What can we learn from R(K) beyond it being a null test of the SM?

BSM model building

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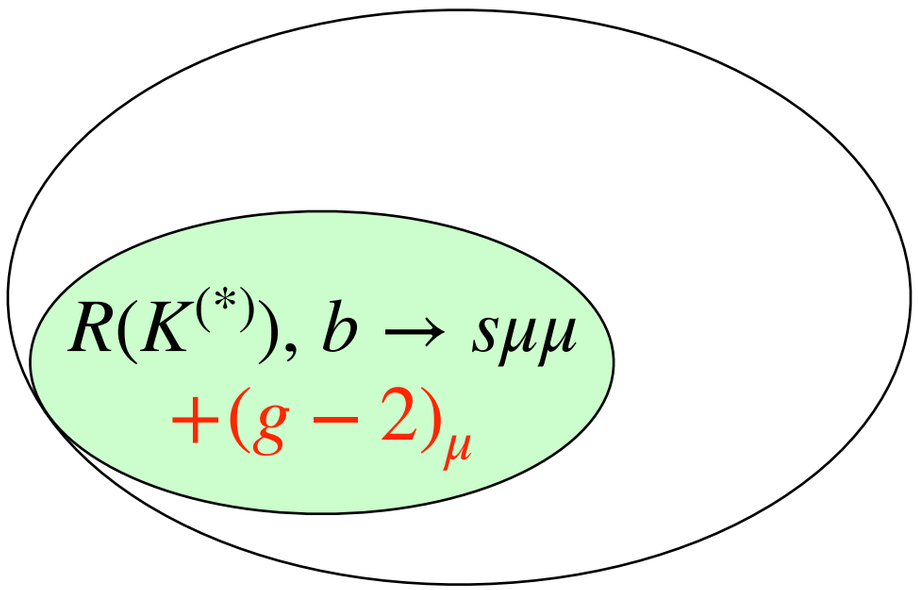
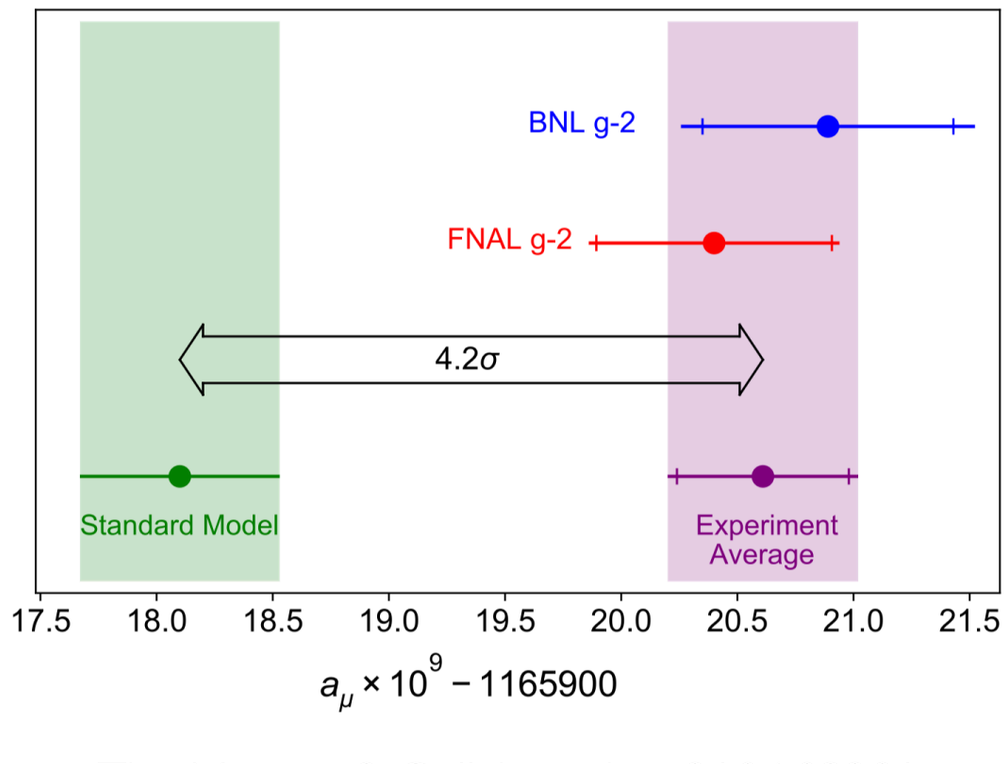
UNIVERSITÄT BERN

Beyond the Flavour Anomalies II, 20.04.2021

Models of **Muon Anomalies**

- Focus:





