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Eccellenza, Project-186866

Muonic force behind flavor anomalies

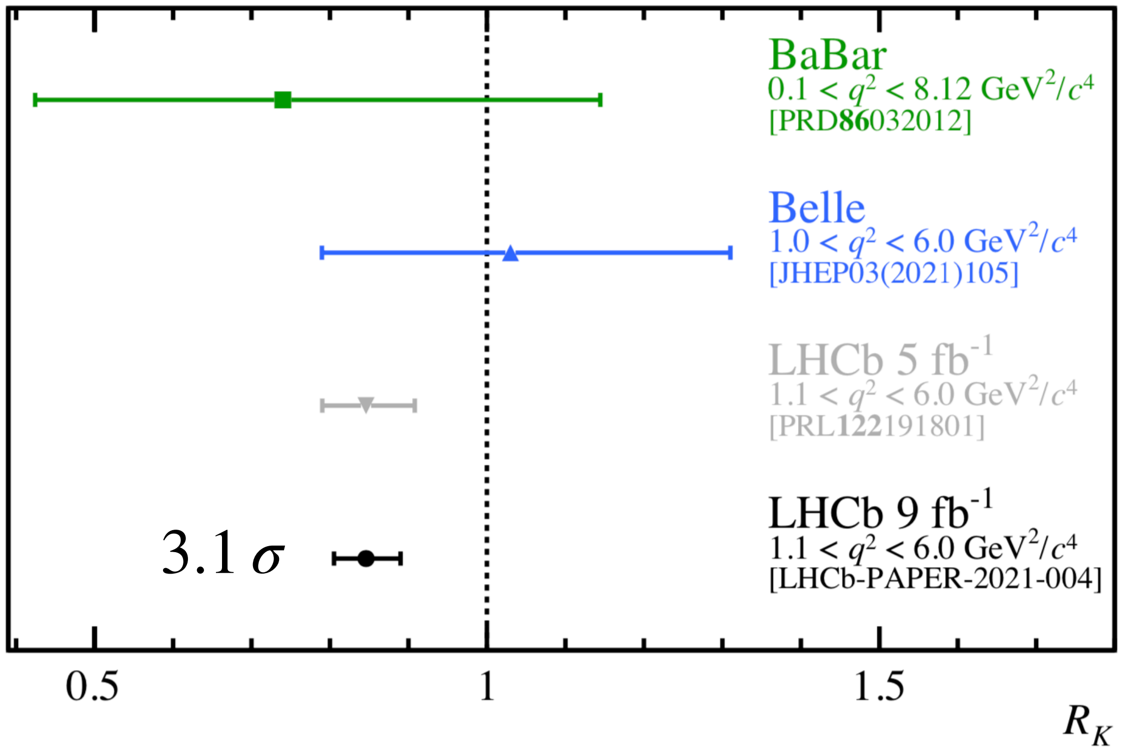
Admir Greljo

I will review our recent work on lepton flavor non-universal and anomaly-free U(1) gauge extensions of the SM. The phenomenological discussion will be centered around flavor anomalies in rare B-meson decays and muon g-2. This talk is based on 2103.13991 (AG, Stangl, and Thomsen) and 2107.07518 (AG, Soreq, Stangl, Thomsen, and Zupan).

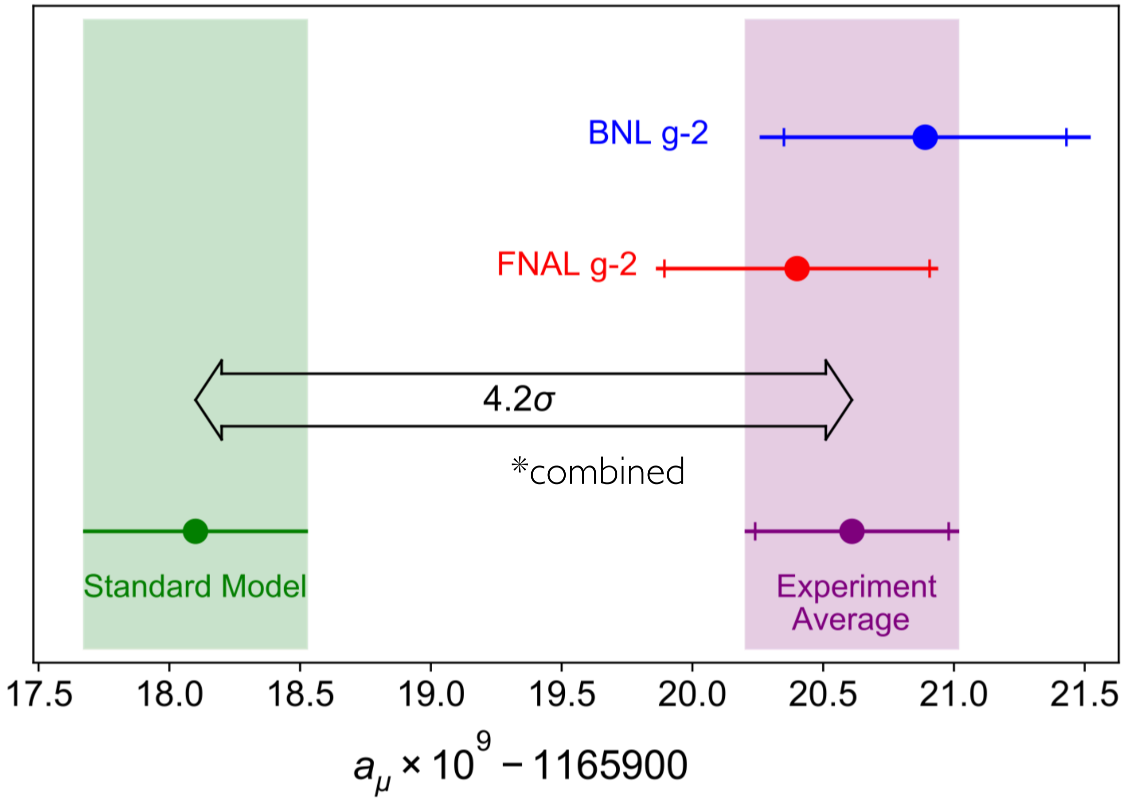
24.09.2021, Portorož

Muon Anomalies

Footprints of a next layer?



LHCb, CERN, 2103.11769

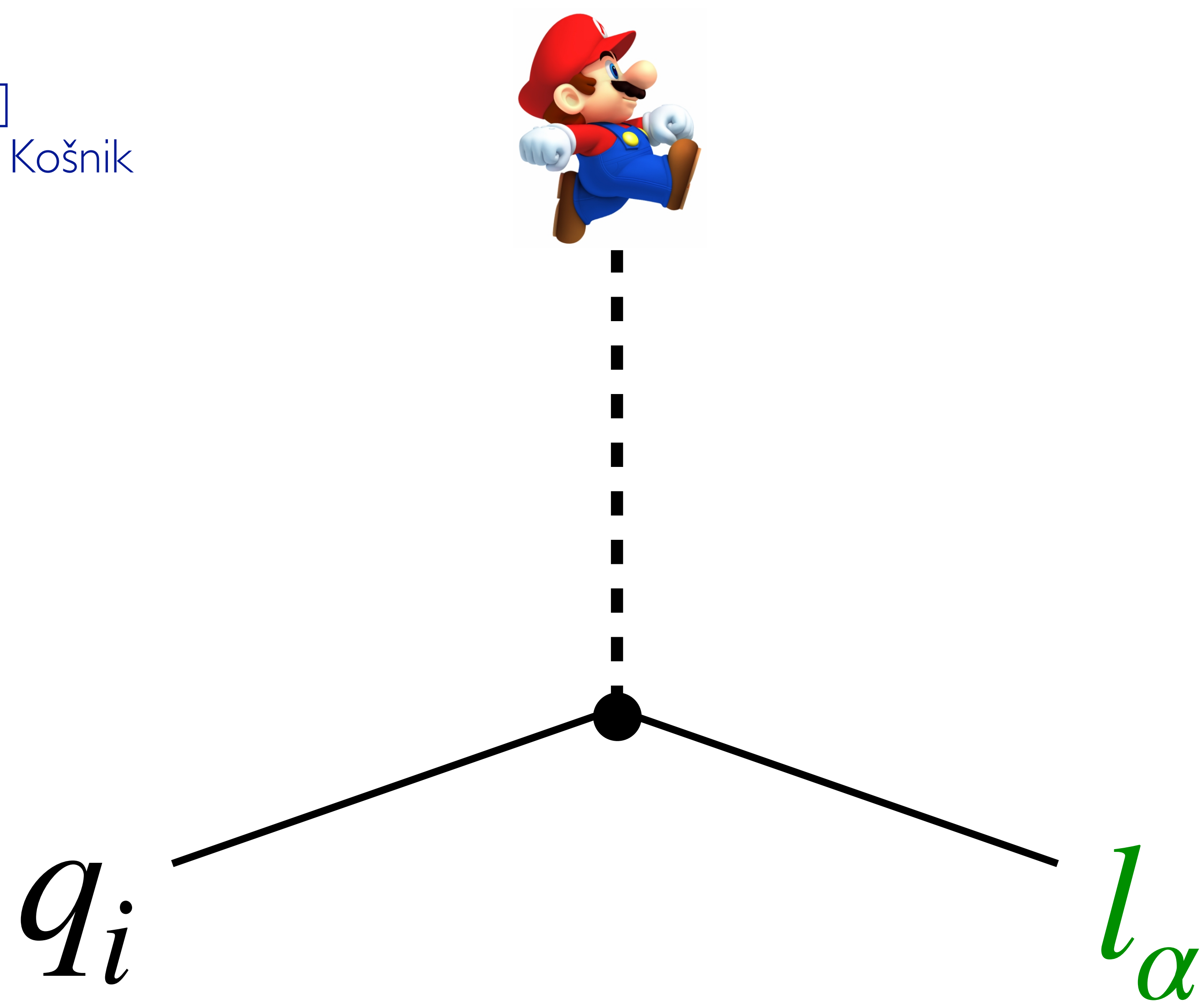


The Muon g-2, Fermilab, 2104.03281

+ other $b \to s\,\mu\mu$ observables

Leptoquark

[Phys.Rept. 641 (2016) 1-68]
Doršner, Fajfer, AG, Kamenik, Košnik



$$\alpha = e, \mu, \tau$$

- Portorož 2021's favourite game
- TeV-scale LQs were not exactly a popular game before the anomalies => [next slide]

Leptoquark

$$\mathcal{L}_4 \mathrel{+}= y_{ij} Q^i L^j S + z_{ij} Q^i Q^j S^\dagger$$

$B(S) = \frac{-1}{3}$ $\quad$ $B(S) = \frac{2}{3}$

- Abrupt violation of the SM (exact and approximate) accidental symmetries

~~$U(1)_B$~~	Proton decay	$[z \cdot y]$	probes scales up to 10^{13} TeV
~~$U(1)_e \times U(1)_\mu \times U(1)_\tau$~~	$\mu \to e \gamma$	$[i \neq j]$	probes scales up to 10^5 TeV
~~CP~~	Electron EDM	$[\mathrm{Im}\, y]$	probes scales up to 10^6 TeV
~~$U(3)_L \times U(3)_E$~~	LFUV, …		$R(K)$ probes up to 10^2 TeV

