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Theoretical Interpretation of Flavour Anomalies

Admir Greljo

Abstract: I will present 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).

12.11.2021, Anomalies-2021, Hyderabad

Part I: Introduction

$\mathscr{L}_4$: Accidental symmetries

$\mathscr{L}_4^{SM}$ sans Yukawa: $U(3)_q \times U(3)_U \times U(3)_D \times U(3)_l \times U(3)_E$

$$-\mathscr{L}_{\text{Yuk}} = \bar{q} V^\dagger \hat{Y}^u \tilde{H} U + \bar{q} \hat{Y}^d H D + \bar{l} \hat{Y}^e H E$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

$\mathscr{L}_4^{SM}$: $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Prediction: No proton decay nor cLFV

Experiment: $\tau_p \gtrsim 10^{34}$ years, $BR(\mu \to e\gamma) \lesssim 10^{-13}, \ldots$

- Λ_{NP}^{-1} truncation at the $[\mathscr{L}^{\text{SMEFT}}] \leq 4 \implies$ **Exact** accidental symmetries
- Peculiar observed values of $Y^{u,d,e} \implies$ **Approximate** accidental symmetries

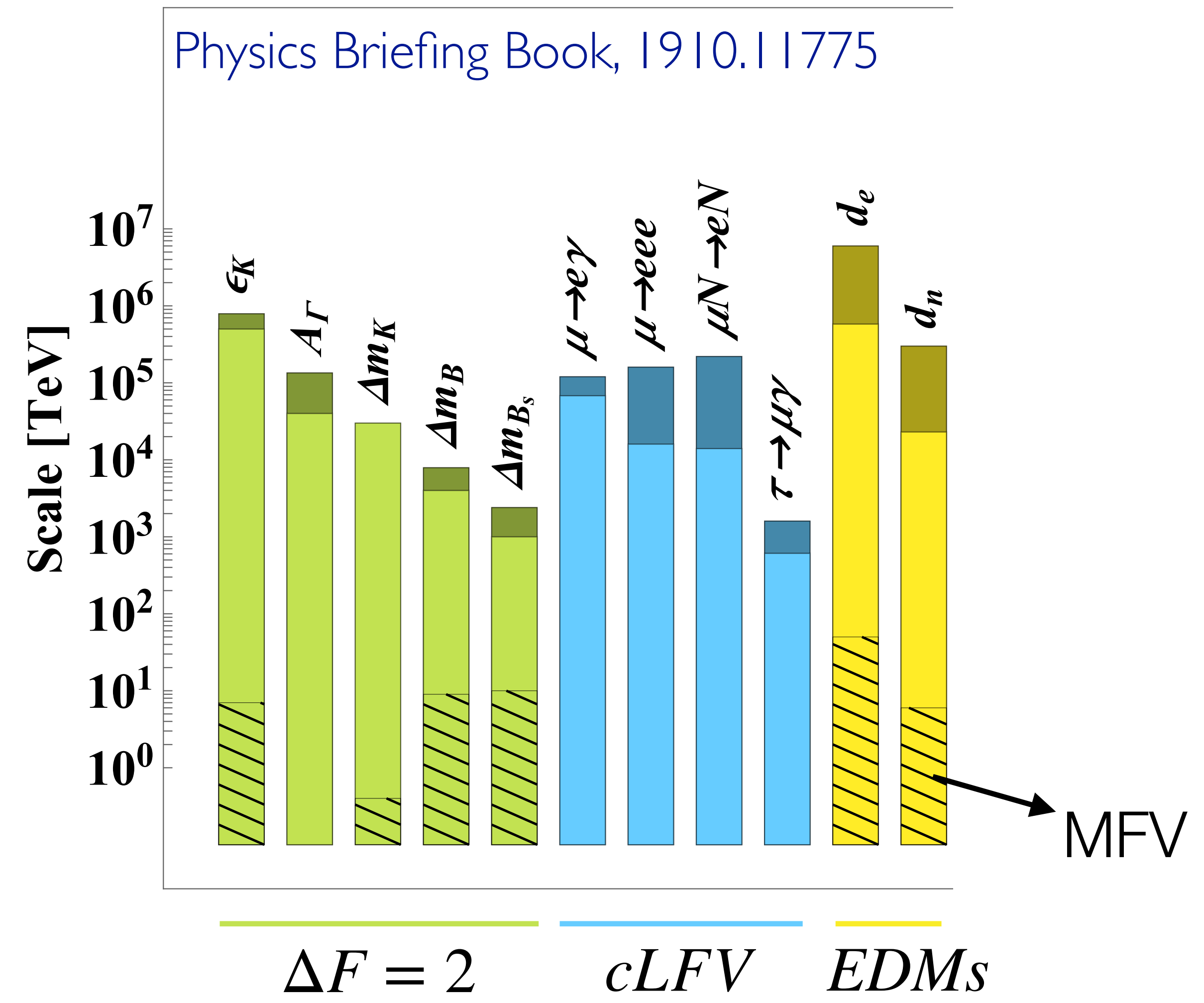
  [Mass hierarchy & CKM alignment] [Quark flavour, CP, etc]

$\mathcal{L}_6$: Constraints

$$\mathcal{L}_6^{SMEFT} \supset \frac{1}{\Lambda^2} qqq\ell$$

$\Lambda > 10^{12}\,\text{TeV}$

Proton decay

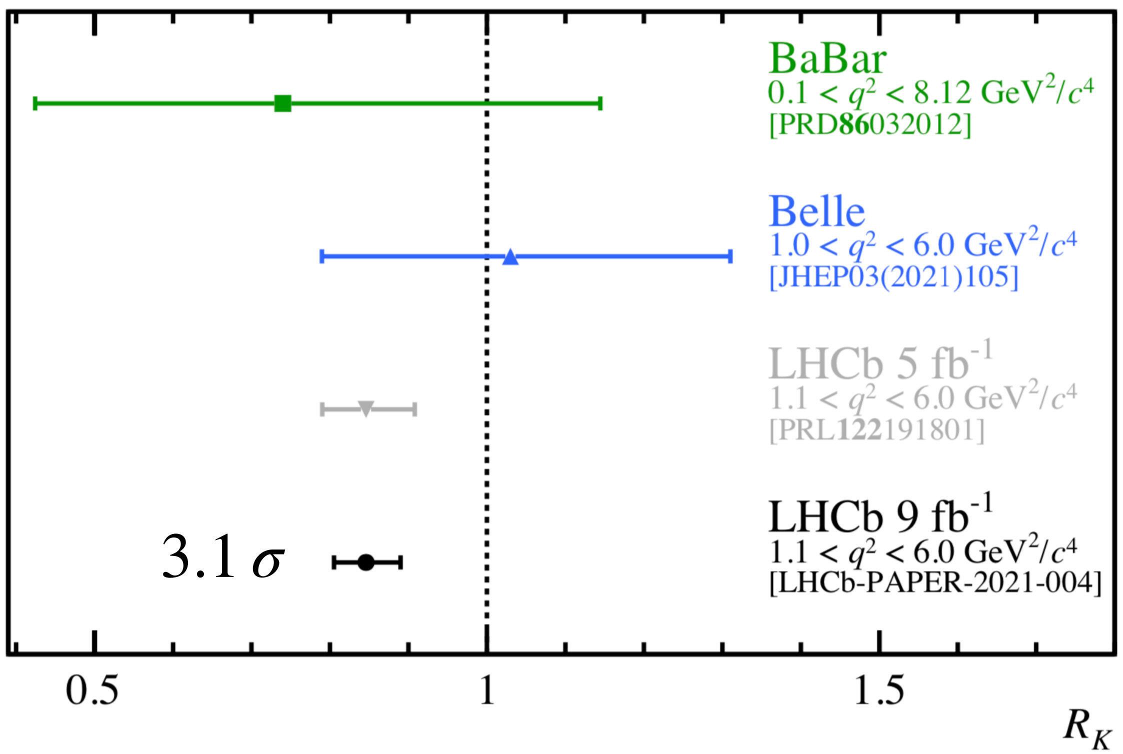


- Accidental symmetries (exact and approximate) are broken by the irrelevant couplings.
- Testing accidental symmetries is an opportunity
  $\Longrightarrow$ Efficient probe of high-energy dynamics.
- A viable BSM at the TeV-scale should have accidental symmetries similar to the SM.

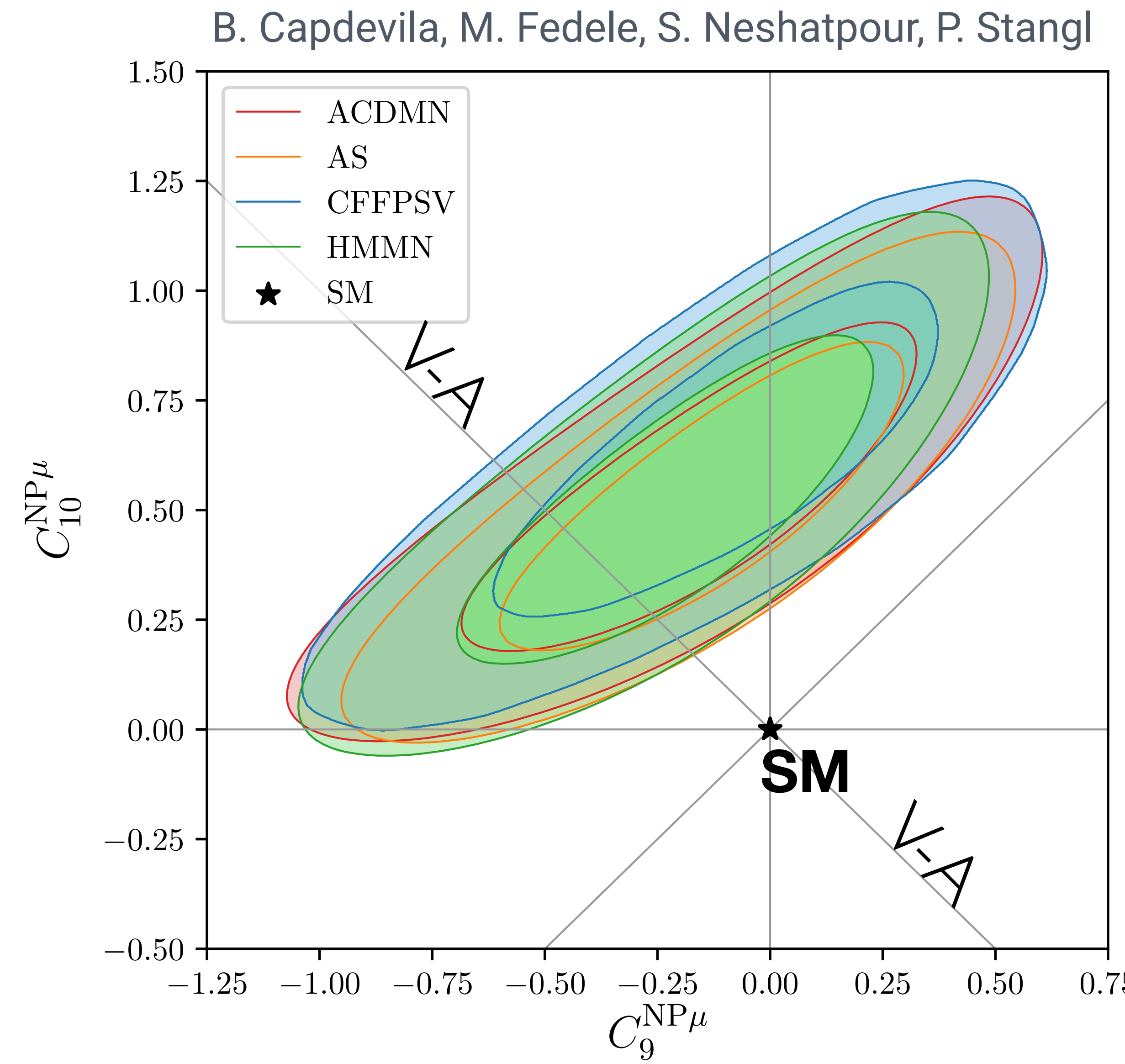
Part II: Flavour anomalies

This talk: $b \to s\ell\ell$ and $(g-2)_\mu$

Footprints of a next layer?