The Muon g-2 Collaboration, 2104.03281

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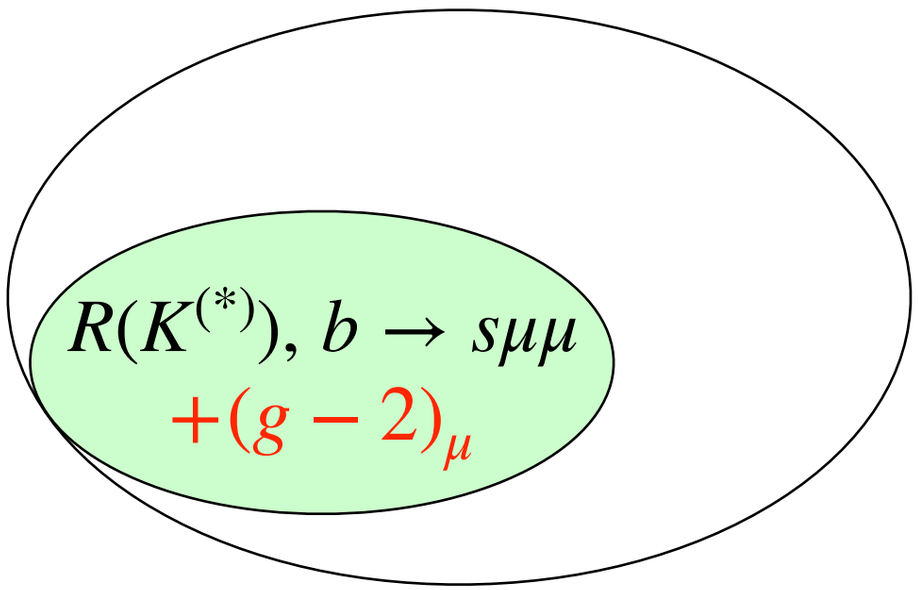
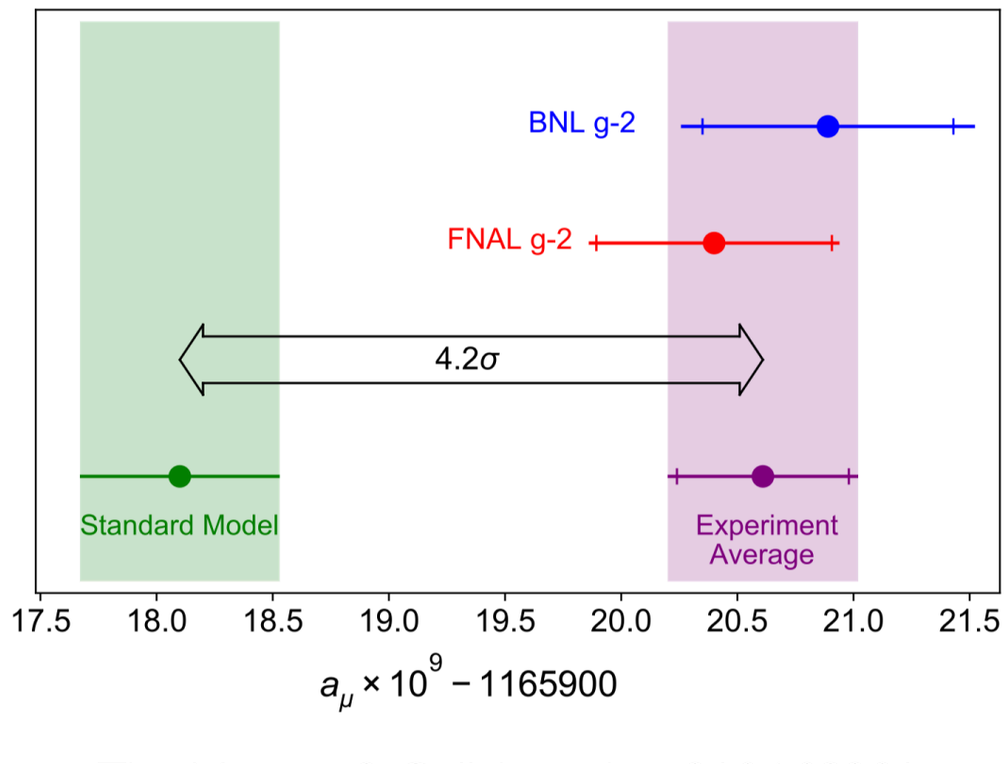




The Muon g-2 Collaboration, 2104.03281

- A sketch of a minimal structure:

$R(K^{(*)}),\ b \to s\mu\mu$ tree-level

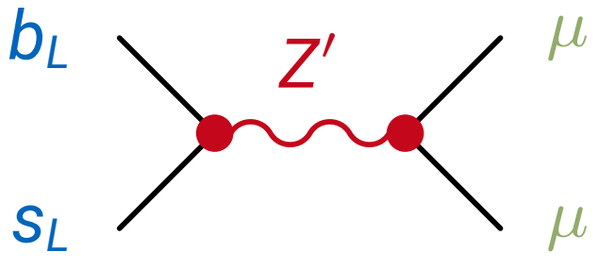
$(g-2)_\mu$ one-loop

{ *LQs & Z's*

Greljo, Stangl, Thomsen, 2103.13991

For both at one-loop see e.g.:
Arcadi, Calibbi, Fedele, Mescia, 2104.03228

Z' models for $R(K)$



$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2} \sim \frac{1}{(36\,\text{TeV})^2}$$

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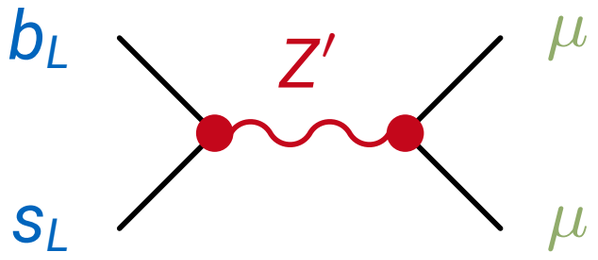


$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2} \sim \frac{1}{(36\,\text{TeV})^2}$$

- Constraints:

1. Neutral meson mixing:

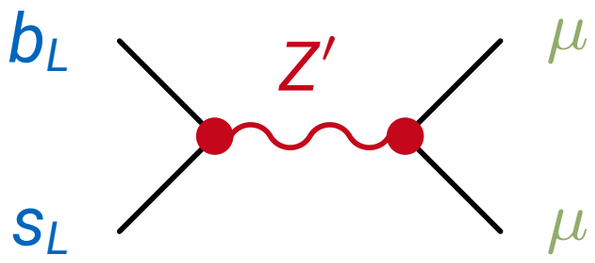
$$\sim \frac{g_{bs}^2}{m_{Z'}^2} \lesssim \frac{\left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| / 10\%}{(244\,\text{TeV})^2} \qquad \left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| \approx 10\% \Downarrow \frac{g_{\mu\mu}}{m_{Z'}} \gtrsim \frac{1}{5.3\,\text{TeV}}$$

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)

Z' models for $R(K)$



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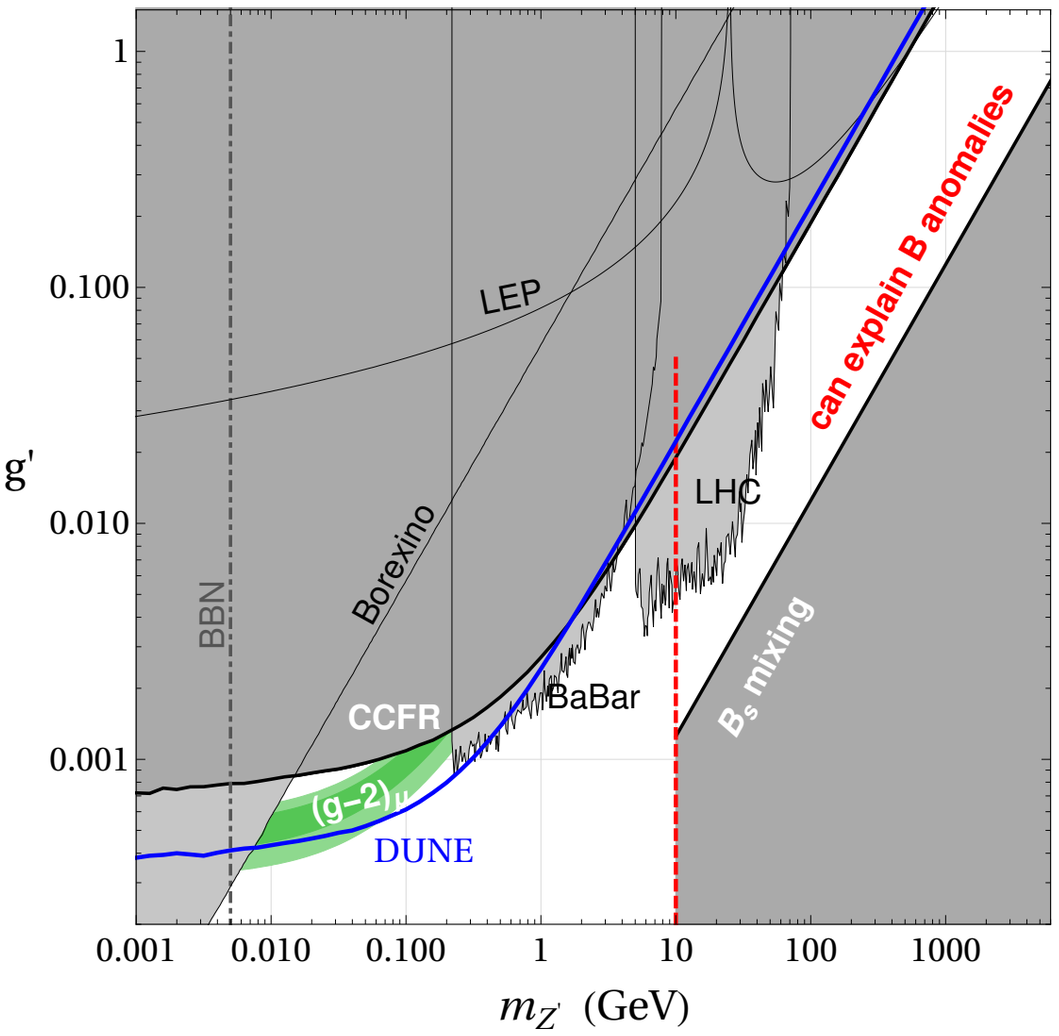
$$L_\mu - L_\tau$$