Accidental symmetries

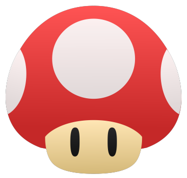
- Accidental symmetries emerge from:
  1. Spacetime + *Gauge symmetry* and Field content.
  2. Lagrangian(x) = infinite polynomial in fields and derivatives,
  but only a finite number of IR relevant operators $\mathbf{dim}[\mathscr{L}] \leq 4$

- In the SM, all IR relevant operators respect:
  $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Leptoquark

+

Gauged lepton flavor $U(1)_X$



Muoquark

= LQ with the $U(1)_X$ charge:

✓ $q\mu S$

✗ $qeS, q\tau S, qqS^\dagger$
$qqS^\dagger H, qqS^\dagger \phi$

- The accidental symmetry is $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ and the LQ charge is $(-1/3, 0, -1, 0)$

Hambye, Heeck; 1712.04871
Davighi, Kirk, Nardecchia, 2007.15016
AG, Stangl, Thomsen, 2103.13991
AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

The $U(1)_X$ atlas

- $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X$ gauge group

- Chiral fermions:

$$Q_i \sim (\mathbf{3}, \mathbf{2}, \tfrac{1}{6}, X_{Q_i}), \qquad U_i \sim (\mathbf{3}, \mathbf{1}, \tfrac{2}{3}, X_{U_i}), \qquad D_i \sim (\mathbf{3}, \mathbf{1}, -\tfrac{1}{3}, X_{D_i}),$$
$$L_i \sim (\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}, X_{L_i}), \qquad E_i \sim (\mathbf{1}, \mathbf{1}, -1, X_{E_i}), \qquad N_i \sim (\mathbf{1}, \mathbf{1}, 0, X_{N_i})$$

Left-handed ⟷ Right-handed

- The symmetry breaking scalar fields:

$$H = \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, X_H\right) , \qquad \phi = (\mathbf{1}, \mathbf{1}, 0, X_\phi)$$

- Without loss of generality $X_H = 0$

* By field redefinitions, shifting $X_f \to X_f - aY_f$ for all fields, gives an equivalent theory.

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

The $U(1)_X$ atlas

- $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X$ gauge group

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$$L_i \sim (\mathbf{1},\mathbf{2},-\tfrac{1}{2},X_{L_i}), \quad E_i \sim (\mathbf{1},\mathbf{1},-1,X_{E_i}), \quad N_i \sim (\mathbf{1},\mathbf{1},0,X_{N_i})$$

Anomaly cancelation conditions:

$$\mathrm{SU}(3)_C^2 \times \mathrm{U}(1)_X: \sum_{i=1}^{3}(2X_{Q_i} - X_{U_i} - X_{D_i}) = 0\,,$$
$$\mathrm{SU}(2)_L^2 \times \mathrm{U}(1)_X: \sum_{i=1}^{3}(3X_{Q_i} + X_{L_i}) = 0\,,$$
$$\mathrm{U}(1)_Y^2 \times \mathrm{U}(1)_X: \sum_{i=1}^{3}(X_{Q_i} + 3X_{L_i} - 8X_{U_i} - 2X_{D_i} - 6X_{E_i}) = 0\,,$$
$$\mathrm{Gravity}^2 \times \mathrm{U}(1)_X: \sum_{i=1}^{3}(6X_{Q_i} + 2X_{L_i} - 3X_{U_i} - 3X_{D_i} - X_{E_i} - X_{N_i}) = 0\,,$$
$$\mathrm{U}(1)_Y \times \mathrm{U}(1)_X^2: \sum_{i=1}^{3}(X_{Q_i}^2 - X_{L_i}^2 - 2X_{U_i}^2 + X_{D_i}^2 + X_{E_i}^2) = 0\,,$$
$$\mathrm{U}(1)_X^3: \sum_{i=1}^{3}(6X_{Q_i}^3 + 2X_{L_i}^3 - 3X_{U_i}^3 - 3X_{D_i}^3 - X_{E_i}^3 - X_{N_i}^3) = 0\,.$$

The $U(1)_X$ atlas

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\mathrm{U}(1)_Y^2 \times \mathrm{U}(1)_X &: \sum_{i=1}^{3}(X_{Q_i} + 3X_{L_i} - 8X_{U_i} - 2X_{D_i} - 6X_{E_i}) = 0 \ , \\
\mathrm{Gravity}^2 \times \mathrm{U}(1)_X &: \sum_{i=1}^{3}(6X_{Q_i} + 2X_{L_i} - 3X_{U_i} - 3X_{D_i} - X_{E_i} - X_{N_i}) = 0 \ , \\
\mathrm{U}(1)_Y \times \mathrm{U}(1)_X^2 &: \sum_{i=1}^{3}(X_{Q_i}^2 - X_{L_i}^2 - 2X_{U_i}^2 + X_{D_i}^2 + X_{E_i}^2) = 0 \ , \\
\mathrm{U}(1)_X^3 &: \sum_{i=1}^{3}(6X_{Q_i}^3 + 2X_{L_i}^3 - 3X_{U_i}^3 - 3X_{D_i}^3 - X_{E_i}^3 - X_{N_i}^3) = 0 \ .
\end{aligned}$$

- Unification => Rational charges. Rescale g_X => Integer charges.

$-10 \leq X_{F_i} \leq 10$ => 21'546'920 inequivalent solutions (i.e. up to flavor permutation, etc)

*to be explored

Allanach, Davighi, Melville; 1812.04602

The $U(1)_X$ atlas

Quark flavor universal

$-10 \leq X_{F_i} \leq 10$

- $Y^{u,d}$ are allowed => $X_{Q_i} = X_{U_j} = X_{D_k}$ [276 inequivalent solutions]

  $(X_H = 0)$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

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  $(X_H = 0)$

- Muoquark requirement
  eg. S_3 LQ: $X_{L_2} \neq \{X_{L_{1,3}}, -3X_q\}$ [273 inequivalent solutions]

Y^e allowed => $\textbf{vector category}: \quad X_{L_i} = X_{E_i}$ [252 inequivalent solutions]

$\textbf{chiral category}: \quad \text{the rest.}$ [21 inequivalent solutions]

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

The $U(1)_X$ atlas

Third-family-quark

- The "2+1" charge assignment

$$X_{Q_i} = X_{U_j} = X_{D_k} \equiv X_{q12} \quad \text{for all} \quad i, j, k = 1, 2, \quad \text{and}$$

$$X_{Q_3} = X_{U_3} = X_{D_3} \equiv X_{q3} \ . \quad (X_H = 0)$$

- The CKM elements (V_{td}, V_{ts}) at dim-5:

$$\mathcal{L} \supset \frac{x_i^u}{\Lambda} \overline{Q}_i \tilde{H} \phi U_3 + \frac{x_i^d}{\Lambda} \overline{Q}_i H \phi D_3 \ + \ \text{H.c.}$$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

The $U(1)_X$ atlas

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- The ACC conditions are satisfied provided

$$2X_{q12} + X_{q3} = 3X_q$$

*The quark flavor-universal solutions can immediately be extended to the 2 + 1 case.

- The muoquark conditions slightly change: $X_{q12} = 0$

eg. S_3 LQ: $X_{L_2} \neq \{X_{L_{1,3}}, X_{L_{1,3}} - X_{q3}, -X_{q3}, -2X_{q3}, -3X_{q3}\}$ [171 inequivalent sol.] $-10 \leq X_{F_i} \leq 10$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Example: **Vector category**

- Two scalar LQs:

$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3, X_{S_3})$ + $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3, X_{S_1})$

$\mathscr{L} \supset \eta^{3L} Q_3 L_2 S_3$

$\mathscr{L} \supset \eta^{1L} Q_3 L_2 S_1 + \eta^{1R} U_3 E_2 S_1$

See the talk by David Marzocca

(*) The X_μ decoupling: $g_X \to 0, m_X \to \infty$

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See the talk by David Marzocca

- $U(1)_X$ examples: 
  - $U(1)_{B-3L_\mu}$ with LQ charges +8/3
  - $U(1)_{B_3-\frac{8}{3}L_\mu-\frac{1}{3}L_\tau}$ with LQ charges +7/3

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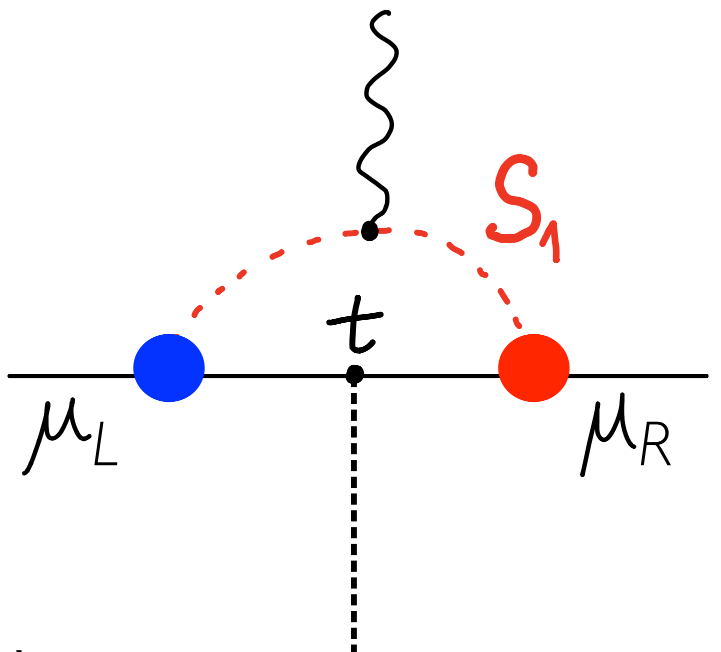
Quark Flavour Structure

$$\eta^{1(3)\mathrm{L}} \propto \mathcal{O}(V) \oplus 1$$
$$\eta^{1\mathrm{R}} \propto \mathcal{O}(\Delta_u^\dagger V) \oplus 1$$

$V = (\mathbf{2}, \mathbf{1}, \mathbf{1}) = (V_{td}, V_{ts})^T$, $\Delta_u = (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})$ and $\Delta_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$ under $U(2)_Q \times U(2)_U \times U(2)_D$ Barbieri et al; 1105.2296