LHCb, CERN, 2103.11769



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

$= 4.3\,\sigma$ conservative global significance

[Isidori, Lancierini, Owen, Serra, 2104.05631]

fit to LFU observables + $B_s \to \mu\mu$

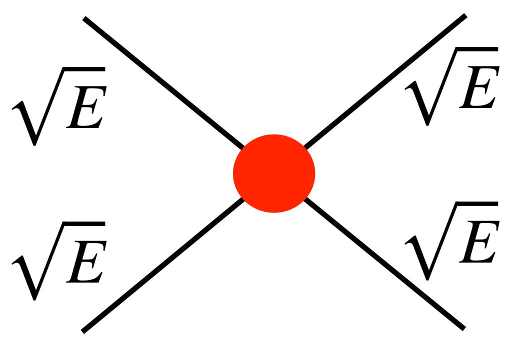
A word of caution:
More EXP/TH work is needed to prove NP is behind these effects.

New mass scale?

- IF $b \to s\ell^+\ell^-$ anomalies are genuine new physics effect
  $\Longrightarrow$ Major Revolution in HEP

$$\mathscr{L} \supset \frac{1}{(40\ \mathrm{TeV})^2}\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\mu}_L\gamma_\mu\mu_L)$$

4-fermion scattering at $E \gg v_{EW}$



$$\mathscr{A} \sim \frac{E^2}{(40\ \mathrm{TeV})^2}$$

$\Longrightarrow$ Violation of perturbative unitary $\lesssim 100\,\mathrm{TeV}$

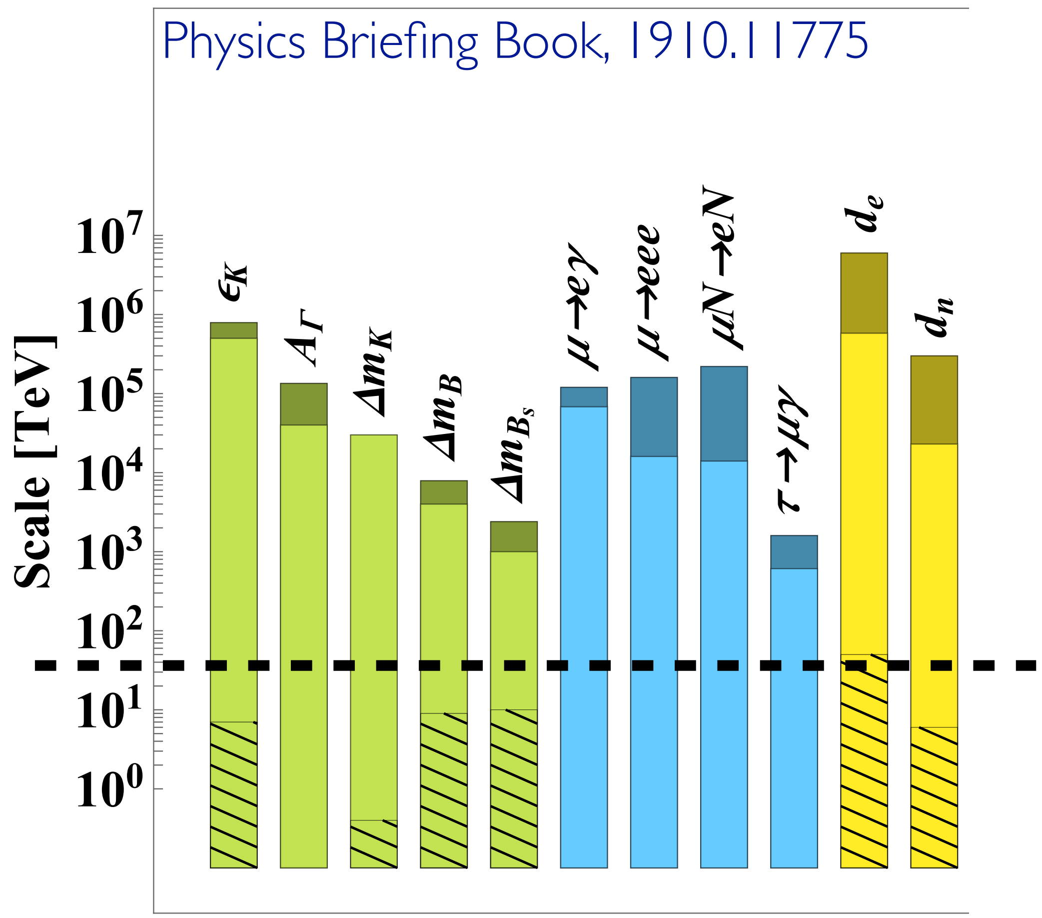
Di Luzio, Nardecchia; 1706.01868

- Observational evidence!
  (Argument stronger than EW naturalness)

- The scale indicated from the perturbative unitary tends to be overly pessimistic

$$\mathrm{Weak\ interactions:}\ \ G_F \Longrightarrow \Lambda \lesssim 1\,\mathrm{TeV}\,, \quad m_W \approx 80\,\mathrm{GeV}$$

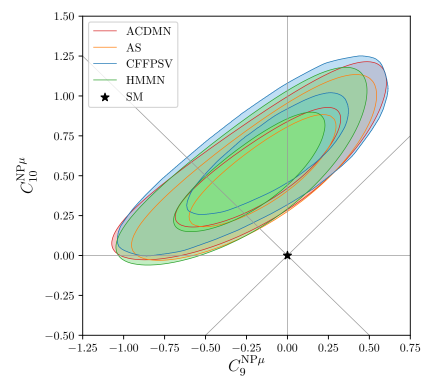
New mass scale?



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

$3_q \to 2_q$

$|V_{cb}| \approx 0.04$

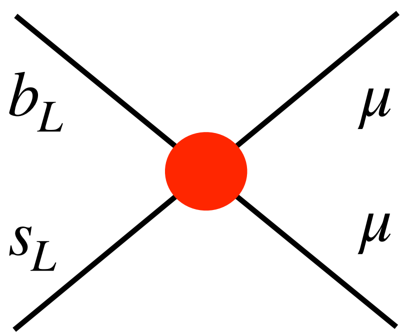


fit to LFU observables + $B_s \to \mu\mu$

- A <u>consistent</u> theory should have a well-defined flavour symmetry and a symmetry breaking pattern (e.g. MFV, U(2), partial compositeness, etc).
- Thus, $3_q \to 2_q$ transition should carry a corresponding flavour spurion suppression.

$$\mathscr{L}_6 \supset \frac{V_{cb}}{(8\ \mathrm{TeV})^2}\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\mu}_L\gamma_\mu\mu_L)$$

Mediators



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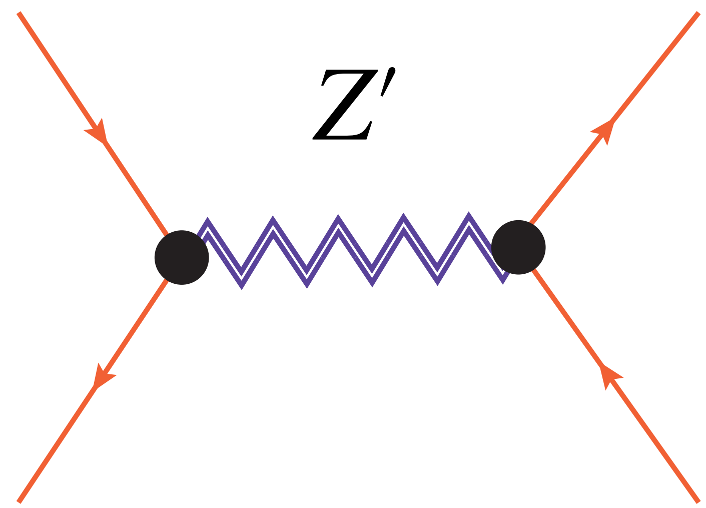
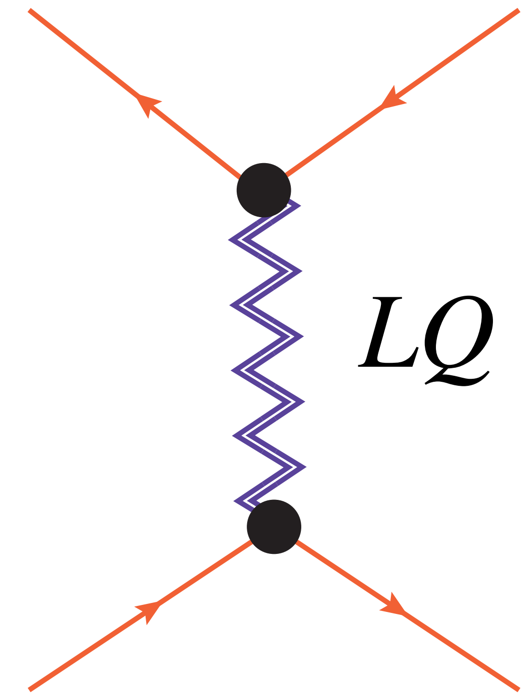
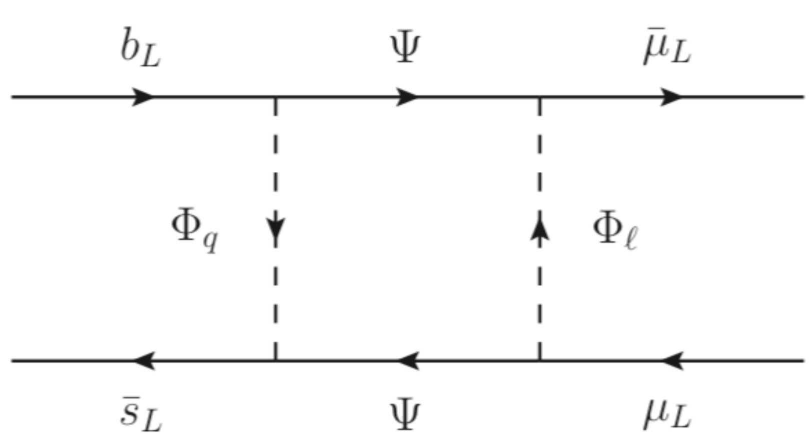


or



or



+ other loop models

$$\mathscr{L} \supset \frac{1}{16\pi^2} \frac{|V_{cb}|}{(0.6\ \text{TeV})^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