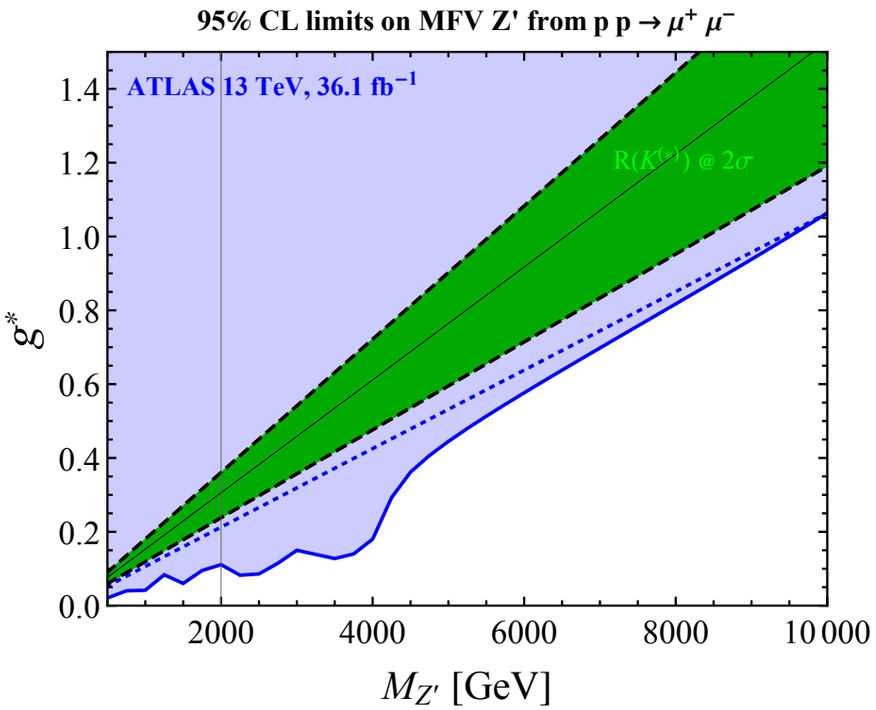
Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



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

Z' models for $R(K)$

- Resonant and non-resonant searches in $pp \to \mu^+\mu^-$



Greljo, Marzocca, arXiv:1704.09015

- MFV-like Z'-quark couplings already excluded

e.g. $U(1)_{B-L}$ ✗

e.g. $U(1)_{B_3-L_2}$ ✓

Z' models for $R(K)$

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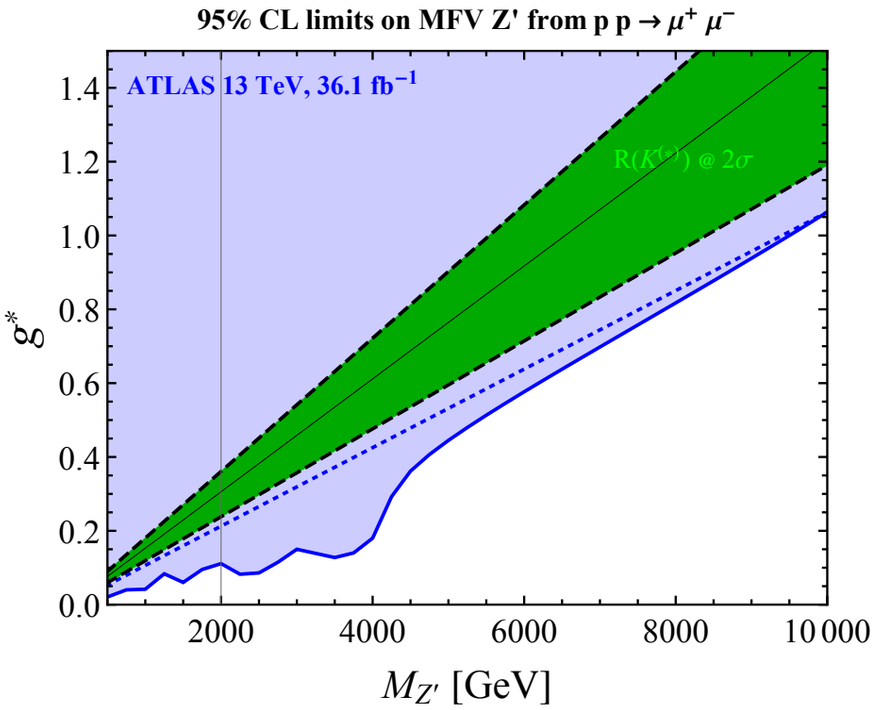

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- MFV-like Z'-quark couplings already excluded