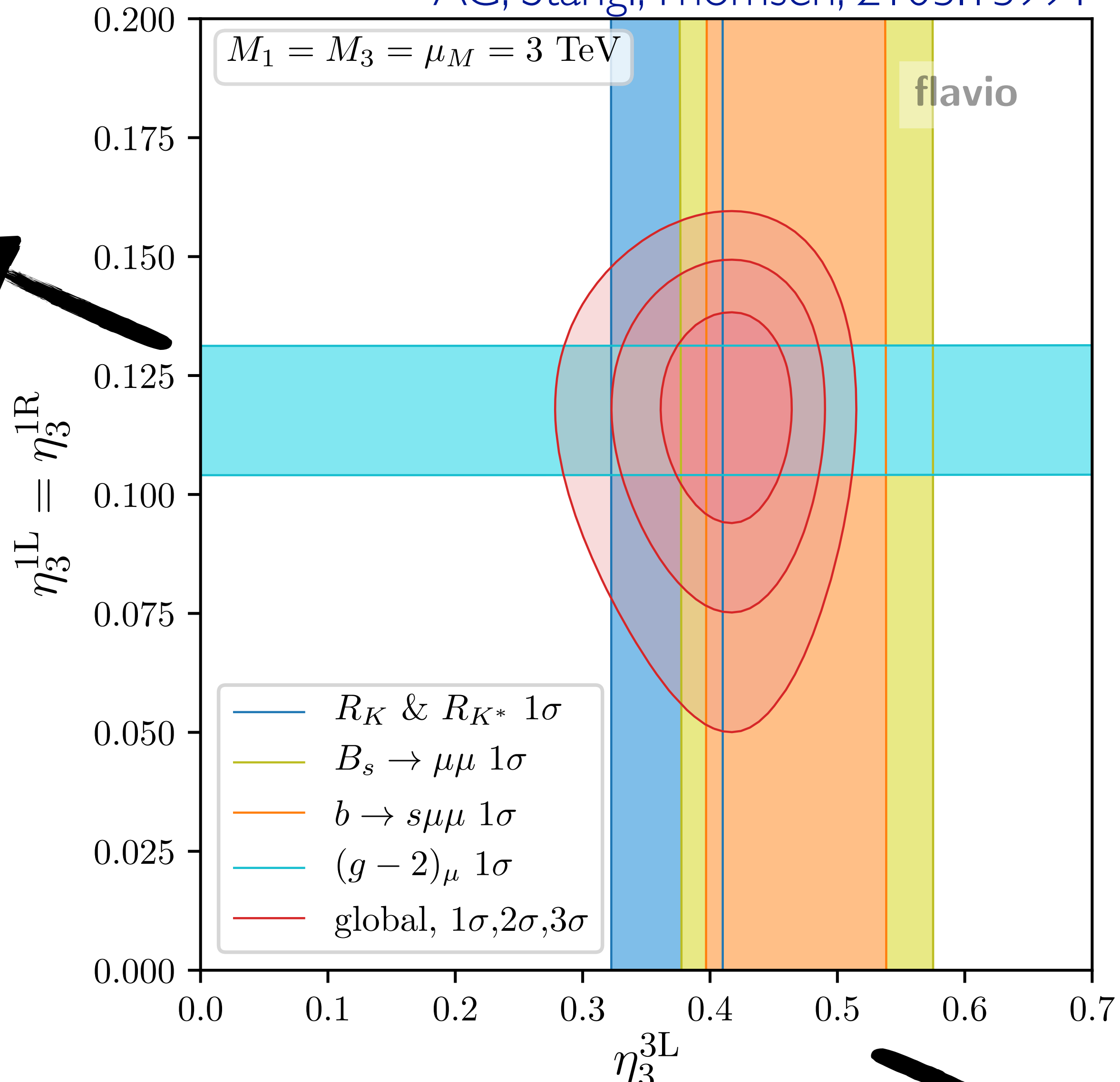
Example: **Vector category**



* m_t/m_μ enhancement

Queiroz, Shepherd; 1403.2309,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Coluccio Leskow, Crivellin, D'Ambrosio, Müller; 1612.06858
Dorsner, Fajfer, Sumensari; 1910.03877
Gherardi, Marzocca, Venturini; 2008.09548
+ many more

AG, Stangl, Thomsen, 2103.13991



$$\eta_i^{3L} = (V_{td},\, V_{ts},\, 1)\,\eta_3^{3L}$$

* V-A structure

Hiller, Schmaltz, 1408.1627,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Buttazzo, AG, Isidori, Marzocca; 1706.07808,
Gherardi, Marzocca, Venturini; 2008.09548
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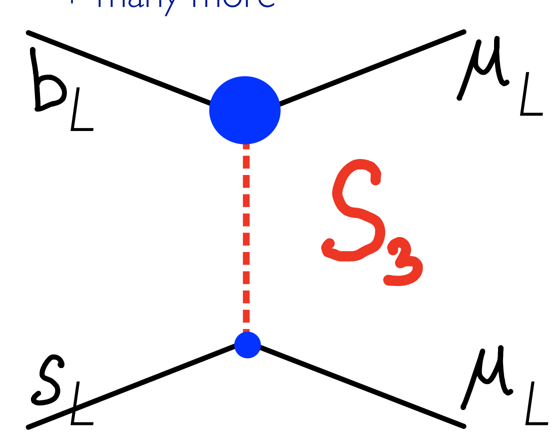
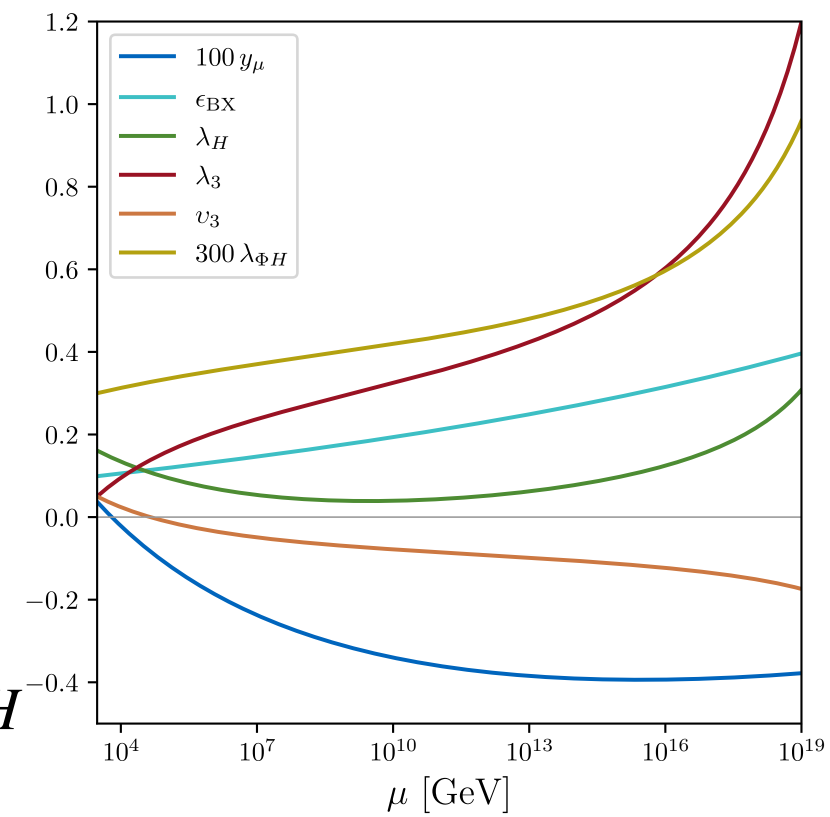


- One-loop matching to SMEFT from 2003.12525
- 399 observables in **smelli** 1810.07698
- EW and flavor opservables, LFV, LFU, magnetic moments, neutral meson mixing, semileptonic and rare B, D, K decays, etc.

- Present collider constraints:
  $M_1 > 1.4\,\mathrm{TeV}, M_3 > 1.7\,\mathrm{TeV}$ [ATLAS]

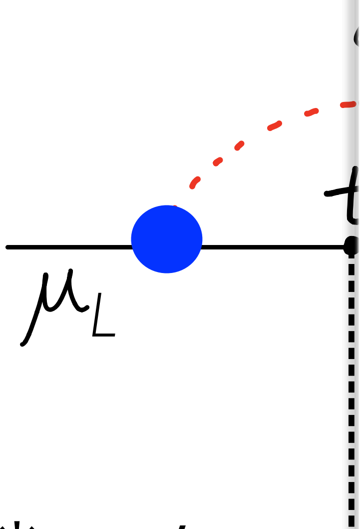
- For $M_{1,3} = 3\,\mathrm{TeV}$ <u>the largest coupling</u> ~ 0.4

- No Landau poles up to the Planck and the potential is stable.
  - Two loop Yukawa and quartic, three loop gauge (**RGBeta** 2101.08265)



- No fine tuning in m_H or m_μ due to $S_{1,3}$.

- This is contrary to the $R(D^{(*)})$ models which should be "around the corner", and sometimes even invoke tuned cancelations to pass complementary observables!



* m_t/m_μ er

Queiroz, Shepherd
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1603.04993,
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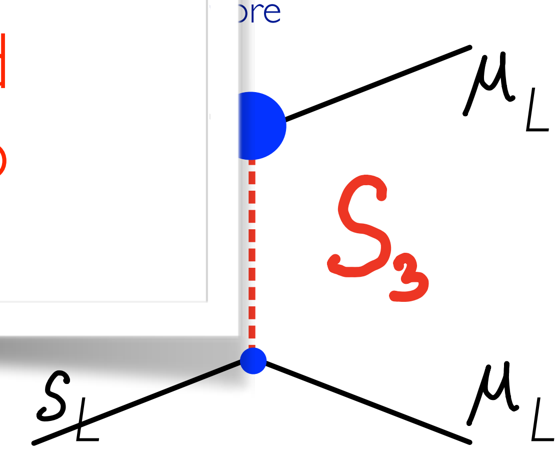


- One-loop match
- 399 observables
- EW and flavor observables, LFV, LFU, magnetic moments, neutral meson mixing, semileptonic and rare B, D, K decays, etc.

Example: **Chiral category**

Backup

Part II

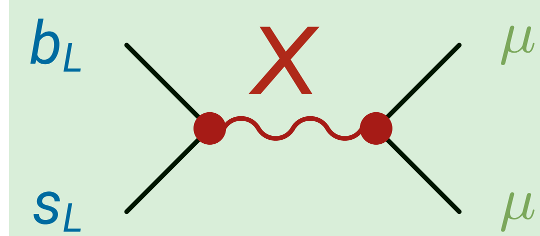
What about the muonic force?

AG, Stangl, Thomsen, 2103.13991

*minimal

	Type A	Type B	Type C
$R_{K^{(*)}}$, $b \to s\mu\mu$	S_3	S_3	heavy X
$(g-2)_\mu$	S_1/R_2	light X	S_1/R_2

What about the muonic force?