See for example:
Arcadi, Calibbi, Fedele, Mescia, 2104.03228

Scalar leptoquark example

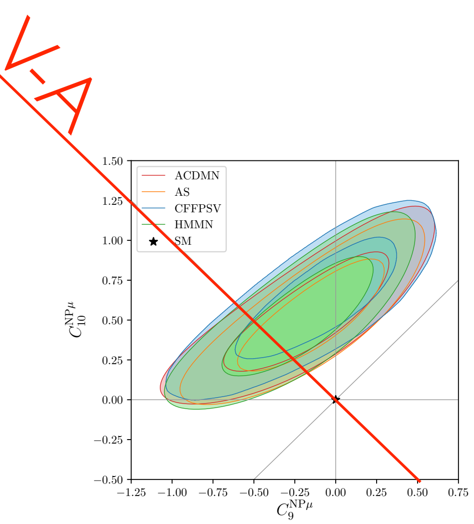
- Tree-level $J_q \times J_\ell$, while $J_q \times J_q$ and $J_\ell \times J_\ell$ loop-suppressed

$$\mathscr{L} \supset \eta_{ij}\, Q_L^i L_L^j S_3$$

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

- V-A structure

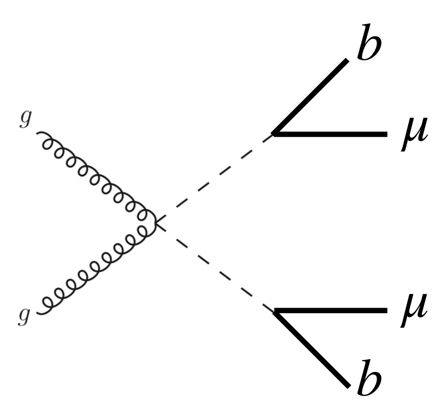
Hiller, Schmaltz, 1408.1627,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Buttazzo, AG, Isidori, Marzocca; 1706.07808,
Gherardi, Marzocca, Venturini; 2008.09548
+ many more



fit to LFU observables + $B_s \to \mu\mu$

$$\Longrightarrow \frac{\eta_{b\mu}\eta_{s\mu}}{M_{LQ}^2} \sim \frac{V_{cb}}{(8\ \text{TeV})^2}$$

Direct LHC searches
LQ pair production:
$m_{LQ} \gtrsim 1.5$ TeV



Leptoquarks

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

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

- Abrupt violation of the SM accidental symmetries

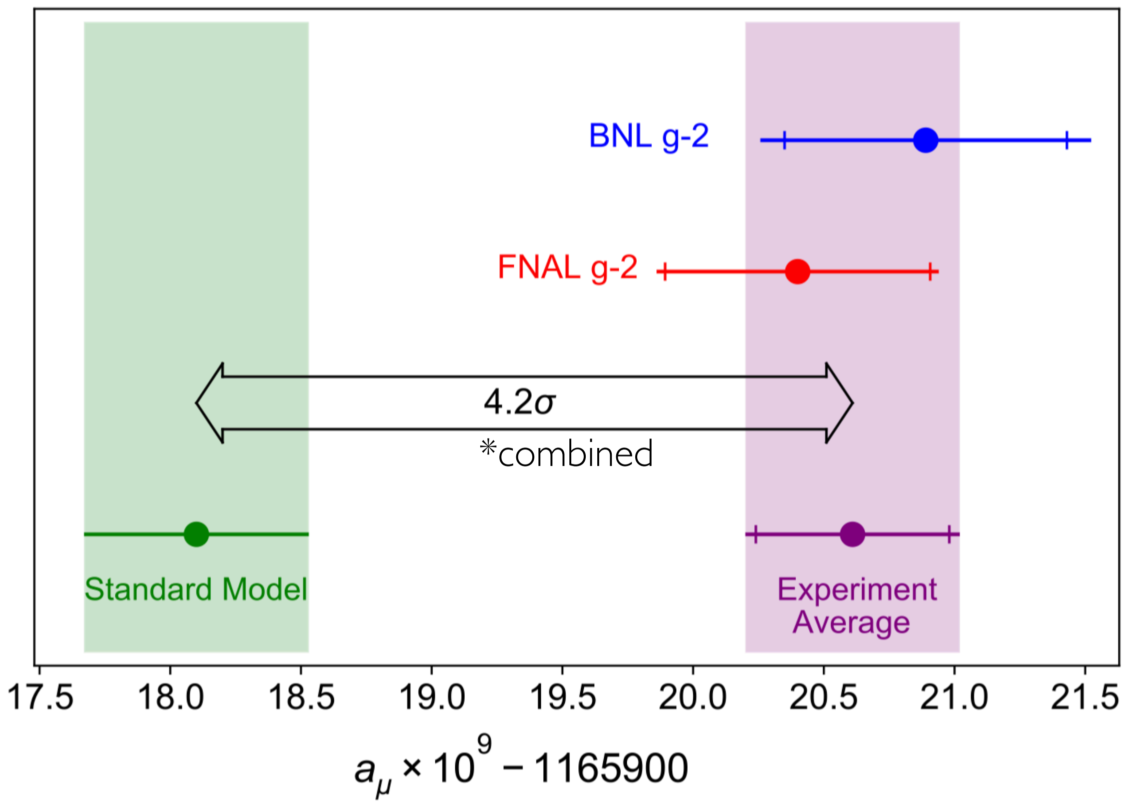
~~$U(1)_B$~~ Proton decay $[z \cdot y]$ probes scales up to 10^{13} TeV

~~$U(1)_e \times U(1)_\mu \times U(1)_\tau$~~ $\mu \to e \gamma$ $[i \neq j]$ 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

Muon $(g-2)$



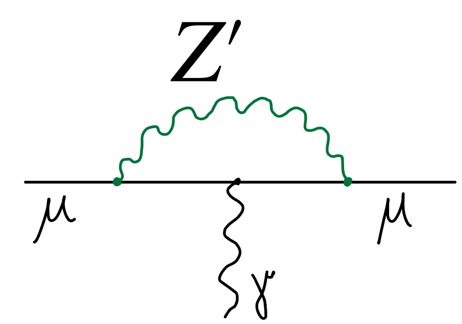
The Muon g-2, Fermilab, 2104.03281

A word of caution:
More EXP/TH work is needed to prove NP is behind these effects.

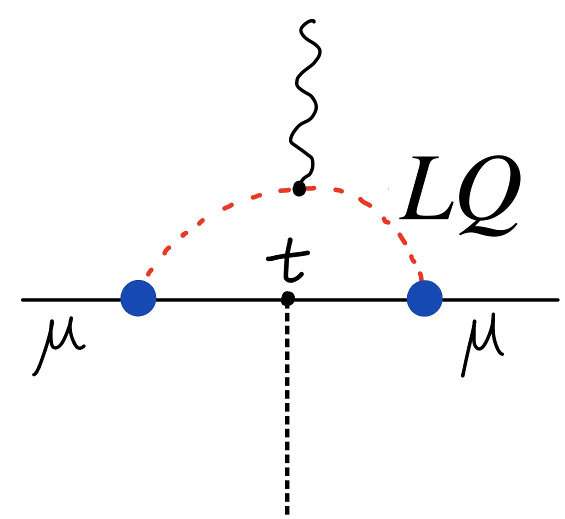
*BMW lattice only 1.6σ [2002.12347]

- New Physics examples

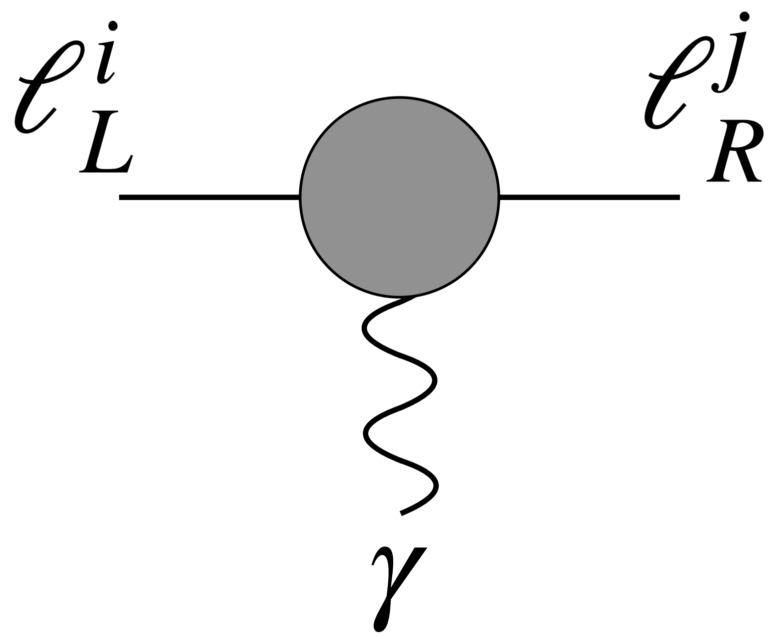
$$\mathcal{L}_6 \supset \frac{y_\mu}{(0.2\,\mathrm{TeV})^2}\frac{e v_{EW}}{16\pi^2}\bar{\mu}_L \sigma^{\mu\nu}\mu_R F_{\mu\nu}$$



$$\mathcal{L}_6 \supset \frac{y_t}{(10\,\mathrm{TeV})^2}\frac{e v_{EW}}{16\pi^2}\bar{\mu}_L \sigma^{\mu\nu}\mu_R F_{\mu\nu}$$



cLFUV but no cLFV



$$\frac{Br(\mu \to e\gamma)}{3 \times 10^{-13}} \approx \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{12}}{10^{-5}}\right)^2$$

$$\frac{Br(\tau \to \mu\gamma)}{4 \times 10^{-8}} \approx \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{23}}{10^{-2}}\right)^2$$

Naive BSM expectation is wrong!

$$\theta_{12} \sim \sqrt{m_e/m_\mu} \sim \mathcal{O}(10^{-1})$$

$$\theta_{23} \sim \sqrt{m_\mu/m_\tau} \sim \mathcal{O}(10^{-1})$$

Nearly exact $\mathrm{U}(1)_\mathrm{e} \times \mathrm{U}(1)_\mu \times \mathrm{U}(1)_\tau$?

Part III: Muonic forces

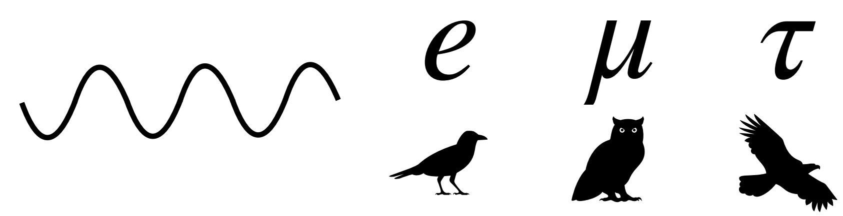
AG, Stangl, Thomsen; 2103.13991

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Gauged lepton flavor

- Extend the SM gauge group with the **lepton flavour non-universal** $U(1)_X$.

$$\text{Gauged U(1)}_{\text{X}}$$



- Natural framework for cLFUV without cLFV.
- $U(1)_X$ gauge boson is a potential mediator behind flavour anomalies.