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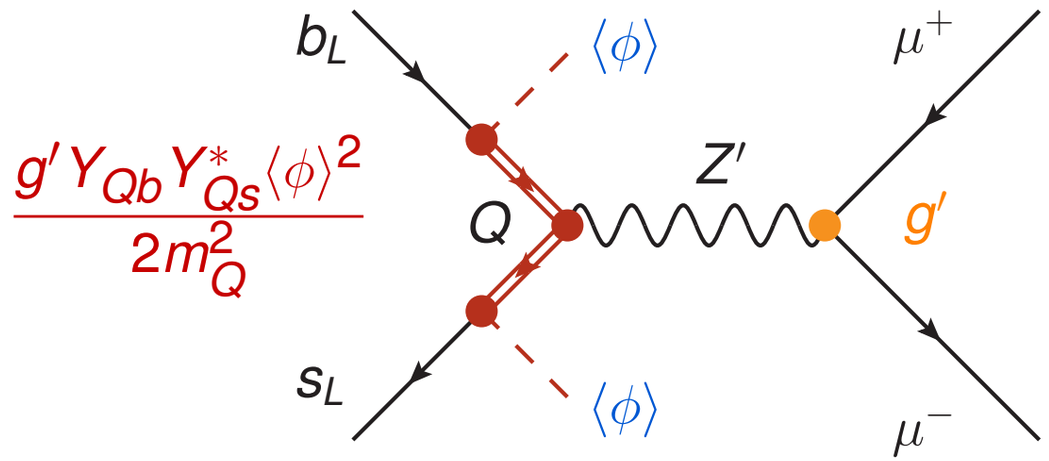
e.g. $U(1)_{B_3-L_2}$ ✓

- UV Completions:

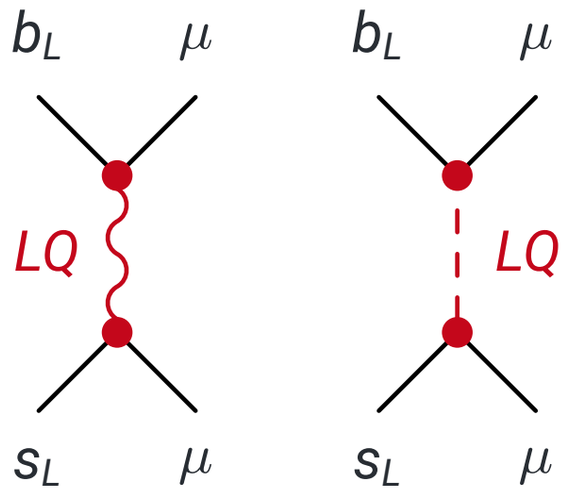
- Vector-like quarks



Altmannshofer, Gori, Pospelov, Yavin, 1403.1269

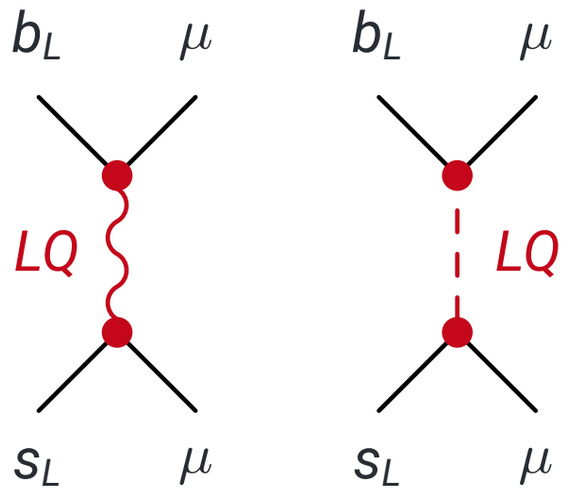
$L_\mu - L_\tau$

LQ models for $R(K)$



$$\sim \frac{g_{b\mu}\, g_{s\mu}}{m^2_{LQ}}$$

LQ models for $R(K)$



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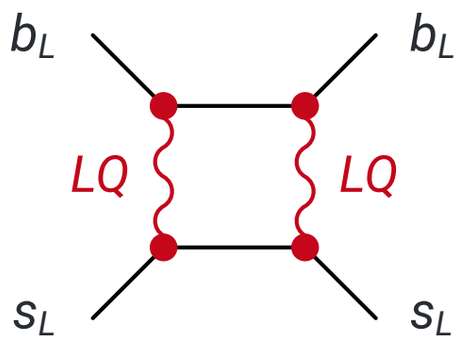
B_s-$\bar{B}_s$ mixing loop-suppressed



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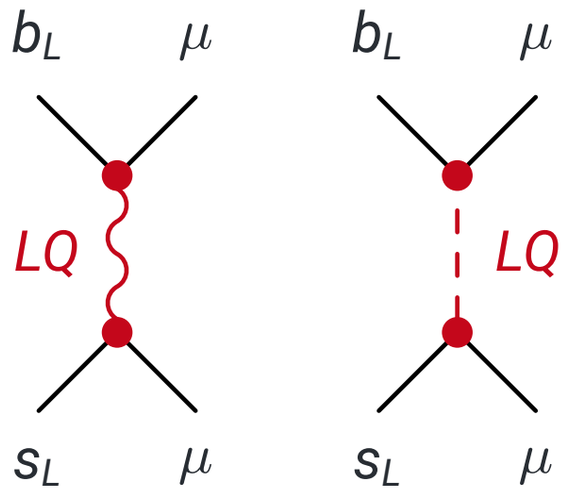

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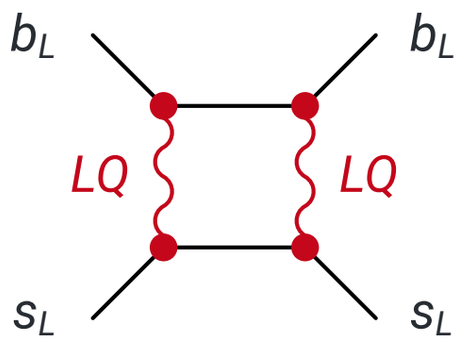
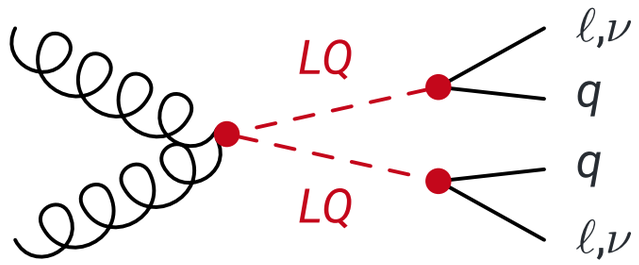