AG, Stangl, Thomsen, 2103.13991

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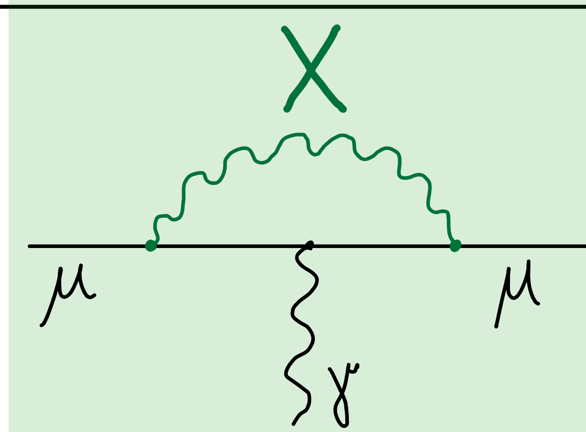
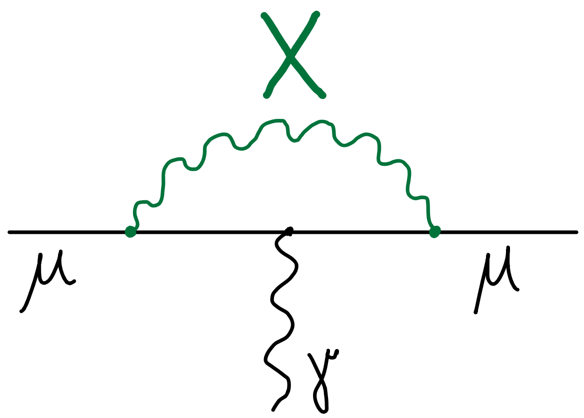


The muonic force

$(g-2)_\mu$:



$$\mathcal{L} \supset g_X \, \overline{\mu} \, \not{X} (q_V - q_A \gamma_5) \mu \quad =>$$

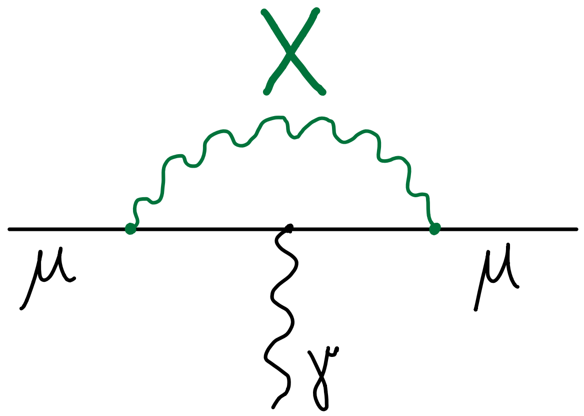
$$r_\ell = m_\ell / m_X$$

$$\Delta a_\mu = \frac{g_X^2}{8\pi^2} r_\mu^2 \left[q_V^2 \, I_V(r_\mu) + q_A^2 \, I_A(r_\mu) \right] = \frac{g_X^2}{8\pi^2} \begin{cases} q_V^2 - 2 \, r_\mu^2 \, q_A^2 , & m_X \ll m_\mu \\ \frac{2}{3} r_\mu^2 \left[q_V^2 - 5 \, q_A^2 \right] , & m_X \gg m_\mu \end{cases}$$

- The right sign => mostly vector coupling => $X_{L_2} \neq 0$

The muonic force

$(g-2)_\mu$:



$$\mathcal{L}_{\rm eff} \supset + g_X\,(q_V + q_A)\,\overline{\nu}_{\mu L}\,\not{X}\,\nu_{\mu L} + g_X\,\overline{\mu}\,\not{X}\,(q_V - q_A\,\gamma_5)\,\mu$$

$$r_\ell = m_\ell/m_X$$

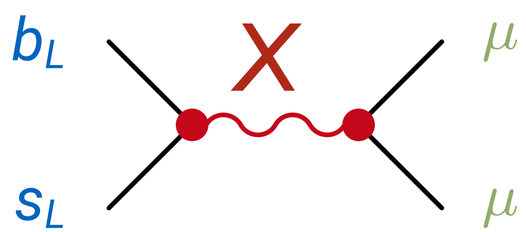
$$\Delta a_\mu = \frac{g_X^2}{8\pi^2} r_\mu^2\,[q_V^2\,I_V(r_\mu) + q_A^2\,I_A(r_\mu)] = \frac{g_X^2}{8\pi^2}\begin{cases} q_V^2 - 2\,r_\mu^2\,q_A^2, & m_X \ll m_\mu \\ \frac{2}{3} r_\mu^2\,[q_V^2 - 5\,q_A^2]\,, & m_X \gg m_\mu \end{cases}$$

- The right sign => mostly vector coupling => $X_{L_2} \neq 0$
- From the $\bar{L}_2 \not{D} L_2$ => neutrino ν_μ couples to X_μ

=> **Neutrino trident production:** $\nu_\mu N \;\to\; \nu_\mu N \mu^+ \mu^-$

The muonic force

$b \to s\mu\mu$:



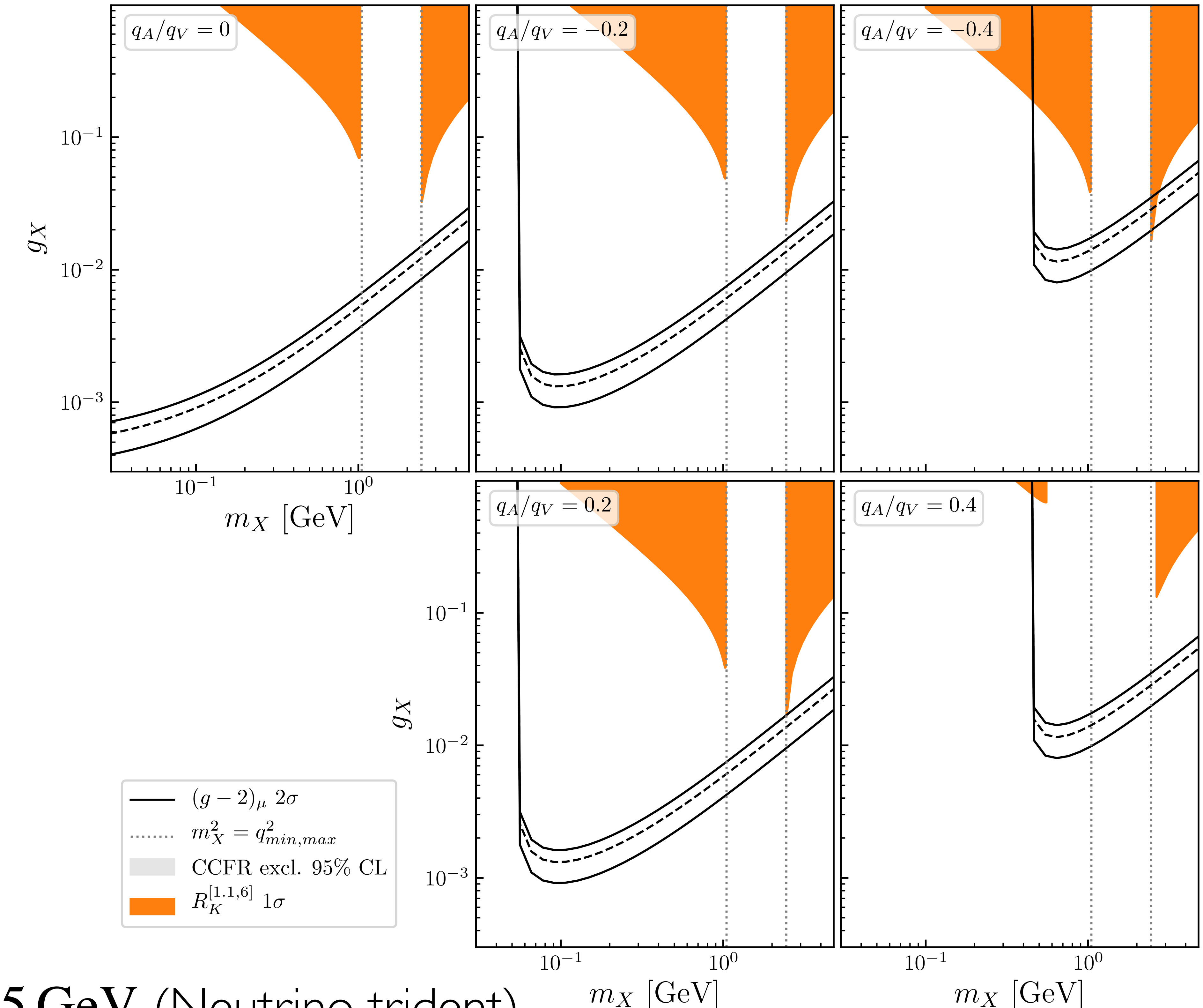
$$\mathcal{L}_{\rm eff} \supset + g_X\,(q_V + q_A)\,\overline{\nu}_{\mu L}\,\not{X}\,\nu_{\mu L} + g_X\,\overline{\mu}\,\not{X}\,(q_V - q_A\,\gamma_5)\,\mu + \left[\bar{b}\,\not{X}\,(g_L^{bs}\,P_L + g_R^{bs}\,P_R)\,s \;+\; \text{H.c.}\right],$$

$$C_{9,10}^{(\prime)} = \frac{q_{V,A}}{N}\,\frac{g_X\,g^{bs}_{L(R)}}{q^2 - m_X^2 + i m_X \Gamma_X}$$

- When $m_X < m_B - m_K$ => strong limits from $B \to KX$ where $X \to \nu\nu$

$$g_L^{bs} \lesssim 0.7 \times 10^{-8}\,\frac{m_X}{\rm GeV}$$

The muonic force

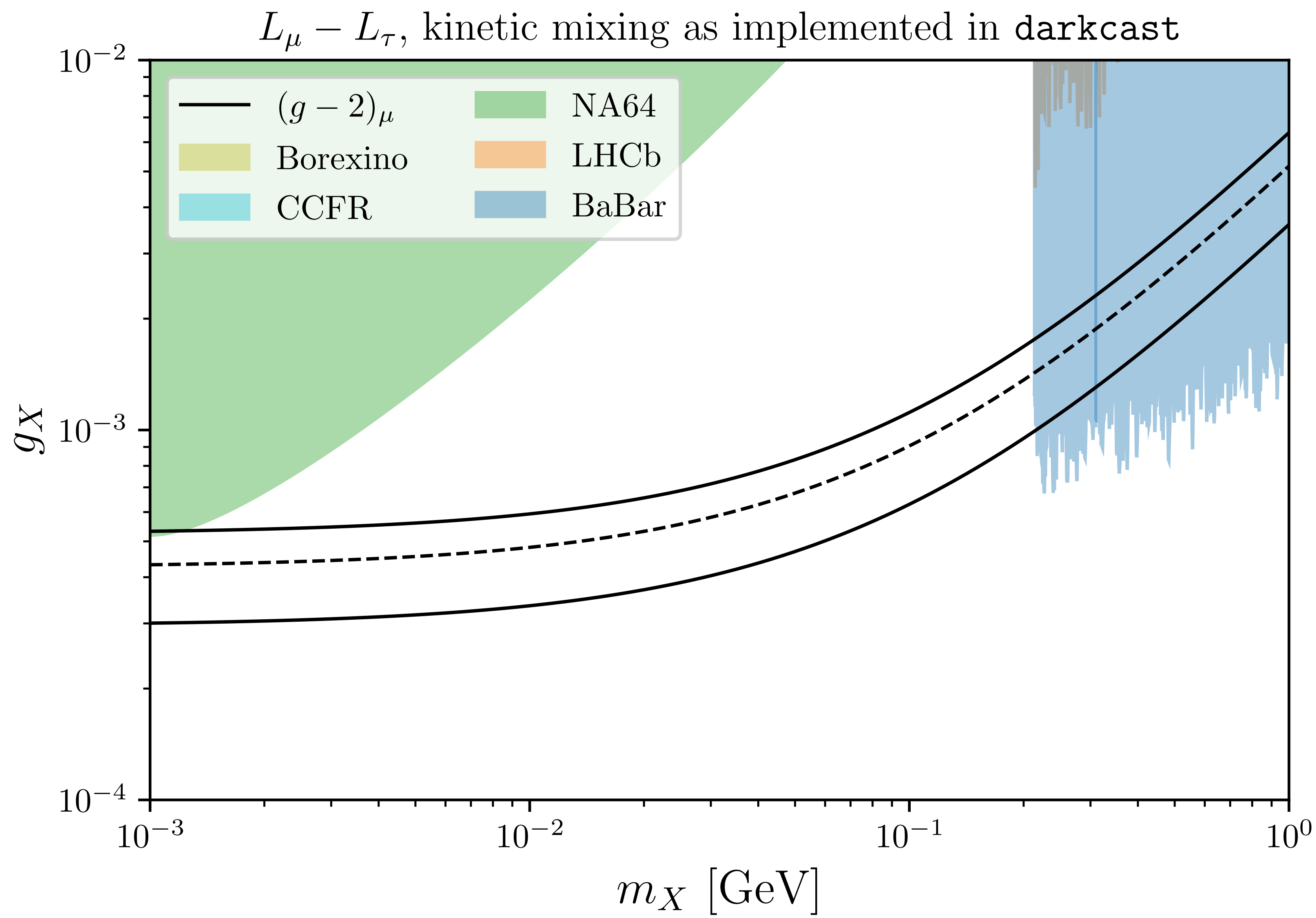


- $m_X \lesssim 0.5\,\mathrm{GeV}$ (Neutrino trident)
- $R(K)$ needs a different mediator