Altmannshofer, Gori, Pospelov, Yavin; 1403.1269,
Crivellin, D'Ambrosio, Heeck; 1501.00993,
Celis, Fuentes-Martin, Jung, Serodio; 1505.03079,
Crivellin, Fuentes-Martin, AG, Isidori; 1611.02703,
Alonso, Cox, Han, Yanagida; 1705.03858,
Bonilla, Modak, Srivastava, Valle; 1705.00915,
Ellis, Fairbairn, Tunney; 1705.03447;
Allanach, Davighi;1809.01158,
Altmannshofer, Davighi, Nardecchia; 1909.02021,
Allanach; 2009.02197,
+ many more …

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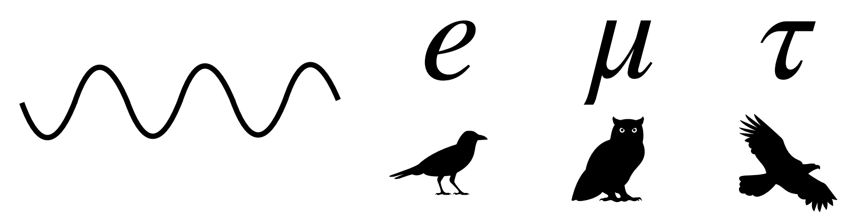
Gauged $\mathrm{U(1)_X}$



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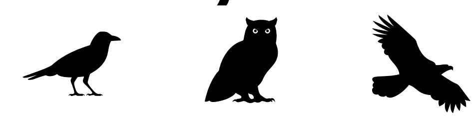
- Another potential mediator
  - Charge a **leptoquark** under $U(1)_X$.
  - Gauge symmetry selection rules: ✓ $q\mu S$ ✗ $qeS, q\tau S, qqS^\dagger$ $qqS^\dagger H, qqS^\dagger \phi$

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

Gauged lepton flavor

- Extend the SM gauge group with the **lepton flavour non-universal** $U(1)_X$.

$$\text{Gauged U(1)}_X \quad e \quad \mu \quad \tau$$



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- Another potential mediator
- Charge a **leptoquark** under $U(1)_X$.
- Gauge symmetry selection rules: ✓ $q\mu S$ ✗ $qeS, q\tau S, qqS^\dagger$, $qqS^\dagger H, qqS^\dagger \phi$ $\Longrightarrow$

The accidental symmetry of $\mathscr{L}_4$ is $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ and the LQ charge is $(-1/3, 0, -1, 0)$

"Muoquark"

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

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

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

- Six anomaly cancelation conditions:

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

- Quark flavour universal

$$X_{Q_i} = X_{U_j} = X_{D_k} \quad (X_H = 0)$$

$-10 \leq X_{F_i} \leq 10$ [276 inequivalent solutions]

(i.e. up to flavor permutation, etc)

Muoquark requirement

eg. S_3 LQ: $X_{L_2} \neq \{X_{L_{1,3}}, -3X_q\}$

[273 inequivalent solutions]

vector category : $X_{L_i} = X_{E_i}$

chiral category : the rest.

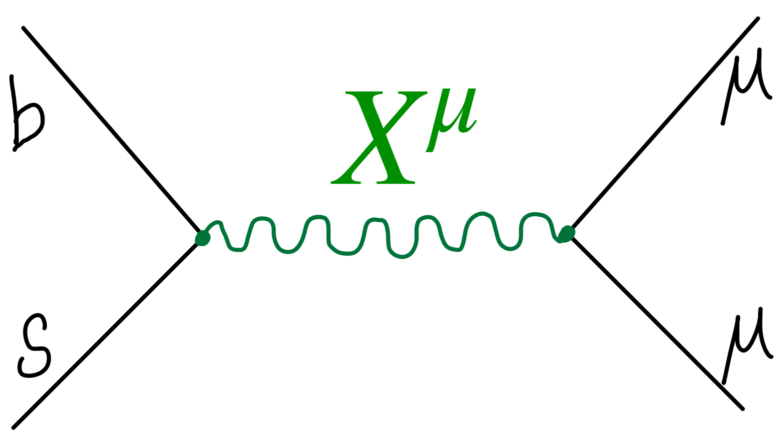
- Third-family quark

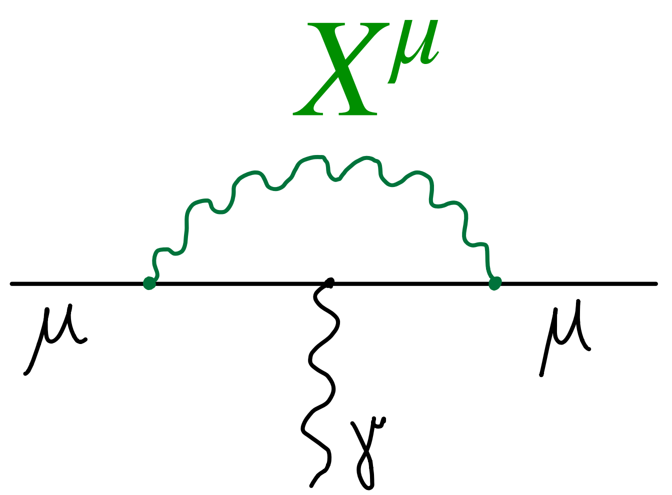
[The "2+1" charge assignment]

Single mediator?

$b \to s\mu\mu$

$(g-2)_\mu$





?

- Answer: **NO** AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

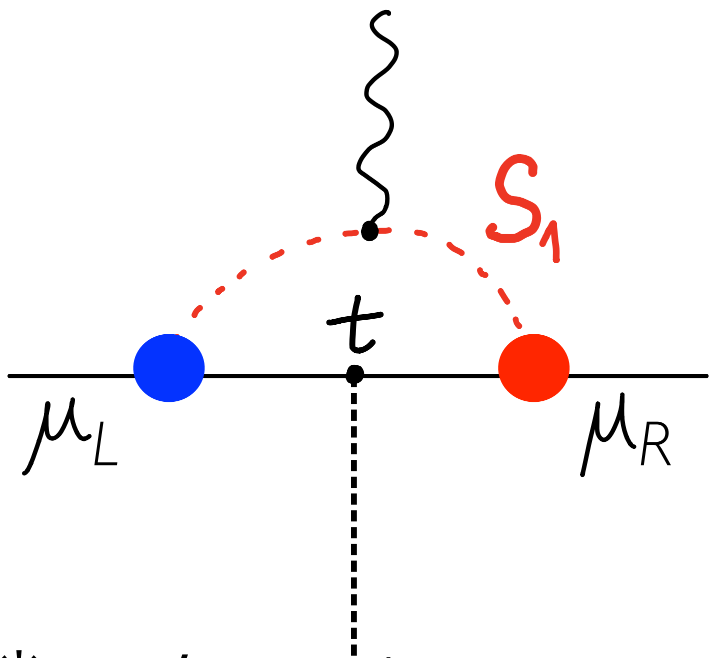
Model Example I

AG, Stangl, Thomsen, 2103.13991

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

- Resolves $b \to s\mu\mu$ and $(g-2)_\mu$ while satisfying all complementary data.
- Minimal type-I seesaw for the neutrino masses. Viable texture.
- No proton decay up to dim-6 nor sizeable cLFV.
- No Landau poles up to the Planck scale.
- Finite naturalness. No tuning.

