,\; e_i$

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Explicit breaking by the Higgs couplings

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

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

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Consequences:

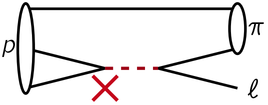
- Conservation of B number
- Conservation of LF

Exceptions:

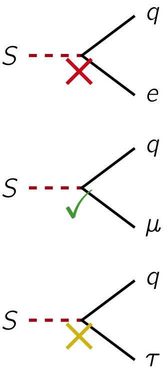
- Non-perturbative violation of $B + L$
- Neutrino oscillations

Selection rules for leptoquarks and muonic forces

Diquark interactions



LQ interactions



Problem: TeV-scale scalar LQ interactions are strongly constrained, e.g.,

- Proton lifetime $\tau_p \gtrsim 10^{34}\,\mathrm{yr}$
- LFV in muon decays: $\mathrm{BR}(\mu \to e\gamma) < 10^{-12}$

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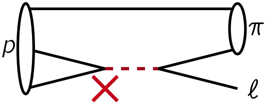

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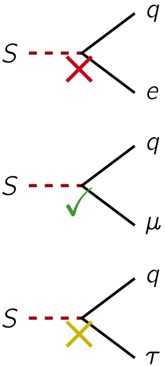

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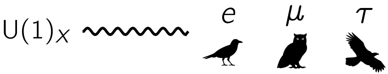
Solution: *Lepton-flavored gauged* $\mathrm{U}(1)_X$

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]



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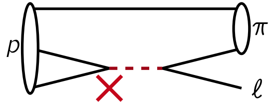

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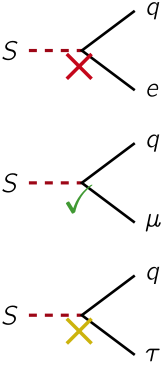

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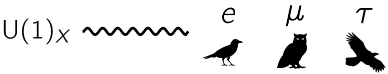


"Muoquark"

The accidental symmetries of $\mathcal{L}_{\mathrm{LQ}}$ are those of the SM, $\mathrm{U}(1)_B \times \mathrm{U}(1)_{L_e} \times \mathrm{U}(1)_{L_\mu} \times \mathrm{U}(1)_{L_\tau}$, and the leptoquarks have charge $S \sim (-1/3, 0, -1, 0)$

The U(1)$_X$ model

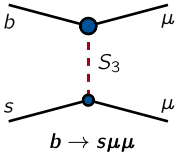
- Initial U(1)$_X$ model: $X = B - 3L_\mu \sim (m = 1,\ n = 3)$
- The generalization: $X = 3m\,(B - L) - n\,(2L_\mu - L_e - L_\tau), \quad \gcd(m,\ n) = 1$

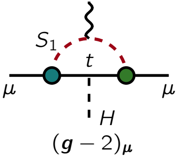
	Fields	U(1)$_X$
Quarks	$q_i,\ u_i,\ d_i$	m
Electrons & taus	$\ell_{1,3},\ e_{1,3},\ \nu_{1,3}$	$n - 3m$
Muons	$\ell_2,\ e_2,\ \nu_2$	$-2n - 3m$
Higgs	H	0
Leptoquarks	$S_3,\ S_1$	$2m + 2n$
SM singlets	$\phi_{e\tau}$	$6m - 2n$
	ϕ_μ	$6m + n$

Muoquark fit

Muoquark mediated anomalies

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





- 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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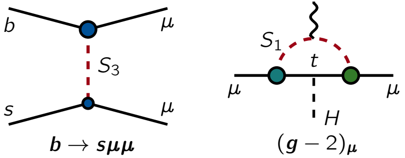

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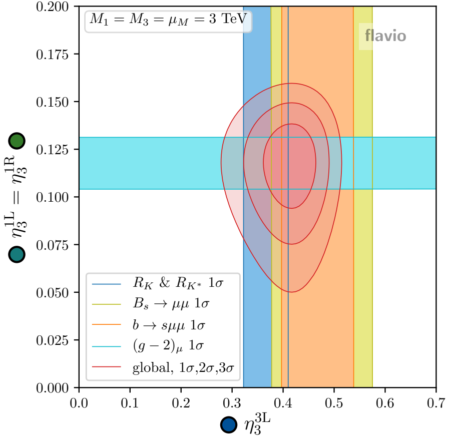
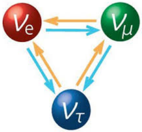


Greljo, Stangl, AET [2103.13991]