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Gauged $L_\mu - L_\tau$

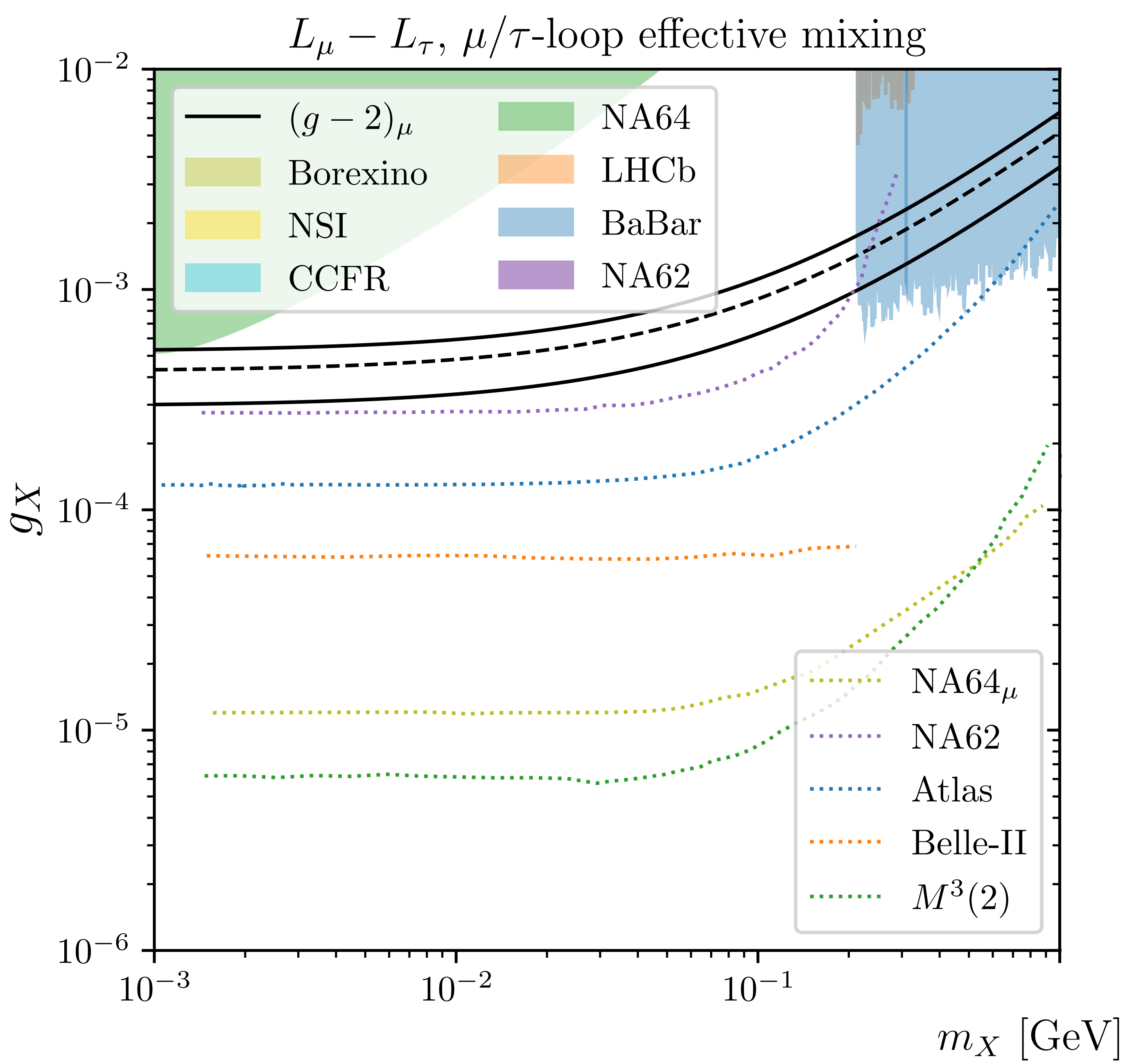
hep-ph/0104141,
hep-ph/0110146,
1311.0870,
1403.1269,
1406.2332,
…



- Dimuon resonances: $m_X \lesssim 0.21\,\mathrm{GeV}$
- Cosmology (BBN): $m_X \gtrsim 0.01\,\mathrm{GeV}$
- Electron bounds (Borexino, NA64):
  - Depend on the Kinetic mixing.

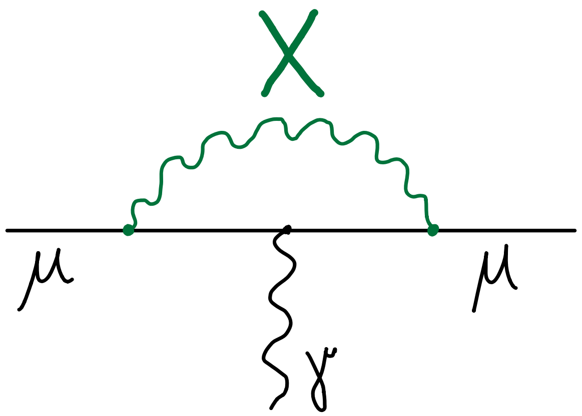
AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Gauged $L_\mu - L_\tau$



Promising projections!

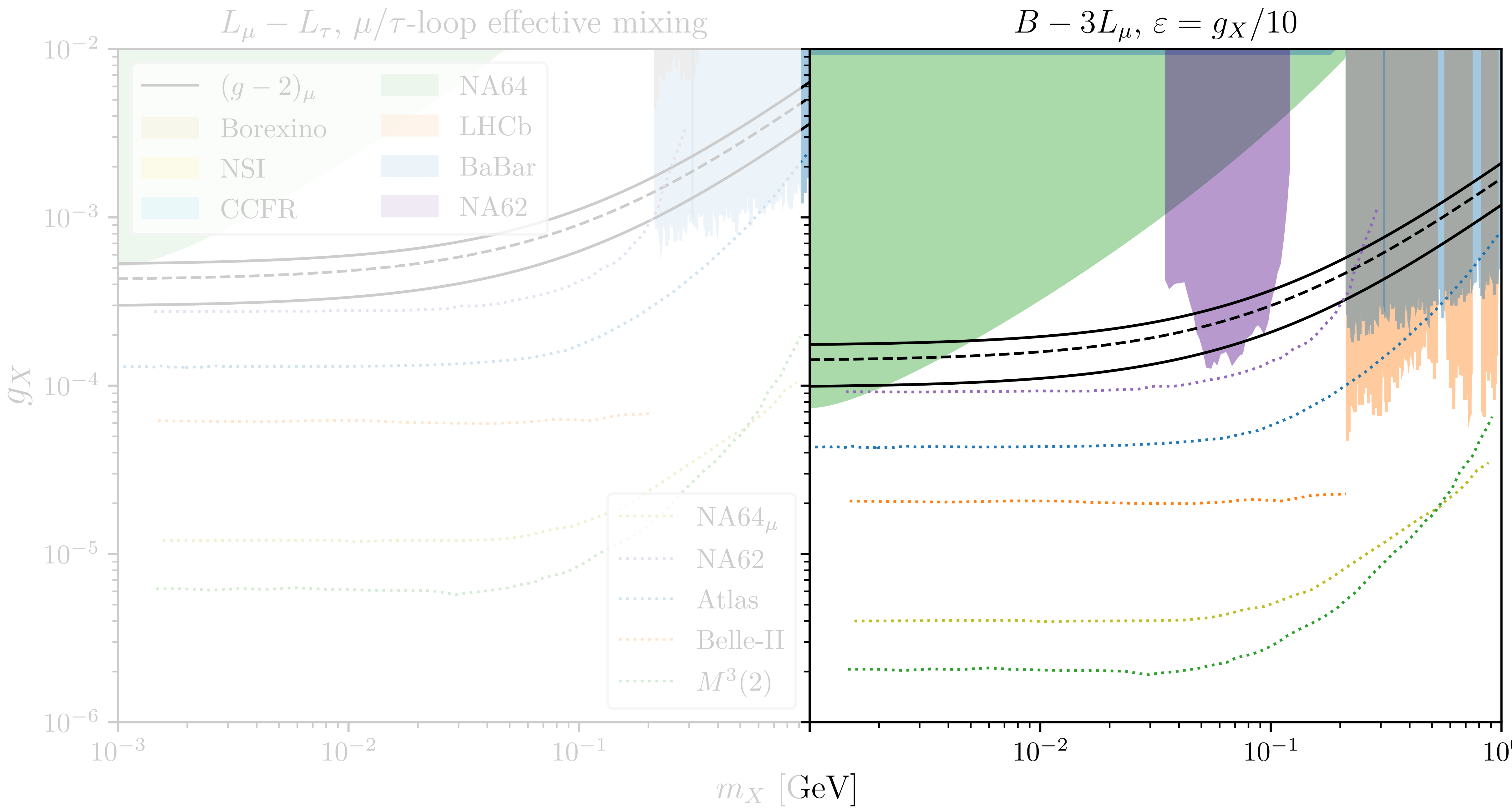
AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518



What about other $U(1)_X$?