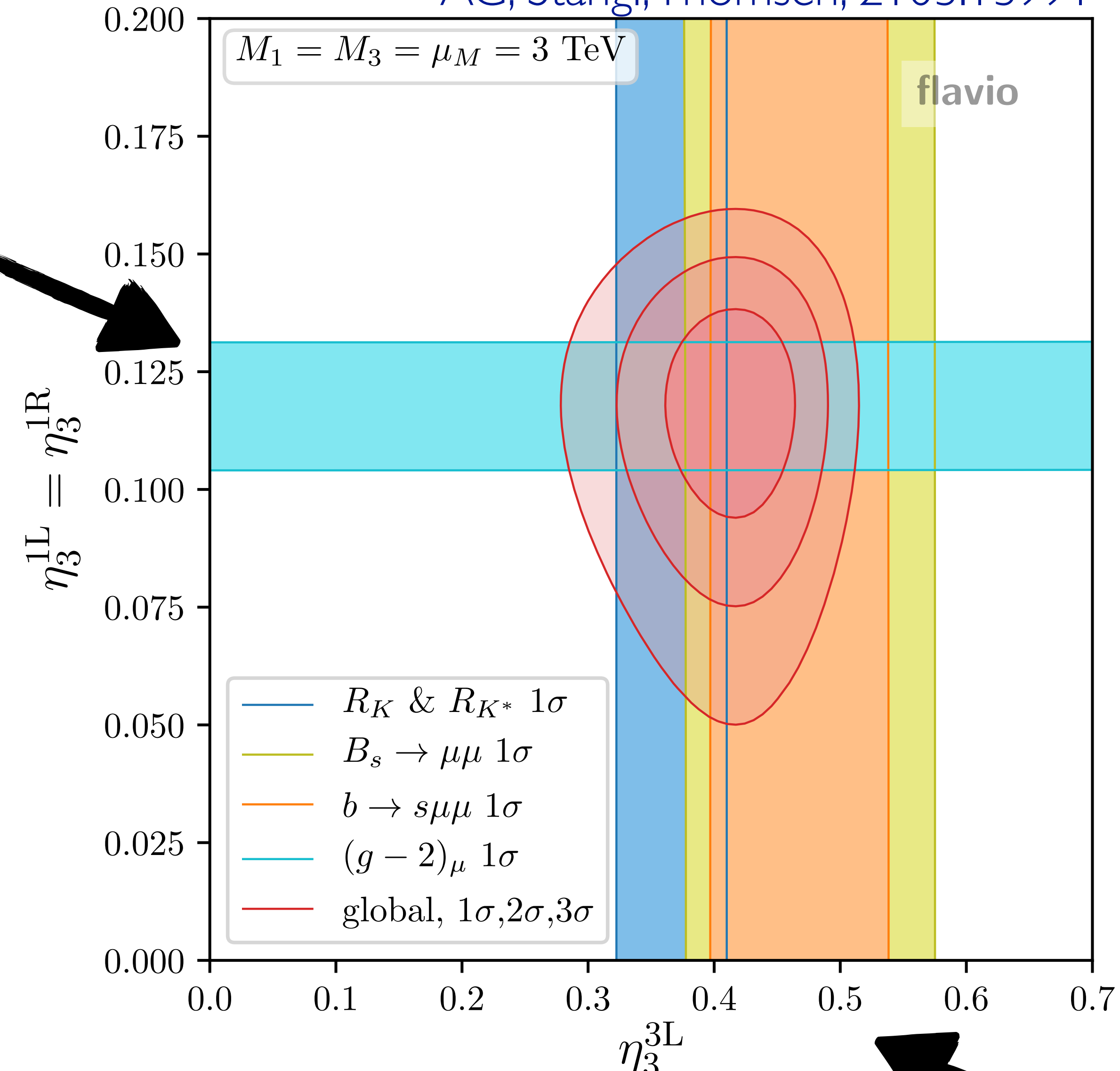
Model Example I



* 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,
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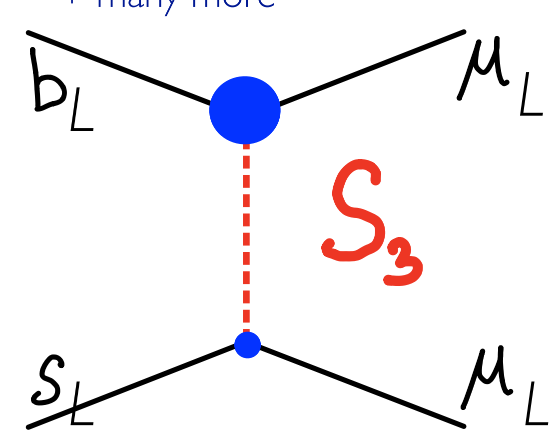
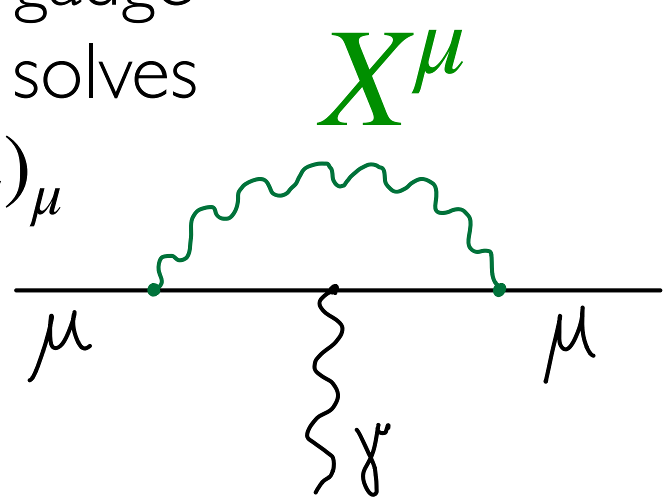


- One-loop matching to SMEFT from 2003.12525
- 399 observables in **smelli** 1810.07698
- EW and flavor opservables, LFV, LFU, magnetic moments, neutral meson mixing, semileptonic and rare B, D, K decays, etc.

Model Example II

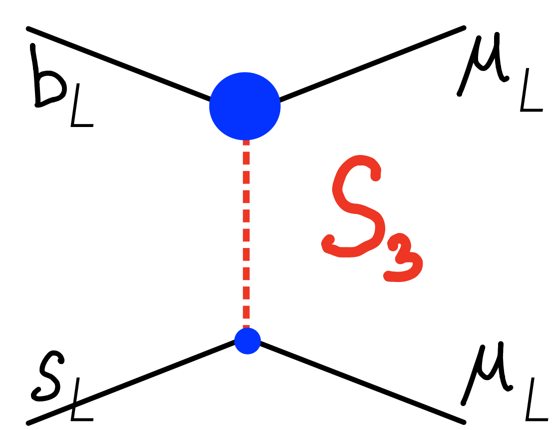
- $U(1)_X$ gauge boson solves $(g-2)_\mu$



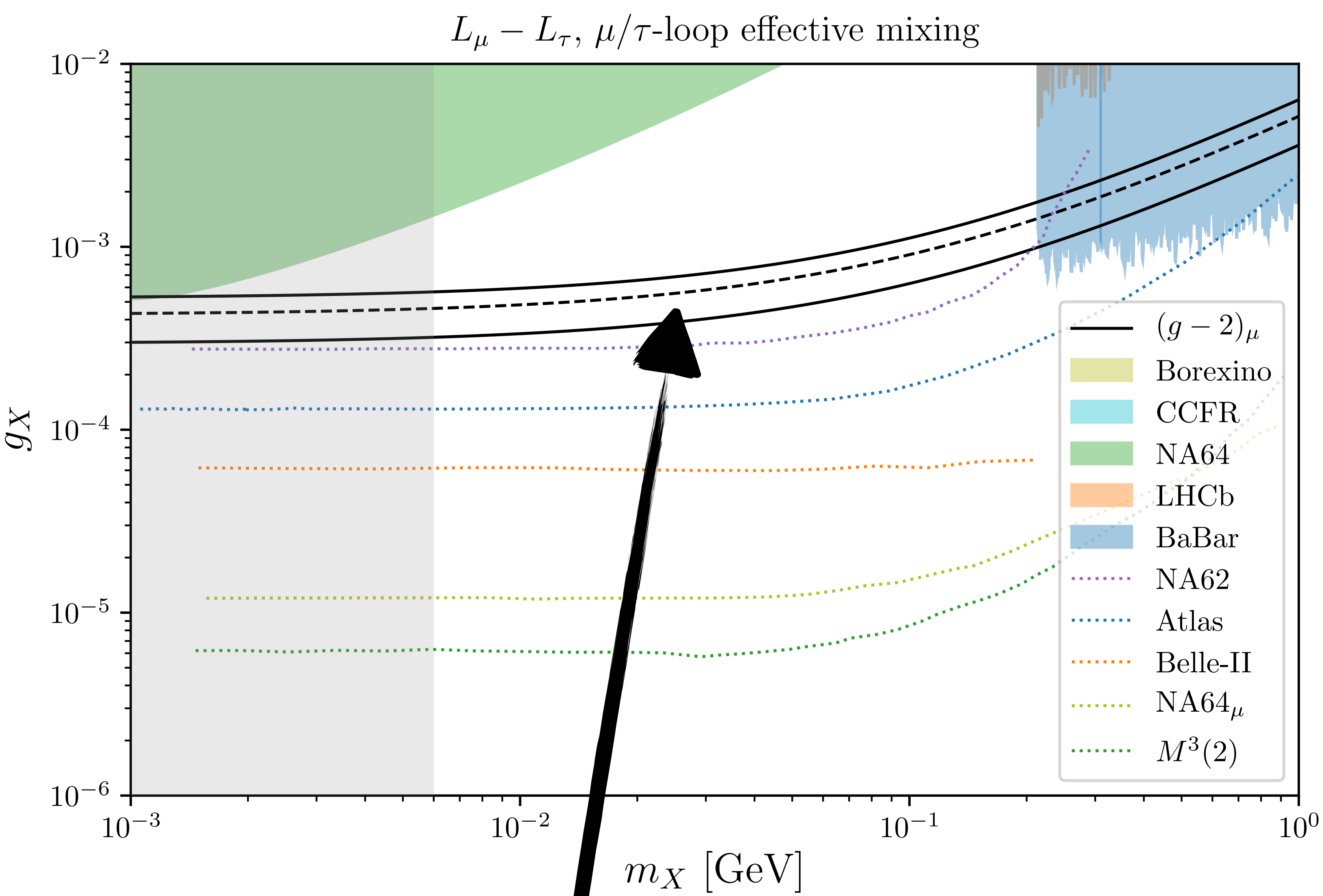
Minimality

AG, Stangl, Thomsen, 2103.13991

- S_3 is charged under $U(1)_X$ such that it becomes a **muoquark**.



Model Example II



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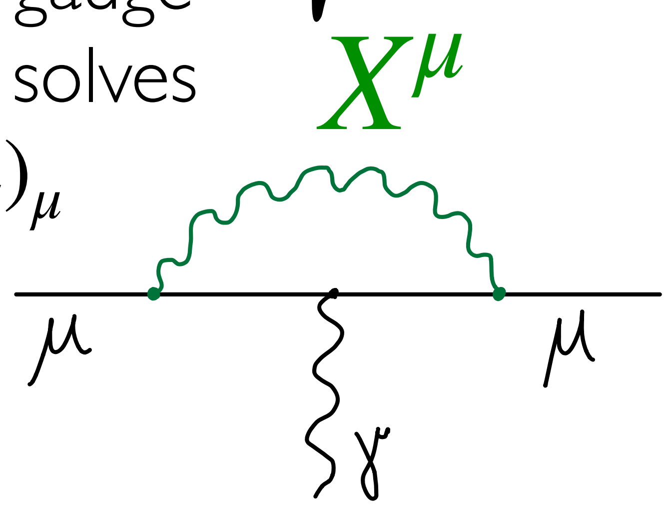

Minimality

AG, Stangl, Thomsen, 2103.13991

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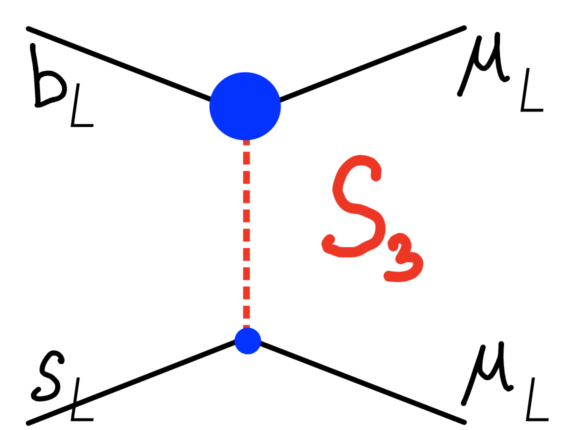


Model Example III : Radiative y_μ

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

$$X_{L_2} \neq X_{E_2} \quad (X_H = 0)$$

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

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

- 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:

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

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

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Model Example III : Radiative y_μ