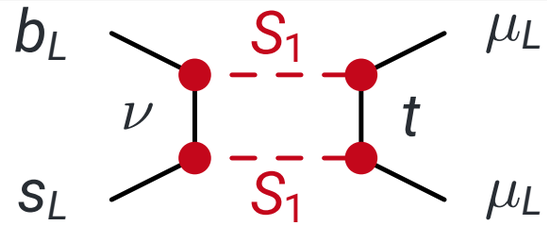
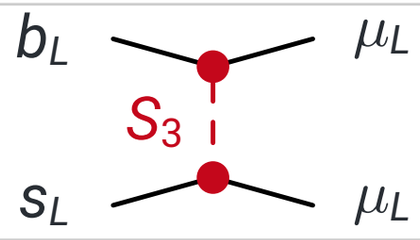
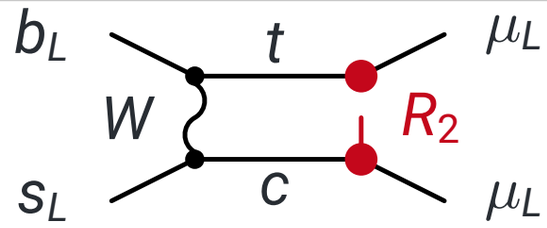
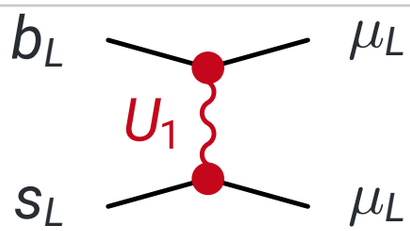
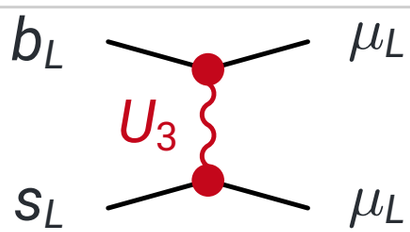
Leptoquarks: direct constraints

- QCD pair production
- Direct searches with $jj\ell\ell$ or $jj\nu\nu$ final states



$m_S \gtrsim 1.5\,\text{TeV}$ $\quad$ $m_V \gtrsim 2.0\,\text{TeV}$

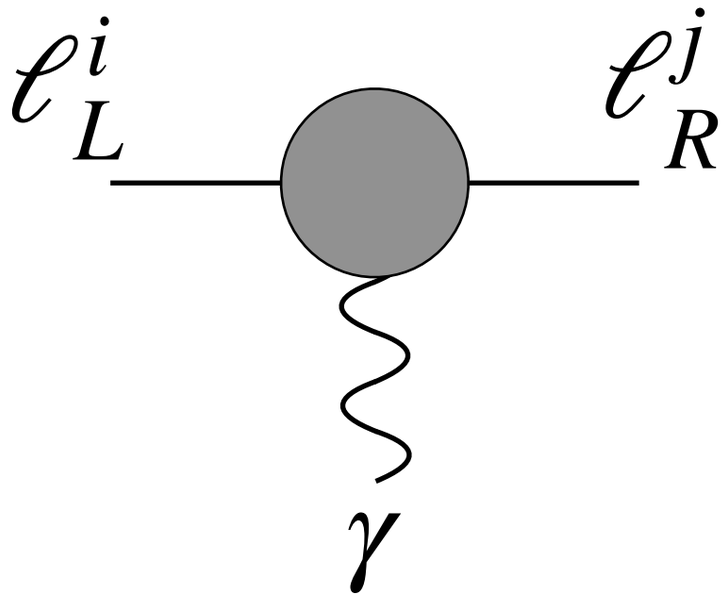
LQ models for $R(K)$

Spin	G_{SM}	Name	Characteristic process	$R_{K^{(*)}}$	
0	$(\bar{3},1)_{1/3}$	S_1		✗	requires too large couplings
0	$(\bar{3},3)_{1/3}$	S_3		✓	
0	$(3,2)_{7/6}$	R_2		✗	tension with LHC limits
1	$(3,1)_{2/3}$	U_1		✓	
1	$(3,3)_{2/3}$	U_3		✓	

cf. Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, arXiv:2103.12504

The $(g-2)_\mu$ input

- **Observation 1**:



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

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

Naive expectation $\theta_{12}^2 \sim m_e/m_\mu$ and $\theta_{23}^2 \sim m_\mu/m_\tau$

Almost exact lepton flavor symmetry $\Longrightarrow$ Gauged lepton flavour $U(1)_{X_\mu}$

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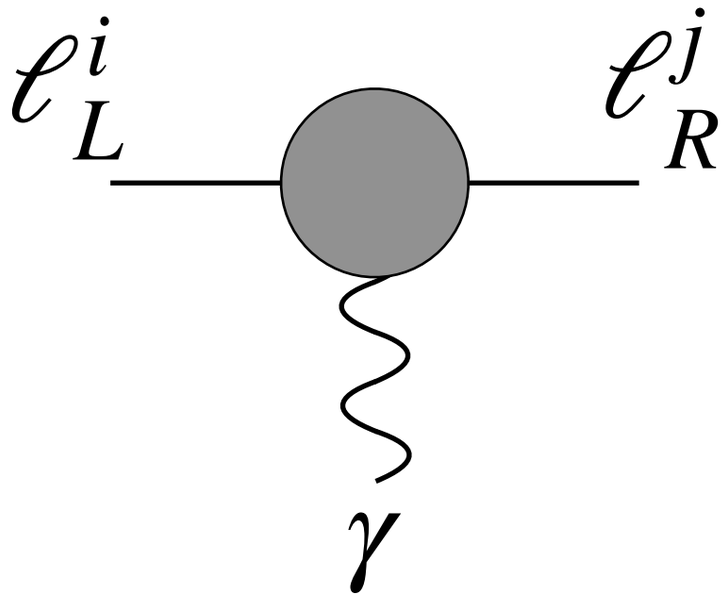

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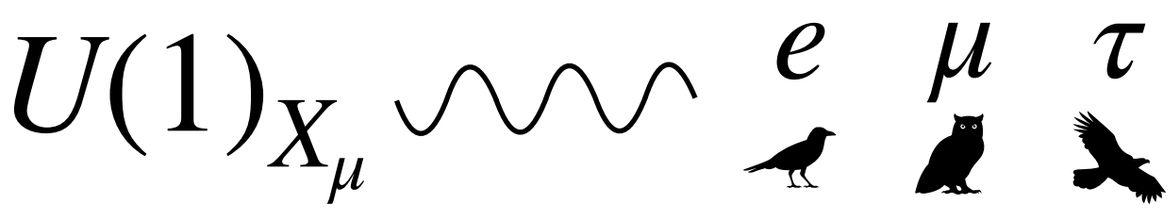
- **Observation II**:

New LFUV force $\Longrightarrow$ Consistent with $R(K)$



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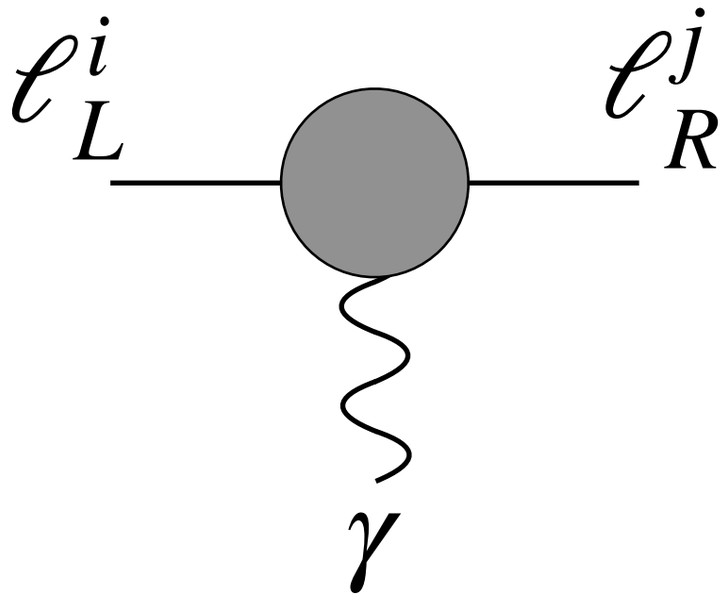

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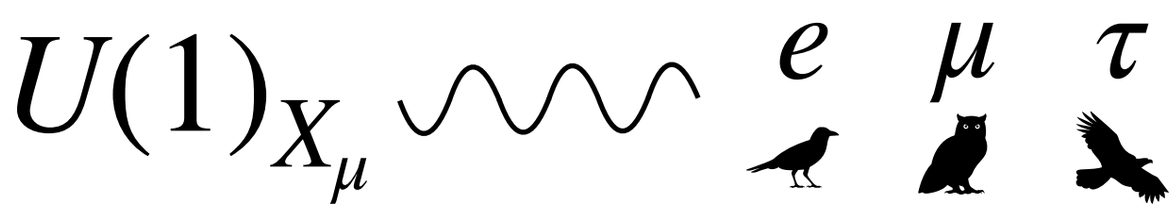
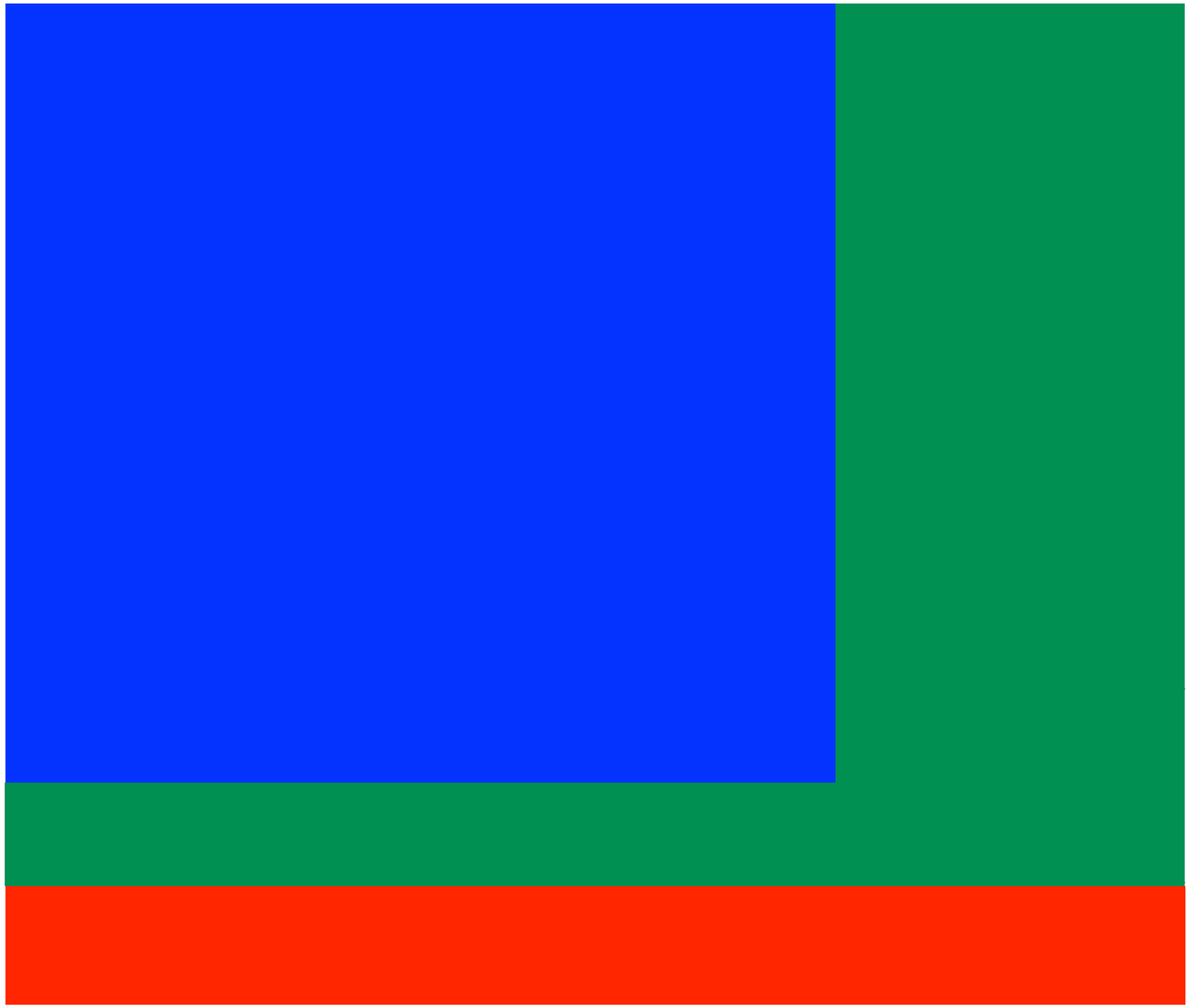


- Many attempts in the literature, mostly either $(g-2)_\mu$ or $R(K)$:

hep-ph/0104141, hep-ph/0110146, 1311.0870, 1403.1269, 1406.2332, 1501.00993, 1611.02703, 1705.03858, 1705.00915, 1712.04871, 1809.01158, 1909.020021, 2007.15016, 2009.02197, 2104.03281

A **minimal** model example

- *SM* × $U(1)_{B-3L_\mu}$ gauge symmetry



Greljo, Stangl, Thomsen, 2103.13991

A **minimal** model example

- *SM* × $U(1)_{B-3L_\mu}$ gauge symmetry

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	3	2	1/6
L_L	1	2	−1/2
u_R	3	1	2/3
d_R	3	1	−1/3
ν_R	1	1	0
e_R	1	1	−1
H	1	2	1/2