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Gauged $B - 3L_\mu$



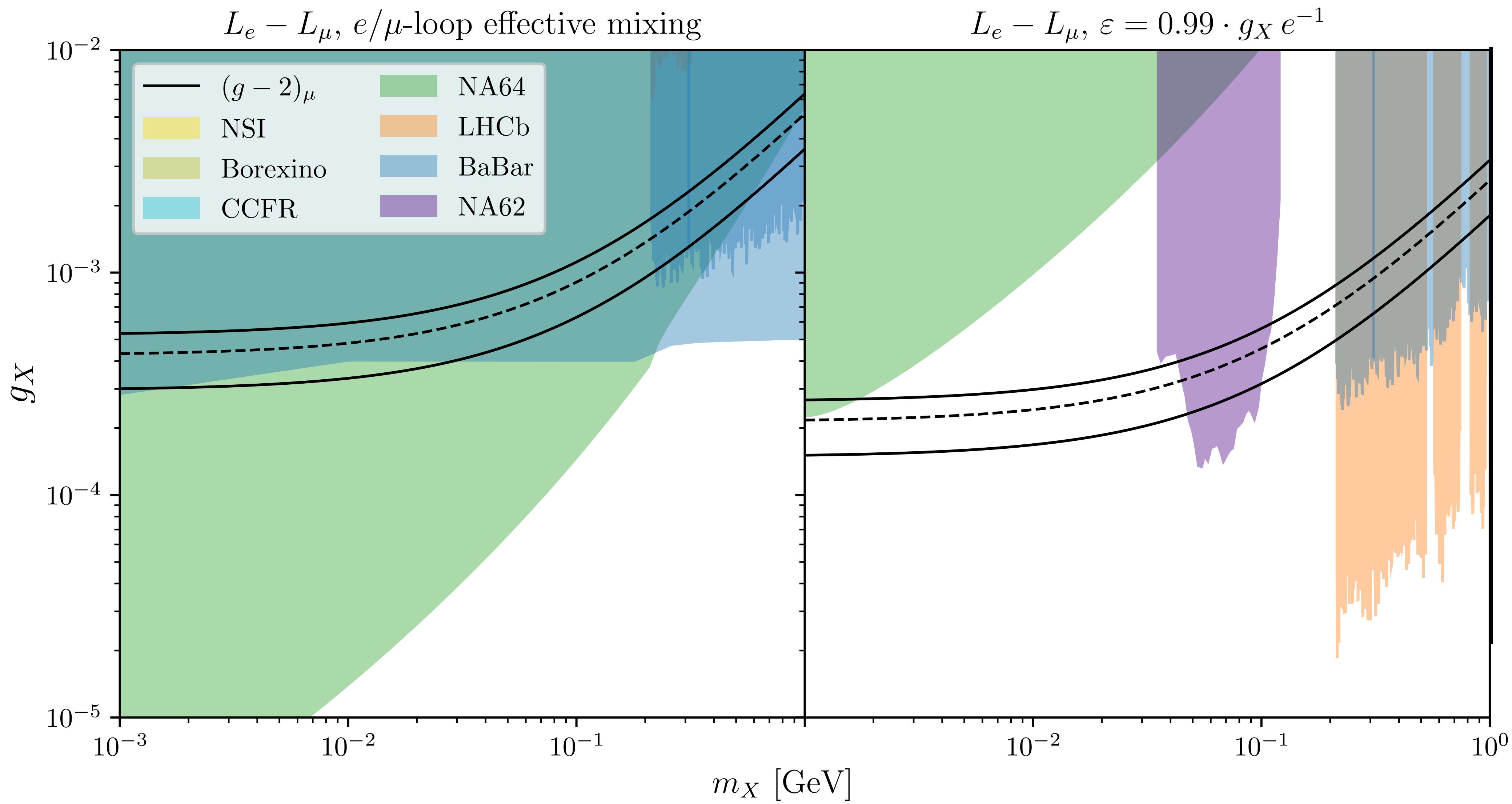
Neutrino NSI important for the valence quarks!

$$\mathcal{L}_{\rm NSI} = -\frac{G_F}{2\sqrt{2}} \sum_{f,\alpha\beta} \varepsilon^f_{\alpha\beta} (\bar{f}\gamma_\mu f)(\bar{\nu}_\alpha P_{\rm L} \nu_\beta)$$

$$f = \{e, p, n\}$$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

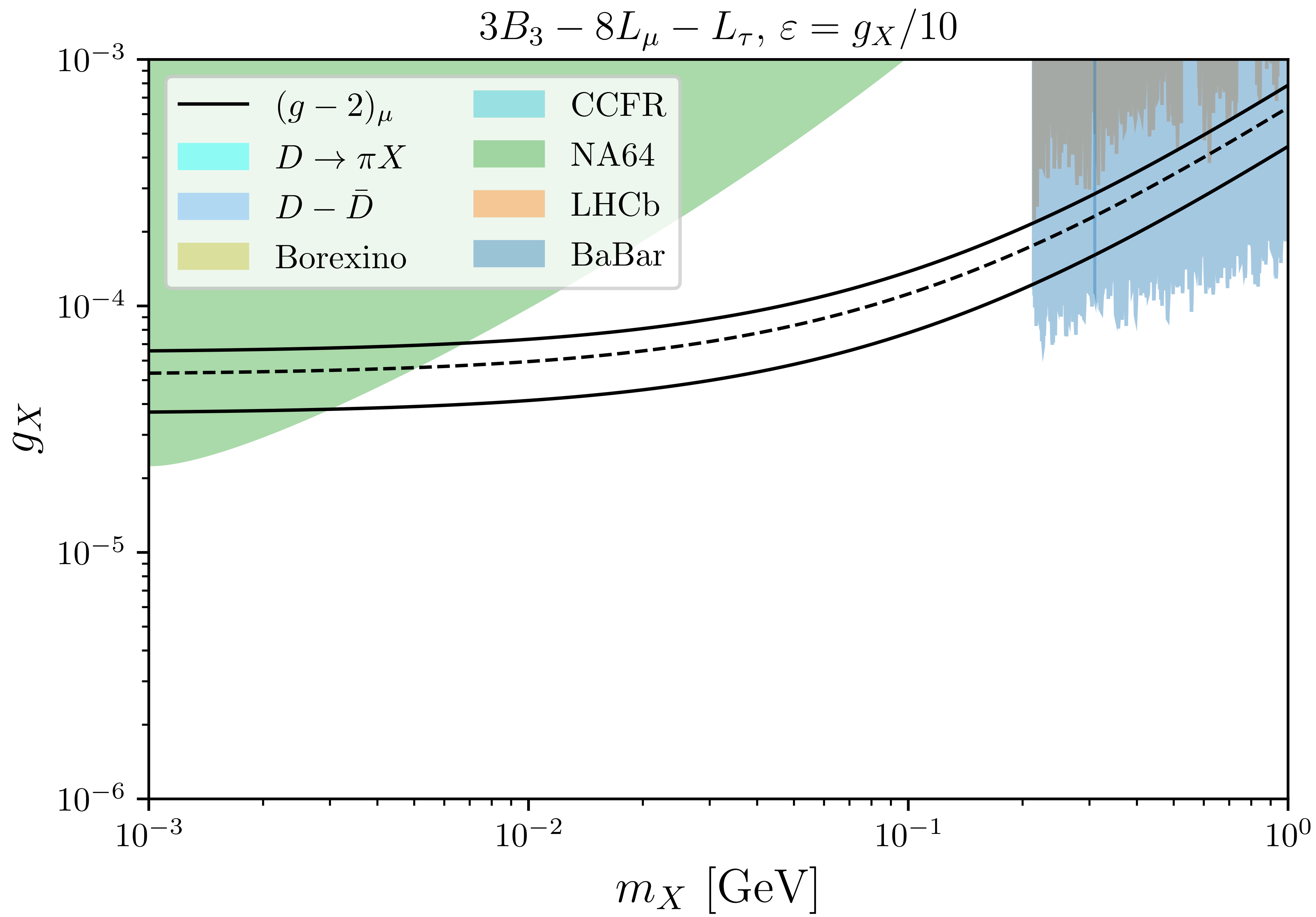
Gauged $L_e - L_\mu$



- The electron induced bounds from NA64, Borexino and NSI
- The kinetic mixing can relax the first two, but not the NSI

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Gauged $3B_3 - 8L_\mu - L_\tau$

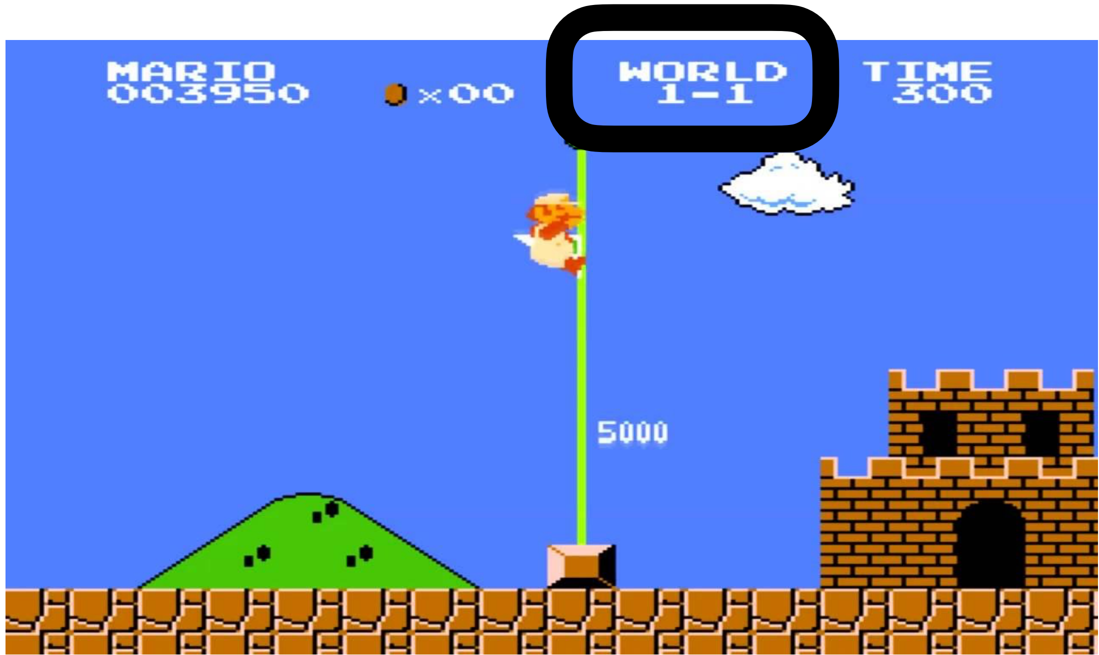


- Third-family quark $U(1)_X$ [down-alignment]
- FCNCs in X_μ interactions call for the quark universality!