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

$$X_{L_2} \neq X_{E_2} \quad (X_H = 0)$$

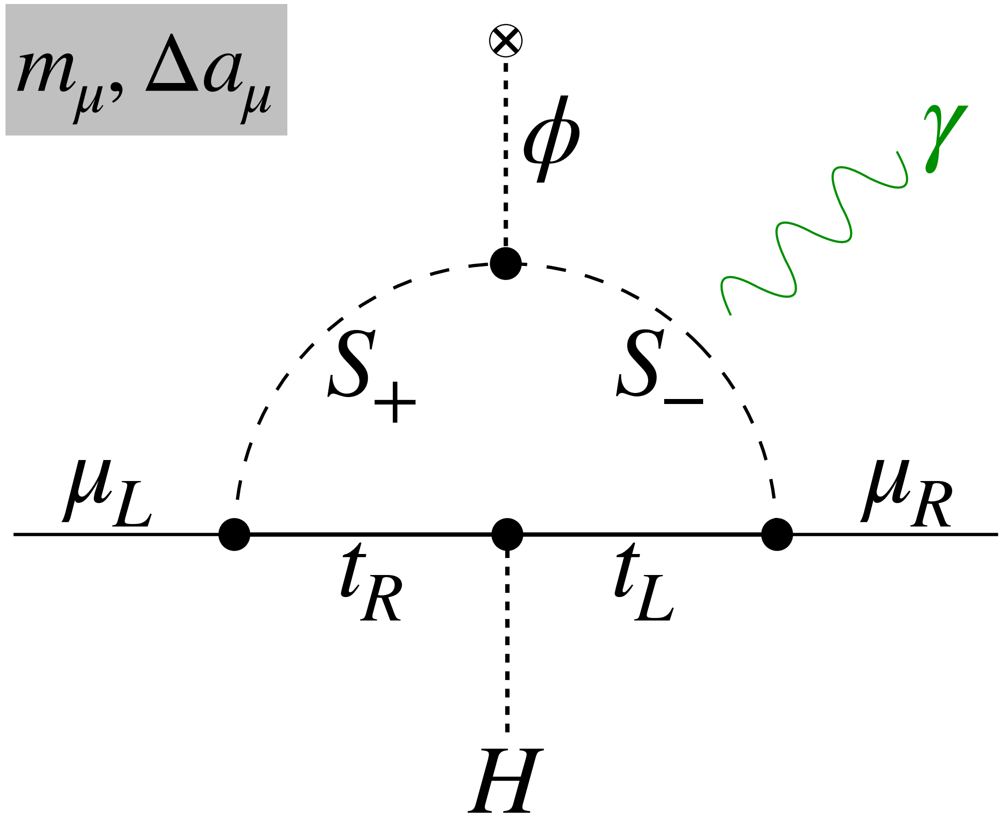
- Introduce two scalar muoquarks $S_\pm = (\mathbf{3}, \mathbf{2}, 7/6, X_{S_\pm})$

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

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

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

$m_\mu, \Delta a_\mu$



$$\Longrightarrow \quad \Delta a_\mu = \frac{m_\mu^2}{m_t^2}\, \tilde{F}\left(\frac{m^2_{S_1}}{m_t^2}, \frac{m^2_{S_2}}{m_t^2}\right)$$

Model Example III : Radiative y_μ

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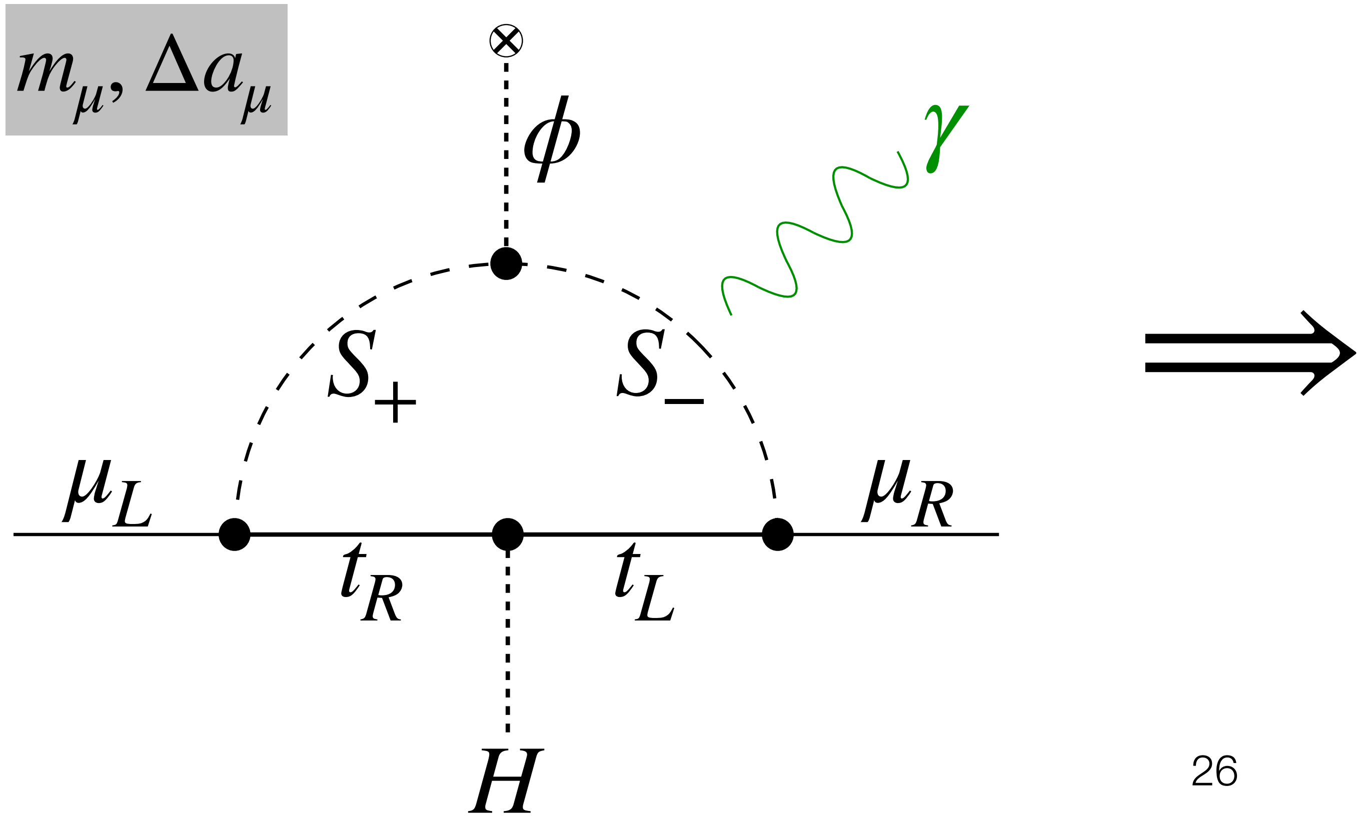
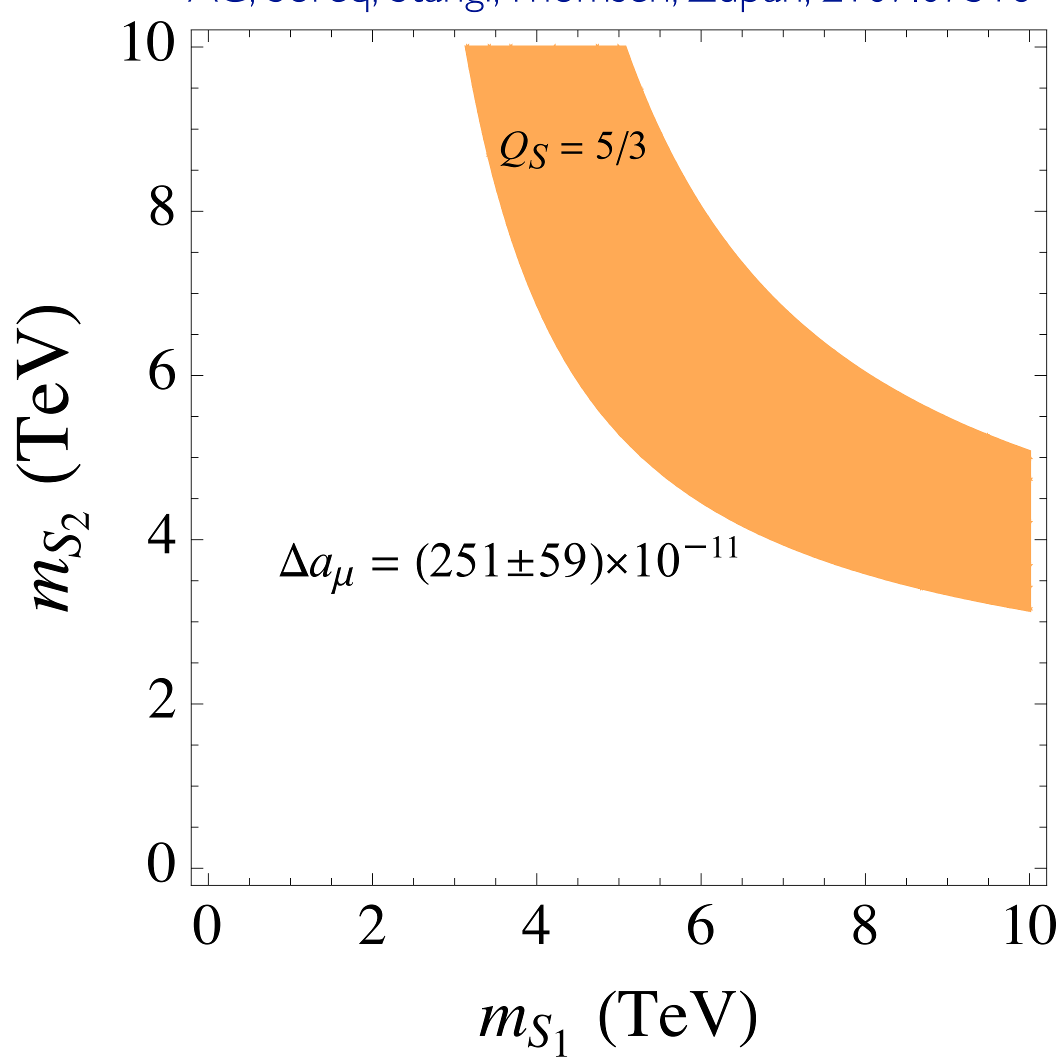
- Mix them via $U(1)_X$ breaking

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



AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518



Conclusions

- Testing accidental symmetries is an opportunity: Efficient probe of high-energy dynamics.
- Flavour anomalies might be footprints of physics beyond the SM.
- Gauged lepton flavor is an interesting direction.
- We have just scratched the surface of $U(1)_X$ phenomenology.