Neutrino masses

$U(1)_X$ + Symmetry-breaking condensate $\langle \phi \rangle$ $\longrightarrow$



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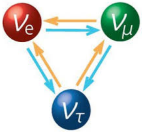

$$\mathcal{L} \supset - y_e^{ij} \bar{\ell}_i e_j H - y_\nu^{ij} \bar{\ell}_i \nu_j H^*$$

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

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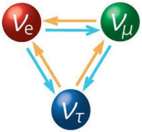

$$\mathcal{L} \supset - y_e^{ij} \bar{\ell}_i e_j H - y_\nu^{ij} \bar{\ell}_i \nu_j H^* - \bar{\nu}^{i\,c} \nu^j (\xi_{e\tau}^{ij} \phi_{e\tau} + \xi_\mu^{ij} \phi_\mu)$$

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$\implies$ Seesaw neutrino masses: $\langle \phi \rangle \lesssim 10^{11}$ TeV

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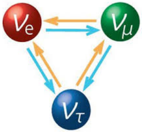

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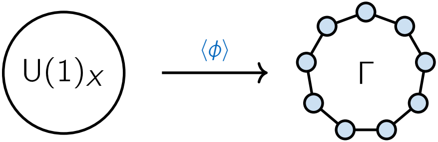
What happens to the accidental symmetries in the $\mathrm{U}(1)_X$ broken phase? Proton decay? cLFV?

Discrete IR remnant



Fixed by neutrino charges

$$U(1)_X \longrightarrow \Gamma = \left\{ e^{i\alpha} \in U(1)_X : \; e^{i\alpha [\phi]_X} \phi = \phi \right\} \cong \mathbb{Z}_k , \qquad k = \gcd([\phi_{e\tau}]_X, [\phi_\mu]_X)$$

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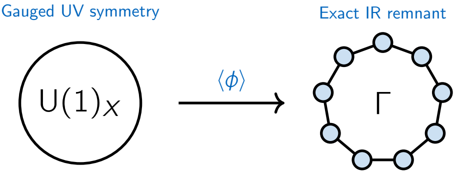

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Diquark operators are banned by Γ *iff*

$$(m, n) = \big(3a + r, 9b + 3r\big), \quad \text{for} \quad r \in \{1, 2\},$$
$$(a, b) \in \mathbb{Z}^2, \quad \text{and} \quad \gcd\big(3a + r, b - a\big) = 1$$

Davighi, Greljo, AET [2202.05275]

$$\Gamma \cong \begin{cases} \mathbb{Z}_9, & \text{for } b + r \in 2\mathbb{Z} + 1 \\ \mathbb{Z}_{18}, & \text{for } b + r \in 2\mathbb{Z} \end{cases}$$

- No proton decay mediated by LQs
- $m, n \neq 0 \implies$ lepton-flavored $\mathrm{U}(1)_X$ symmetry

IR selection rules

$b + r \pmod 2$	Γ	ℓ	q	S	$qS\ell$	qS^*q
0	$\mathbb{Z}_{18}$	9	$3a + r$	$6a + 8r$	0	$12r$
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- Low-energy EFT contains only q and $\ell \implies \Delta B = 0 \pmod 3$!
  - Exact proton stability, no matter other NP (all orders in EFT)
  - Neutron–antineutron oscillations forbidden
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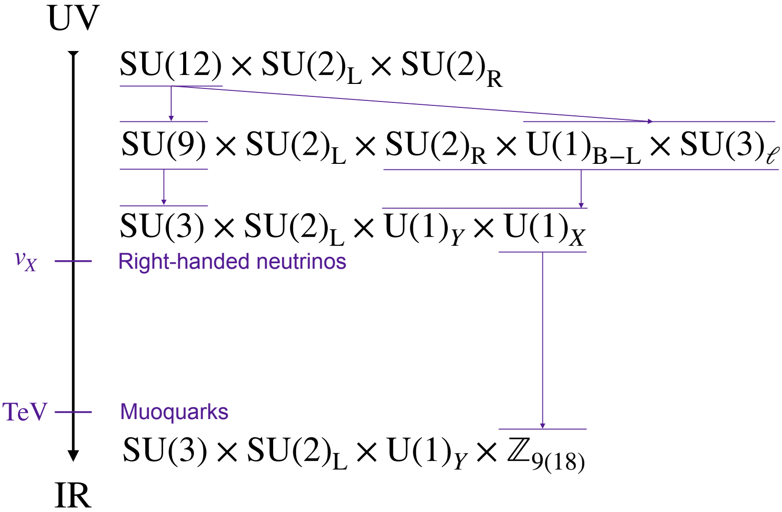
Neutrino masses are compatible with high-quality IR selection rules from a muonic forces

Unification of lepton-flavored $U(1)_X$



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Thank You!