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Conclusions

1. Muon anomalies might be footprints of physics beyond the SM.
2. Gauged lepton flavor is an interesting direction.
3. Successful mediators:
   Muoquarks and *Muonic forces*



Backup

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Example: Chiral category

- The dimension-4 muon Yukawa is forbidden by $U(1)_X$

  $$X_{L_2} \neq X_{E_2}$$

- Introduce two scalar muoquarks $S_\pm = (\mathbf{3}, \mathbf{2}, 7/6, X_{S_\pm})$

  $$\mathcal{L} \supset \eta_{\rm L}\, \bar{t}_{\rm R} \ell_{\rm L}^2\, i\sigma_2 S_+ - \eta_{\rm R}\, \bar{q}_{\rm L}^3\, \mu_{\rm R}\, S_-$$

- Mix them via $U(1)_X$ breaking

  $$\mathcal{L} \supset -A\phi S_+^\dagger S_-$$

Charges:

$$X_{S_+} = -X_{L_2} + X_{U_i}$$
$$X_{S_-} = -X_{E_2} + X_{Q_i}$$
$$X_\phi = -X_{S_-} + X_{S_+}$$

Example:

$\boldsymbol{\tilde{L}_{\mu-\tau}}$ **model:**

$$(X_{L_1}, X_{L_2}, X_{L_3}) = (0, 7, -7),$$
$$(X_{N_1}, X_{N_2}, X_{N_3}) = (5, 3, 8),$$
$$(X_{E_1}, X_{E_2}, X_{E_3}) = (\text{-}3, 8, \text{-}5),$$
$$X_{Q_i, D_i, U_i} = 0.$$

Example: Chiral category

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- Mix them via $U(1)_X$ breaking

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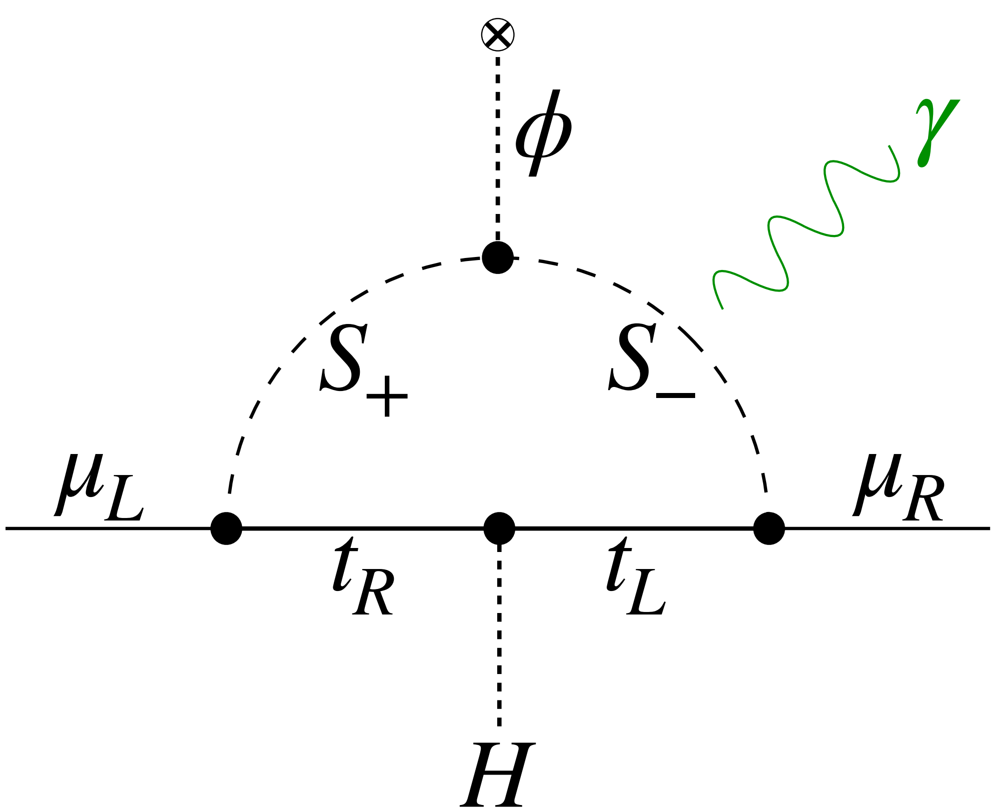

=> m_μ, Δa_μ

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

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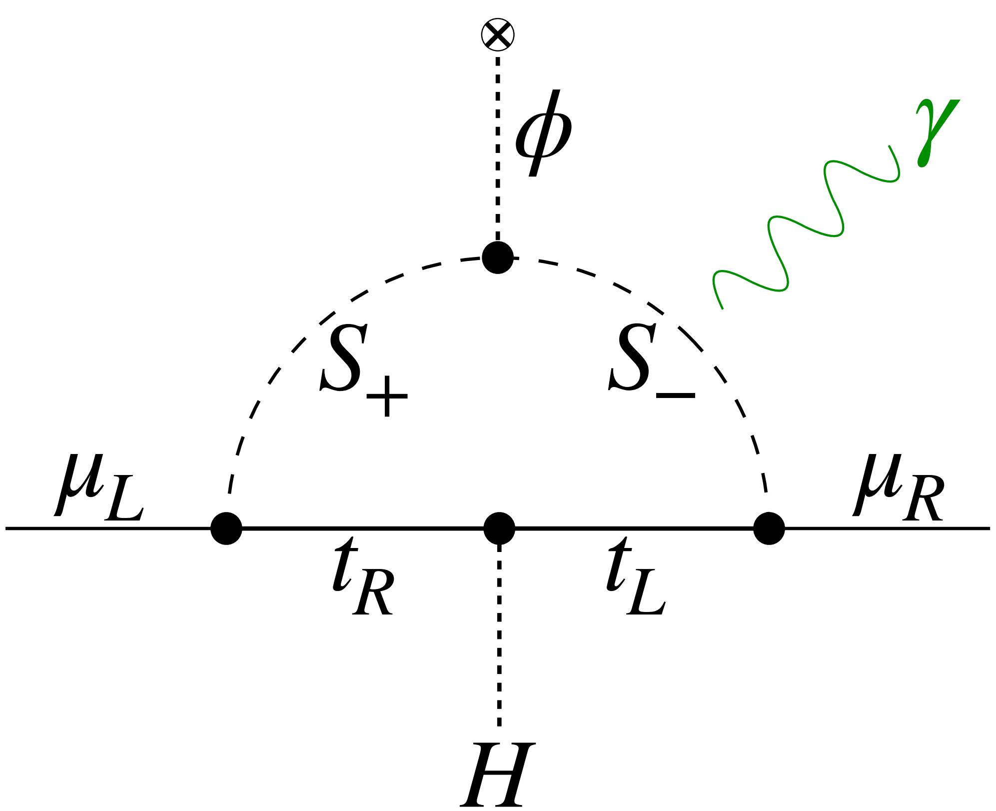

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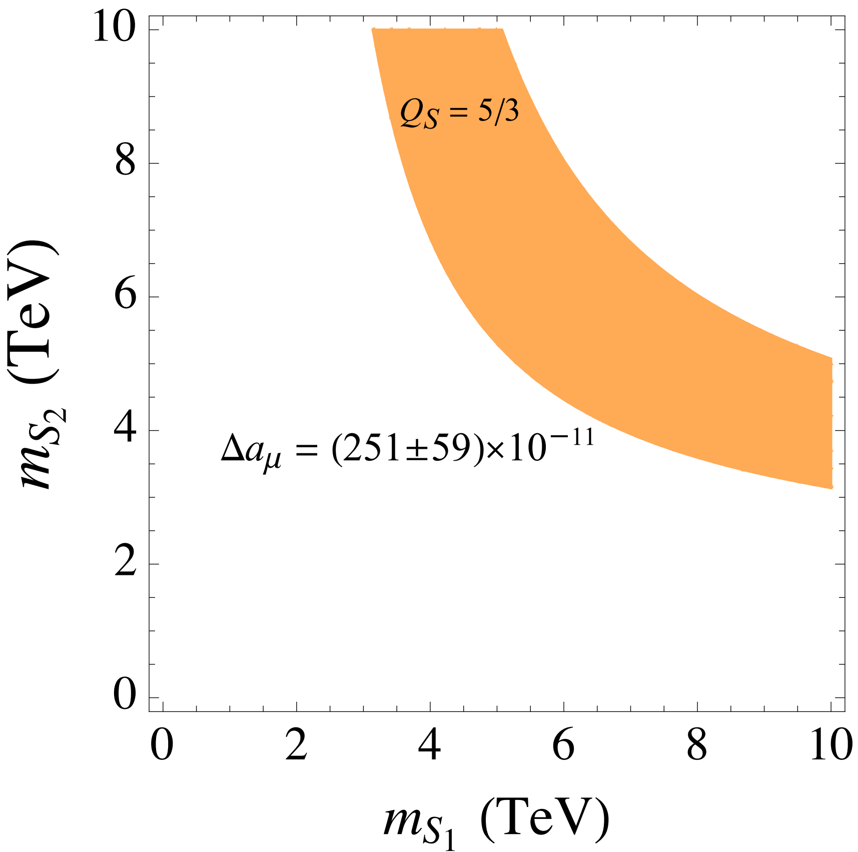


Model Lagrangian

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\mathrm{SM}-V_H} &+ |D_\mu \Phi|^2 + |D_\mu S_1|^2 + |D_\mu S_3|^2 - \tfrac{1}{4} X_{\mu\nu}^2 \\ &- \left(\eta_i^{3\mathrm{L}}\, \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2\, S_3 + \eta_i^{1\mathrm{L}} \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2 S_1 + \eta_i^{1\mathrm{R}} \overline{u}_{\mathrm{R}}^{c\,i} \mu_{\mathrm{R}} S_1 \right. \\ &\qquad \left. + \tilde{\eta}_i^{1\mathrm{R}} \overline{d}_{\mathrm{R}}^{c\,i} \nu_{\mu,\mathrm{R}} S_1 + \mathrm{h.c.}\right) + \tfrac{1}{2} \varepsilon_{BX} B_{\mu\nu} X^{\mu\nu} \\ &- V_{H\Phi}(H, \Phi) - V_{13}(H, \Phi, S_1, S_3) + \bar{\nu}_{\mathrm{R}}^i i \not{D} \nu_{\mathrm{R}}^i \\ &- \left(y_\nu^{ij} \bar{\ell}_{\mathrm{L}}^i \tilde{H} \nu_{\mathrm{R}}^j + M_{\mathrm{R}}^{ij} \bar{\nu}_{\mathrm{R}}^{ci} \nu_{\mathrm{R}}^j + y_\Phi^{ij} \Phi\, \bar{\nu}_{\mathrm{R}}^{ci} \nu_{\mathrm{R}}^j + \mathrm{h.c.}\right)\end{aligned}$$

- The rest of the potential:

$$\begin{aligned}V_{13} = {}& M_1^2 |S_1|^2 + M_3^2 |S_3|^2 + \lambda_{\Phi 1} |\Phi|^2 |S_1|^2 + \lambda_{\Phi 3} |\Phi|^2 |S_3|^2 + \tfrac{1}{2} \lambda_1 (S_1^\dagger S_1)^2 + \lambda_{H1} |H|^2 |S_1|^2 + \lambda_{H3} |H|^2 |S_3|^2 \\ &+ \kappa_{H3} H^\dagger \sigma^I \sigma^J H (S_3^{\dagger I} S_3^J) + (\kappa_{H13} H^\dagger \sigma^I H (S_1^\dagger S_3^I) + \mathrm{h.c.}) + \tfrac{1}{2} \lambda_3 (S_3^\dagger S_3)^2 + \tfrac{1}{2} \kappa_3 (S_3^{\dagger I} S_3^J)(S_3^{\dagger J} S_3^I) \\ &+ \tfrac{1}{2} \upsilon_3 (S_3^{\dagger I} S_3^J)(S_3^{\dagger I} S_3^J) + \lambda_{13} |S_1|^2 |S_3|^2 + \kappa_{13} (S_3^{\dagger I} S_1)(S_1^\dagger S_3^I) + (\upsilon_{13} (S_1^\dagger S_3^I)(S_1^\dagger S_3^I) + \mathrm{h.c.}).\end{aligned}$$