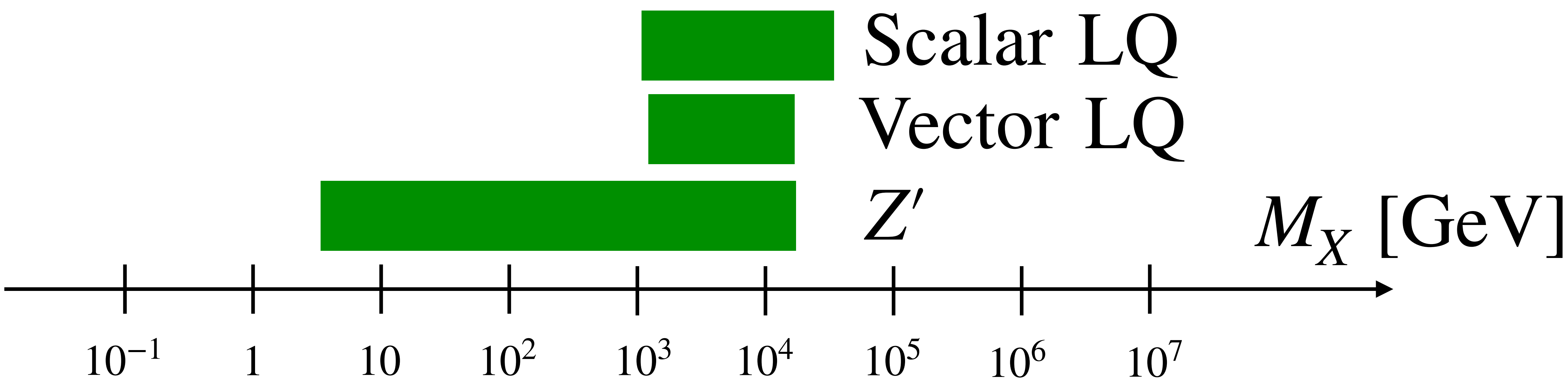
AG, Stangl, Thomsen, 2103.13991

	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

Backup

Mediators

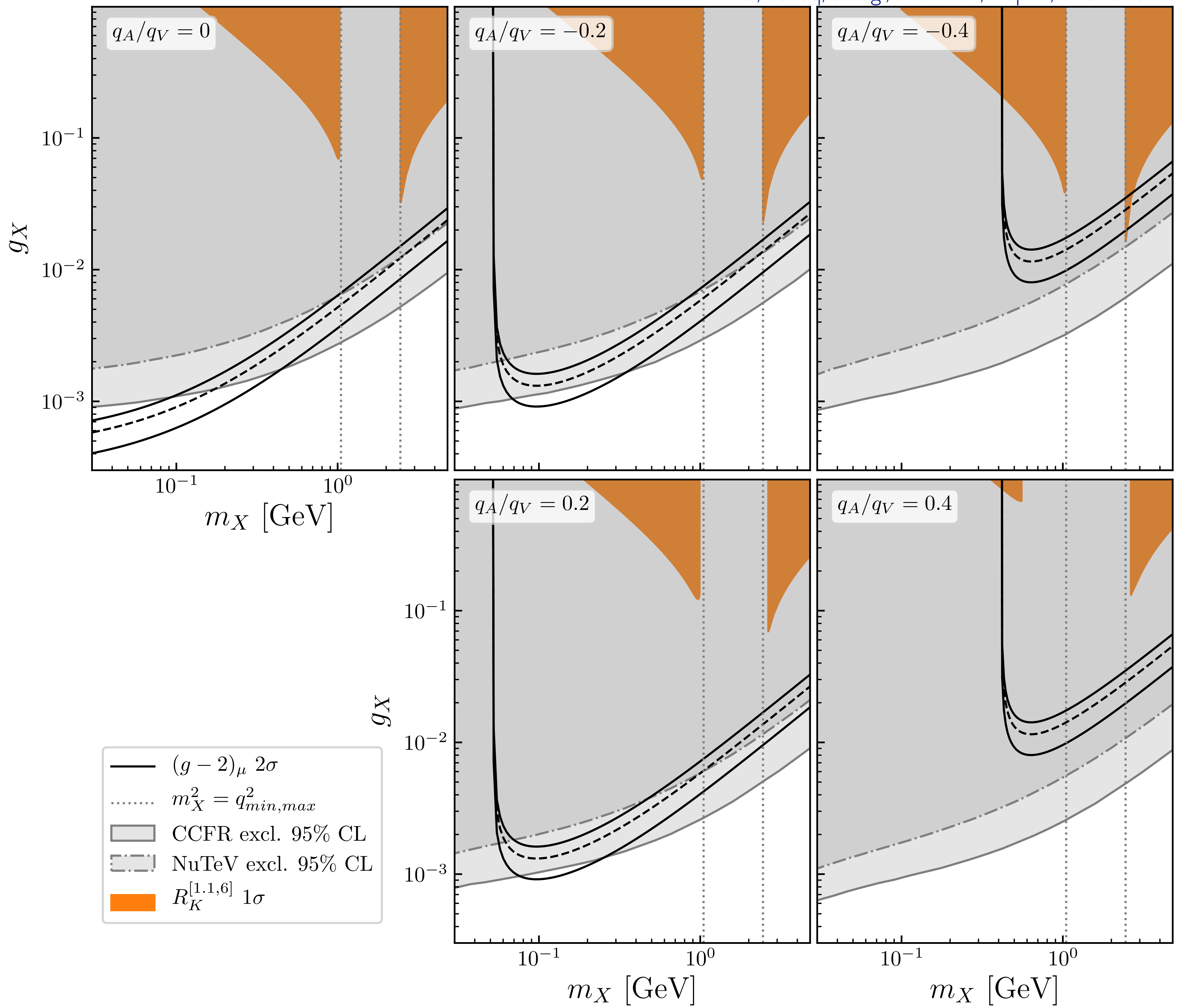
- Tree-level $b \to s\ell\ell$ models
- Targeted mass window:



- Comments on the difference:
  [Upper bound] Z' induces tree-level $B_s - \bar{B}_s$ oscillations. Vector LQ comes with the Z'.
  [Lower bound] LQs are coloured and copiously produced at the LHC.

Single mediator?

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518



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]

  $(X_H = 0)$

- 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:

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

- The ACC conditions are satisfied provided

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

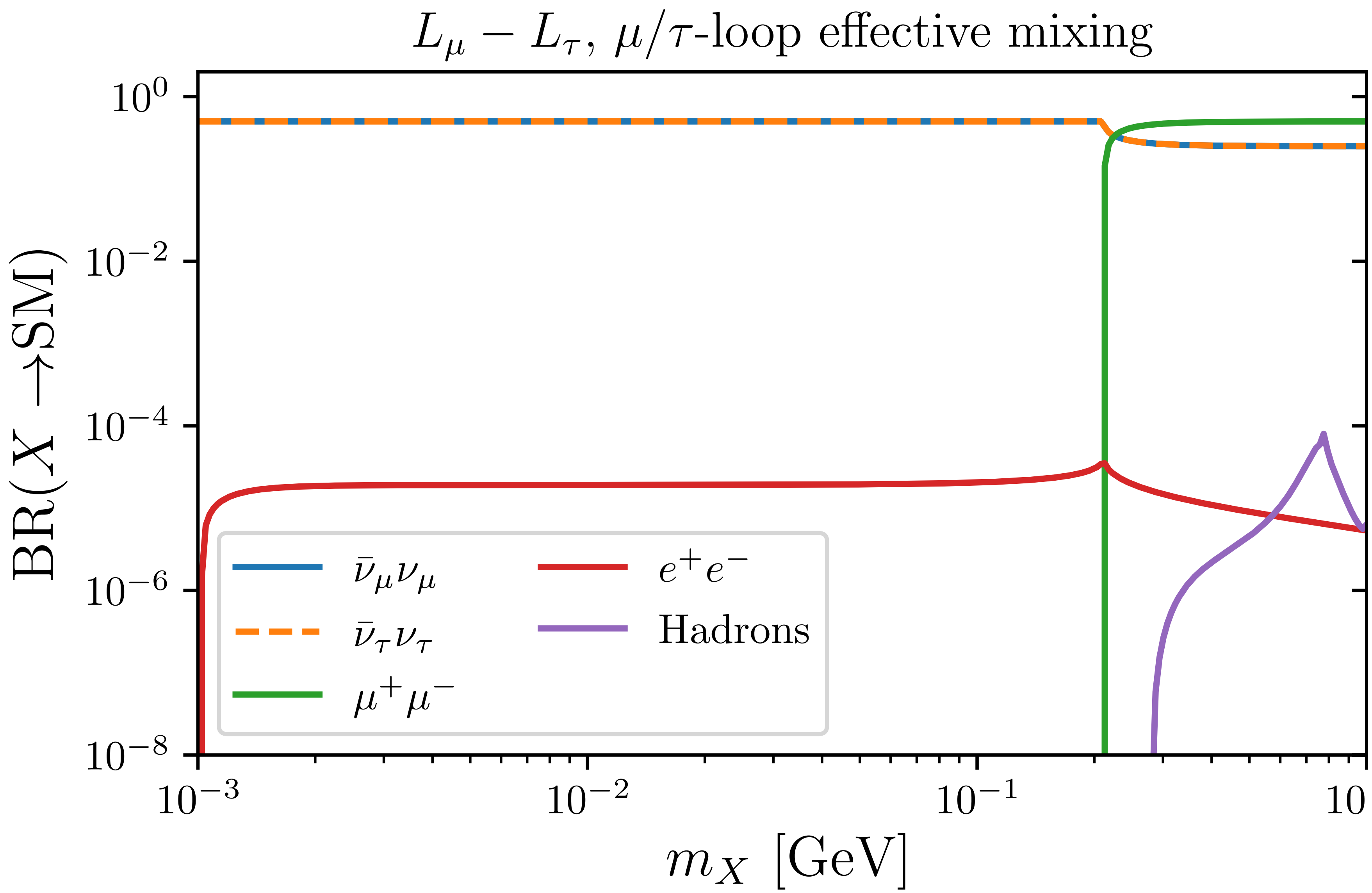
*The quark flavor-universal solutions can immediately be extended to the 2 + 1 case.

- The muoquark conditions slightly change: $X_{q_{12}} = 0$

eg. S_3 LQ: $X_{L_2} \neq \{X_{L_{1,3}}, X_{L_{1,3}} - X_{q_3}, -X_{q_3}, -2X_{q_3}, -3X_{q_3}\}$ **[171 inequivalent sol.]** $-10 \leq X_{F_i} \leq 10$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