SM

Muon force

Muoquark

Greljo, Stangl, Thomsen, 2103.13991

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SM

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L_L	1	2	-1/2	{0, -3, 0}
u_R	3	1	2/3	1/3
d_R	3	1	-1/3	1/3
ν_R	1	1	0	{0, -3, 0}
e_R	1	1	-1	{0, -3, 0}
H	1	2	1/2	0
Φ	1	1	0	3

Muon force

* Minimal type-I seesaw for the neutrino masses

Muoquark

Greljo, Stangl, Thomsen, 2103.13991

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ν_R	1	1	0	{0, -3, 0}
e_R	1	1	-1	{0, -3, 0}
H	1	2	1/2	0
Φ	1	1	0	3
S_3	$\bar{3}$	3	1/3	8/3

SM

Muon force

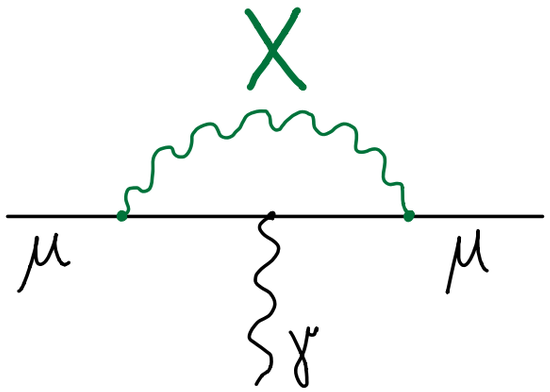
Muoquark

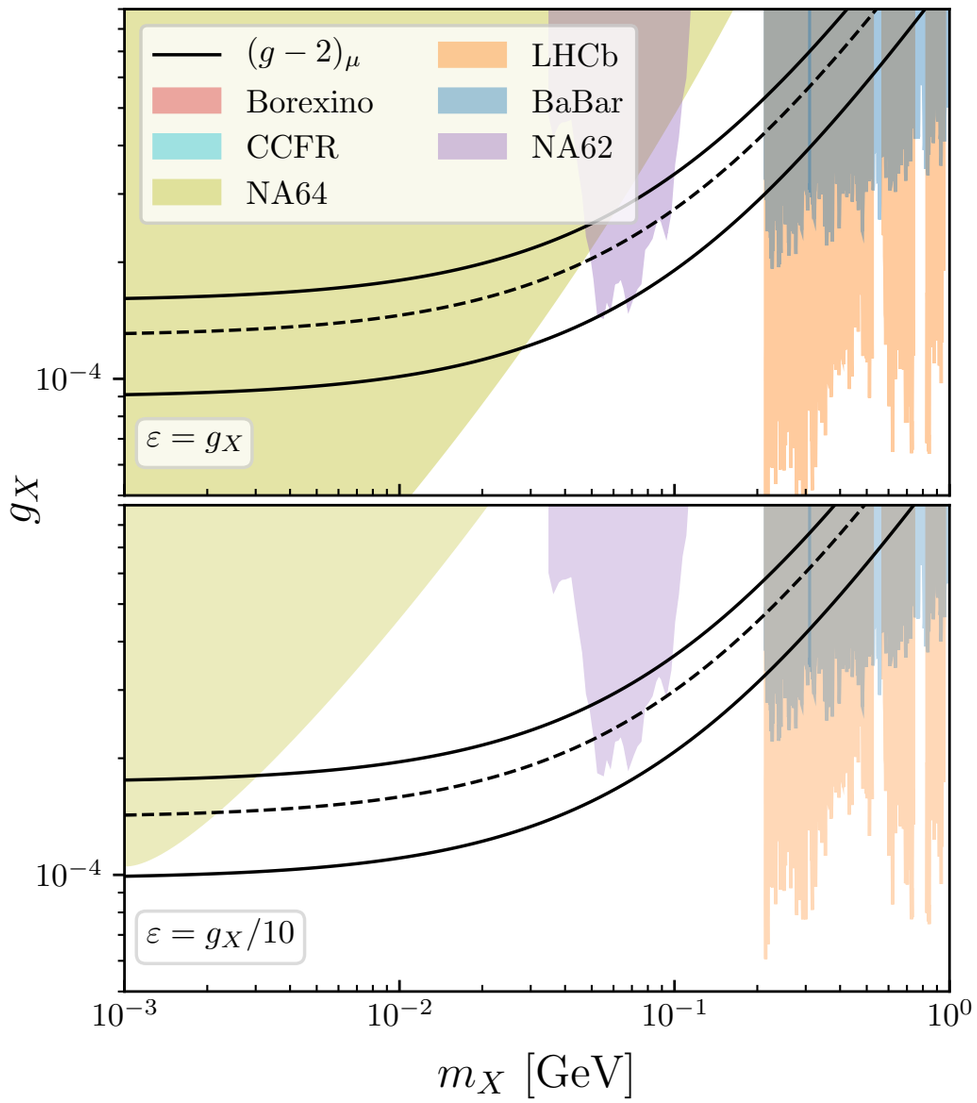
$\mathscr{L} \supset Q_L L_L^{(2)} S_3$

Greljo, Stangl, Thomsen, 2103.13991

A **minimal** model example

Muon force





Greljo, Stangl, Thomsen, 2103.13991

A **minimal** model example