Neutrino masses

- The minimal type-I seesaw mechanism

$$m_\nu \simeq -v^2 y_\nu \left(M_\mathrm{R} + y_\Phi \langle \Phi \rangle\right)^{-1} y_\nu^\mathrm{T}$$

- The $U(1)_{B-3L_\mu}$ imposes a flavor structure for y_ν, M_R, y_Φ.
- The Dirac mass matrix splits into 2x2 $e\tau$ block and a diagonal μ.
- The Majorana mass matrix is entirely populated except $(2,2)$ entry.
- There is enough parametric freedom to accommodate for:

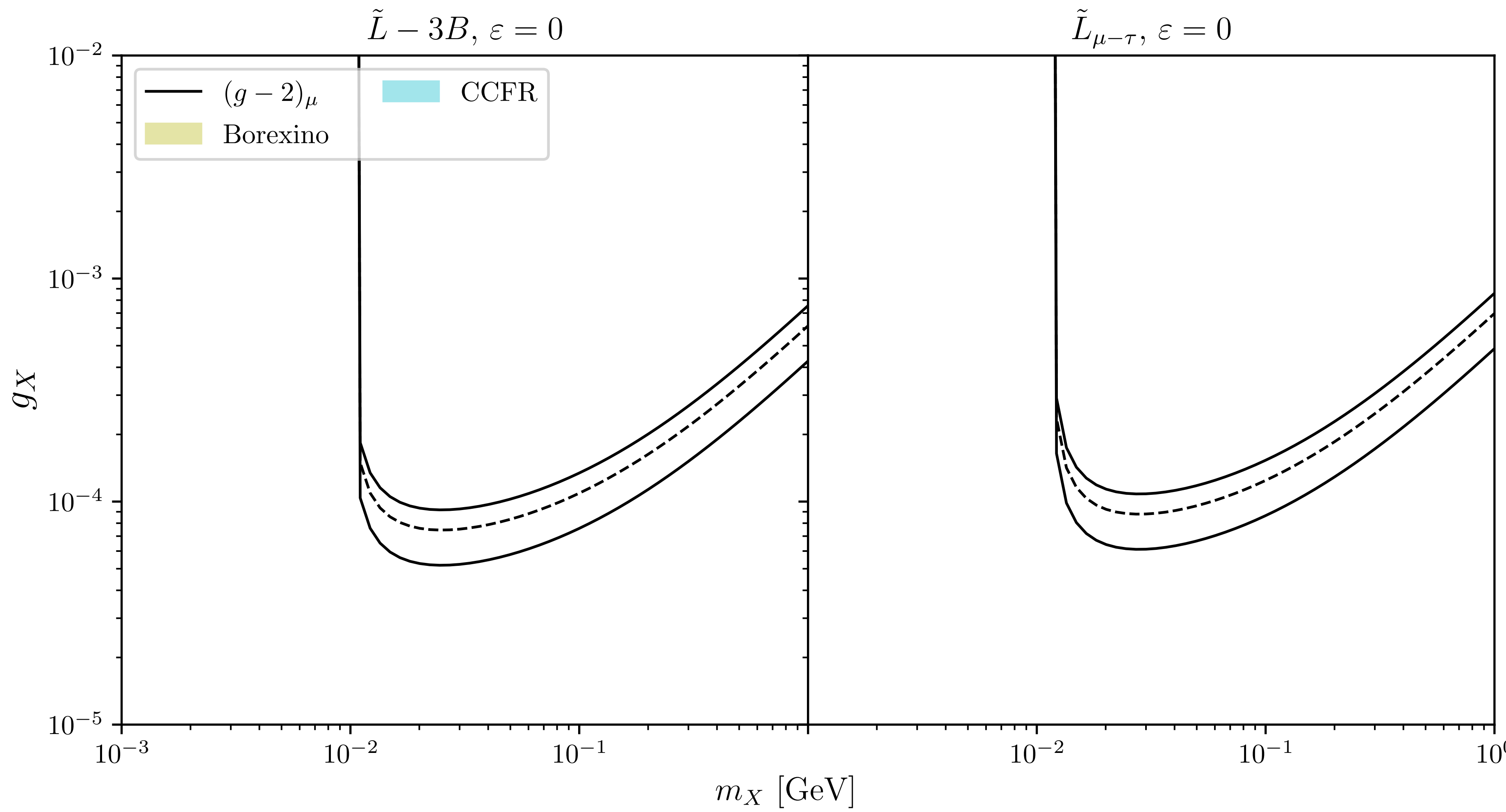
  - *Neutrino oscillations data,*
  - *The Planck limit on the sum of neutrino masses,*
  - *The absence of neutrinoless double beta decay.*

- Not the case for all $U(1)_{X_\mu}$. Example is $U(1)_{L_\mu - L_\tau}$, see 1907.04042.
- However, in general, it is always possible to introduce additional $U(1)_X$ symmetry-breaking scalars whose VEVs then populate the missing entries in the mass matrix.

Proton decay

- What $U(1)_{B-3L_\mu}$ does to a leptoquark?
  - Interacts only with muons
    $\mathscr{L} \supset Q_L L_L^{(2)} S_3$
  - No proton decay up to dim-6
    ~~$QQS_3^\dagger$~~ ~~$QQS_3^\dagger \phi^\dagger$~~
- The $U(1)_{B-3L_\mu}$ gauge symmetry and the available field content ensure that B number is conserved also at the dim-5 effective Lagrangian.
- This is not the case for e.g. $L_\mu - L_\tau$. Quantum gravity is expected to break global charges and dim-5 diquark can be dangerous.
- If $\frac{1}{M_P} q S^\dagger \phi^\dagger q$, together with $q \ell S$ needed for the muon anomalies and TeV-scale S mass, leads to dangerous proton decay.

Chiral models



$\boldsymbol{\tilde{L} - 3B}$ **model:**

$$(X_{L_1},\, X_{L_2},\, X_{L_3}) = (\text{-}3, 8, 4), \qquad (X_{E_1},\, X_{E_2},\, X_{E_3}) = (\text{-}2, 9, 2),$$
$$(X_{N_1},\, X_{N_2},\, X_{N_3}) = (\text{-}1, 3, 7), \qquad X_{Q_i, D_i, U_i} = -1,$$

$\boldsymbol{\tilde{L}_{\mu-\tau}}$ **model:**

$$(X_{L_1},\, X_{L_2},\, X_{L_3}) = (0, 7, -7), \qquad (X_{E_1},\, X_{E_2},\, X_{E_3}) = (\text{-}3, 8, \text{-}5),$$
$$(X_{N_1},\, X_{N_2},\, X_{N_3}) = (5, 3, 8), \qquad X_{Q_i, D_i, U_i} = 0.$$

- + the NSI seems difficult

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

The size of the effect

- $b \to s\mu\mu$

  Heavy NP:

  $$\mathcal{L}_{NP} = G_{NP}\, \bar{b}_L \gamma^\mu s_L\, \bar{\mu}_L \gamma^\mu \mu_L \implies G_{NP} \sim \text{few} \times 10^{-5} G_F$$

- $(g-2)_\mu$

  Light NP: With chiral suppression

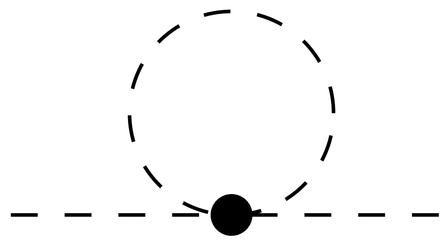
  $$\mathcal{L}_{NP} = G_{NP}\, y_\mu \frac{e v_{EW}}{16\pi^2}\, \bar{\mu}_L \sigma^{\mu\nu} \mu_R F_{\mu\nu} \implies G_{NP} \sim G_F$$

  Heavy NP: No chiral suppression

  $$\mathcal{L}_{NP} = G_{NP} \frac{e v_{EW}}{16\pi^2}\, \bar{\mu}_L \sigma^{\mu\nu} \mu_R F_{\mu\nu} \implies G_{NP} \sim \text{few} \times 10^{-4} G_F$$

Finite naturalness

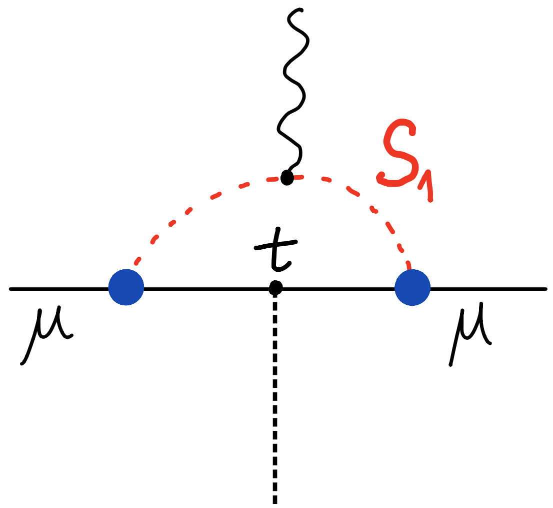
- The Higgs mass



$$\delta\mu_H^2 = -\frac{9(\lambda_{H3}+\kappa_{H3})}{(4\pi)^2} M_3^2\left(1+\ln\frac{\mu_M^2}{M_3^2}\right) + \frac{3\lambda_{H1}}{(4\pi)^2} M_1^2\left(1+\ln\frac{\mu_M^2}{M_1^2}\right) + \mathcal{O}(\mu^4/M_{1,3}^2)$$

For a small RGE-induced quartic couplings $\mathcal{O}(0.05)$, no tuning only if $M_{1,3} \lesssim$ a few TeV

- The muon Yukawa



- Removing the photon → correction to the muon Yukawa

$$\delta y_\mu = -\frac{3}{(4\pi)^2}\left(1+\ln\frac{\mu_M^2}{M_1^2}\right)\eta_i^{1L*} y_u^{ij} \eta_j^{1R}$$

- $(g-2)_\mu$ requires larger couplings for heavier leptoquark
- No tuning only if $M_{1,3} \lesssim$ a few TeV, see also the RG flow

- Finite naturalness provides argument for direct searches at colliders

Implications for Higgs physics

$$V_{H\Phi} = -\mu_H^2|H|^2 - \mu_\Phi^2|\Phi|^2 + \frac{1}{2}\lambda_H|H|^4 + \frac{1}{4}\lambda_\Phi|\Phi|^4 + \lambda_{\Phi H}|\Phi|^2|H|^2$$

- From $(g-2)_\mu$ we have $g_X \sim 10^{-4}$ and $m_X \in [10,200]\,\mathrm{MeV}$.

$$v_\Phi = \sqrt{2}m_X/|q_\Phi|g_X \sim 60\,\mathrm{GeV}/|q_\Phi|$$

- Mixing between real scalars h and ϕ.

$$g_X : X \to \nu_\mu \bar{\nu}_\mu$$

$$\lambda_\Phi : \phi \to XX$$

$$\xrightarrow{\lambda_{\Phi H},\,\lambda_\Phi} \quad h \to inv$$

- This scenario has a chance to leave observable imprints in the overall Higgs couplings or in the invisible Higgs decays.