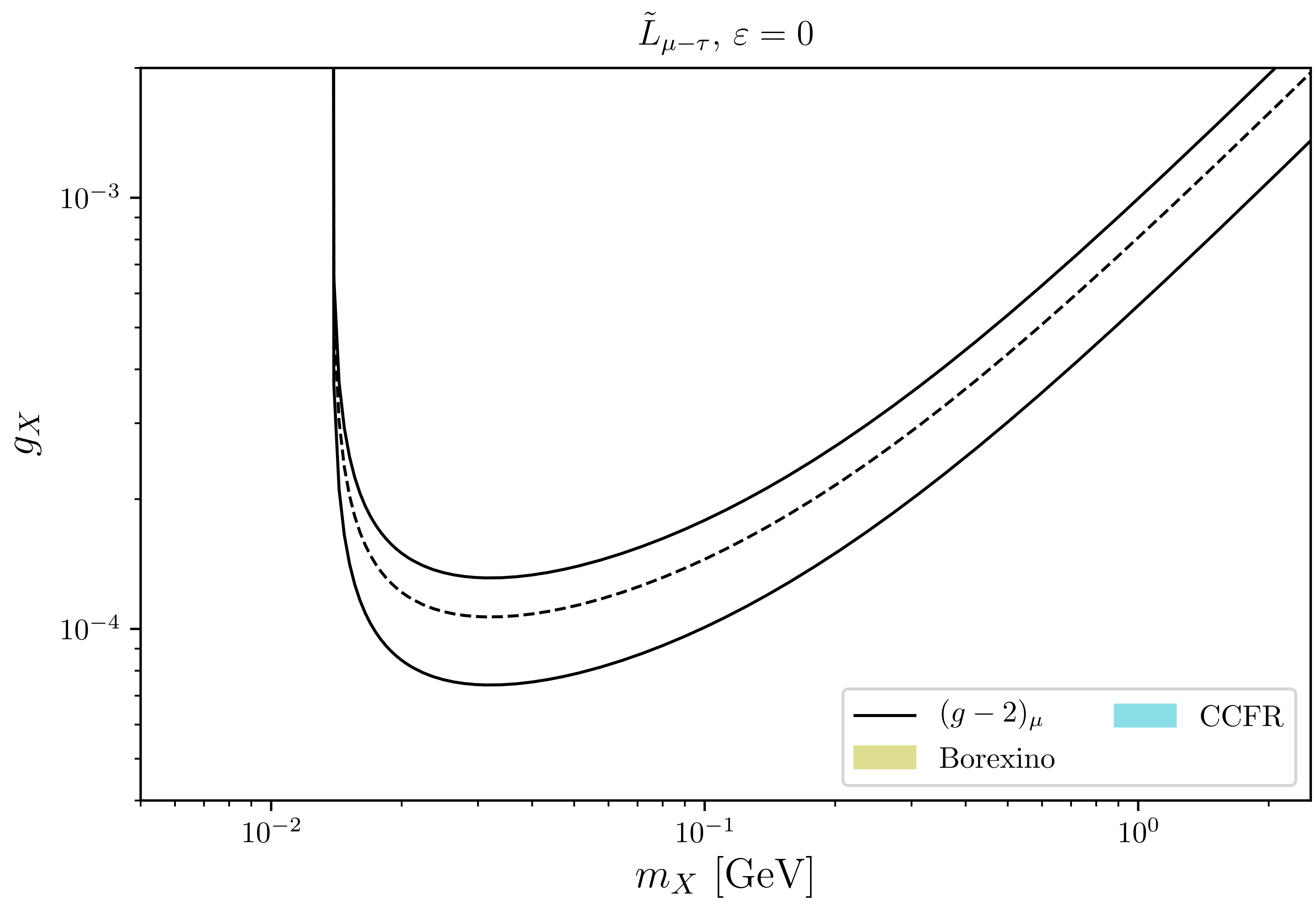
Gauged $L_\mu - L_\tau$



Most studied case:
hep-ph/0104141,
hep-ph/0110146,
1311.0870,
1403.1269,
1406.2332,
...

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Gauged $\tilde{L}_{\mu-\tau}$



$$(X_{L_1}, X_{L_2}, X_{L_3}) = (-1, 7, -6),$$
$$(X_{N_1}, X_{N_2}, X_{N_3}) = (-7, -2, 9),$$

$$(X_{E_1}, X_{E_2}, X_{E_3}) = (1, 6, -7),$$
$$X_{Q_i, D_i, U_i} = 0.$$

- Axial coupling to electrons:
  $\Longrightarrow$ No NSI bounds

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Z' models: $L_\mu - L_\tau$

- Constraints:

1. Neutral meson mixing:

$$\sim \frac{g_{bs}^2}{m_{Z'}^2} \lesssim \frac{\left|\frac{M_{12}}{M_{12}^{SM}} - 1\right| / 10\%}{(244\,\text{TeV})^2}$$

$$\left|\frac{M_{12}}{M_{12}^{SM}} - 1\right| \approx 10\%$$
$$\Downarrow$$
$$\frac{g_{\mu\mu}}{m_{Z'}} \gtrsim \frac{1}{5.3\,\text{TeV}}$$

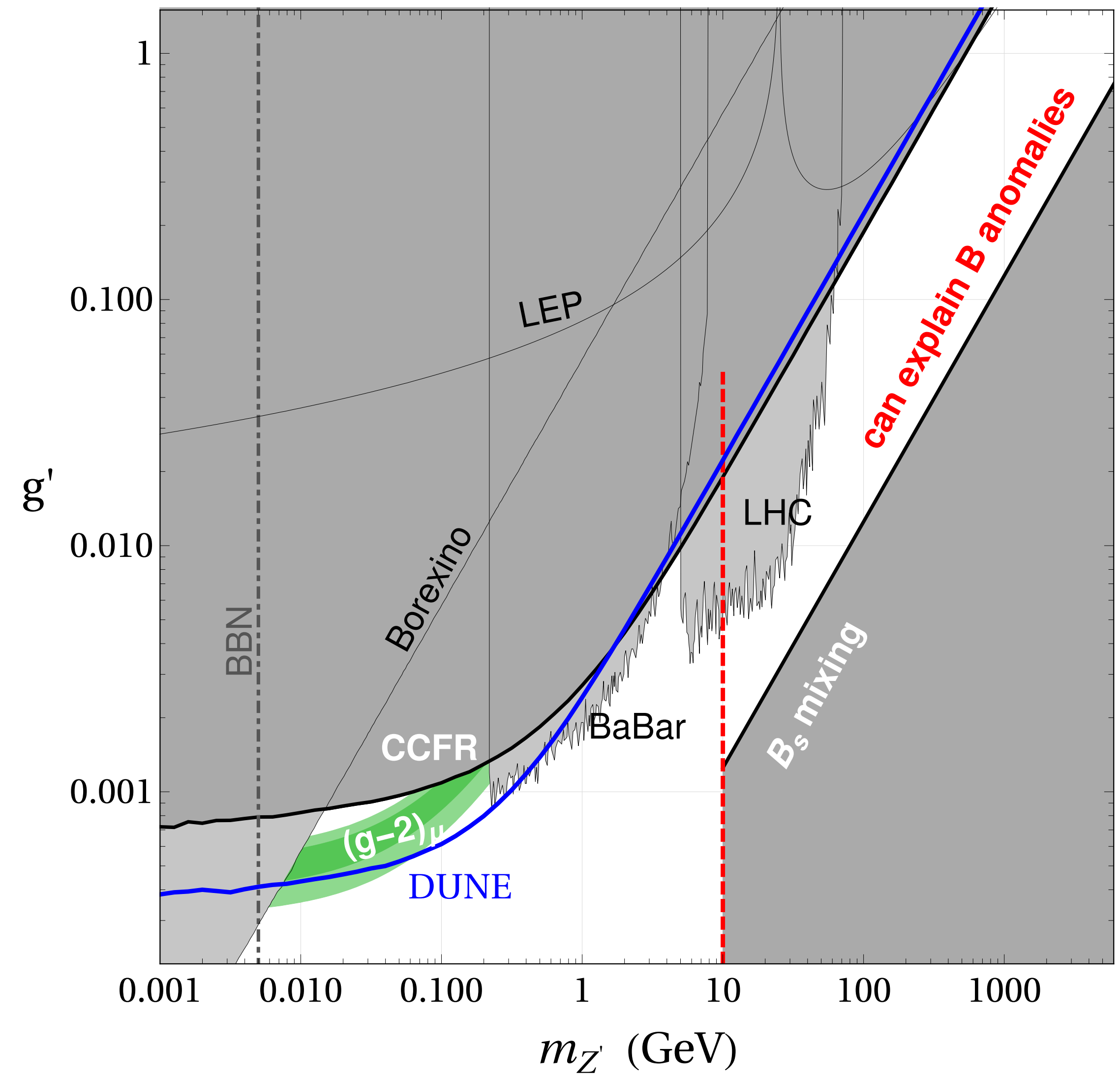
2. Neutrino trident production $\nu\gamma \to \nu\mu\mu$

$$\frac{g_{\mu\mu}}{m_{Z'}} \lesssim \frac{1}{0.5\,\text{TeV}}$$

($b \to s\ell\ell$ fit suggests left-handed lepton doublet is involved)

$L_\mu - L_\tau$

Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



- Simultaneous explanation of $(g-2)_\mu$ not possible

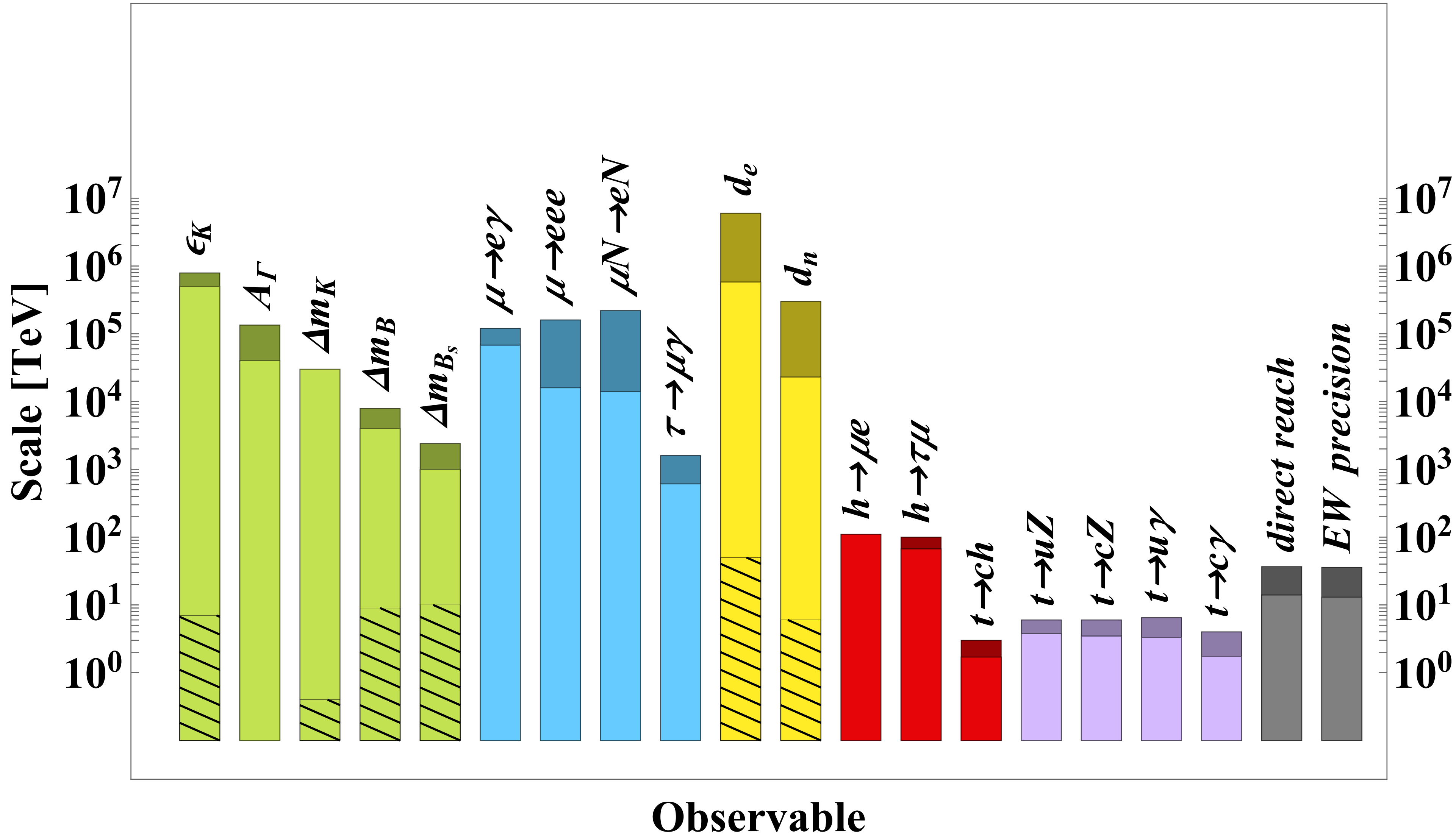


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

Neutrino masses

- The minimal type-I seesaw mechanism

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

- 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.