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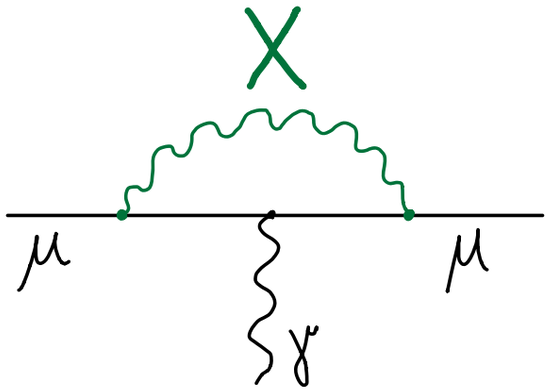
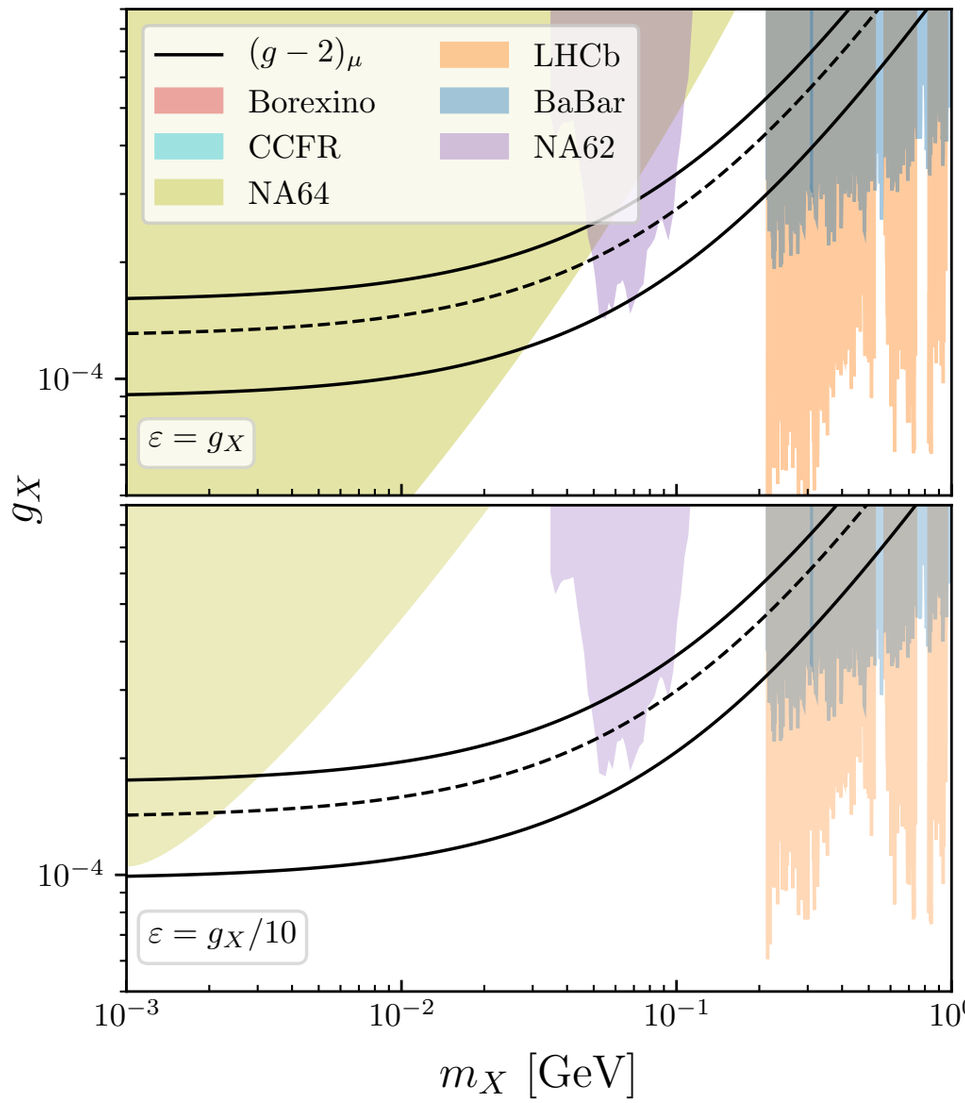
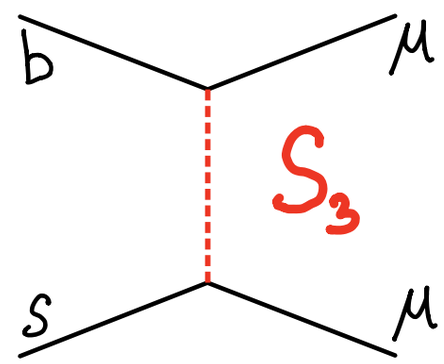




Muoquark



- What $U(1)_{X_\mu}$ 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

~~$QQS_3^\dagger$~~ ~~$QQS_3^\dagger\phi$~~

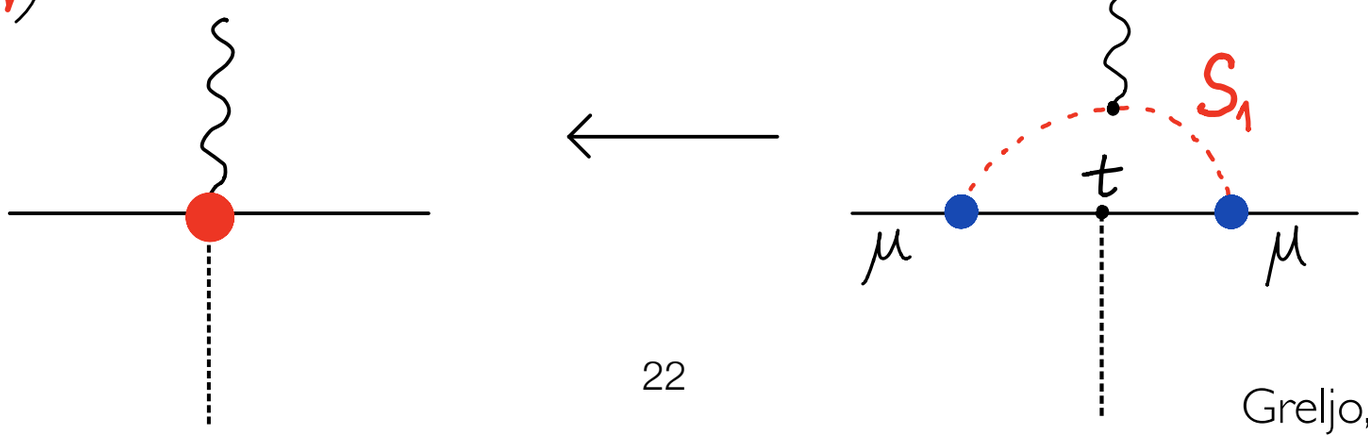
Greljo, Stangl, Thomsen, 2103.13991

A model variation

- Add $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)_{8/3}$ muoquark for $(g-2)_\mu$. Decouple $U(1)_{B-3L_\mu}$.

$$\frac{g_Y\, y_t}{16\pi^2\,(10\ \text{TeV})^2}\, \bar{L}_2 B_{\mu\nu} H \mu_R B^{\mu\nu}$$

$(g-2)_\mu$:



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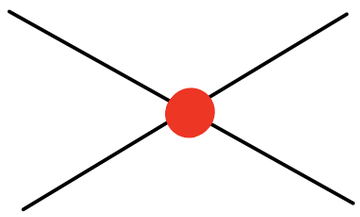
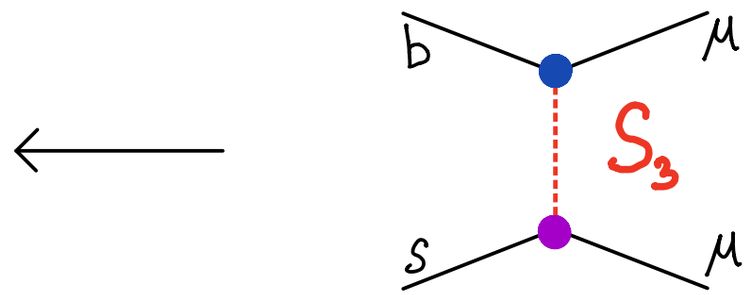
$R(K)$:

$$\frac{1}{(10\,\text{TeV})^2} Q_3 Q_3 L_2 L_2$$

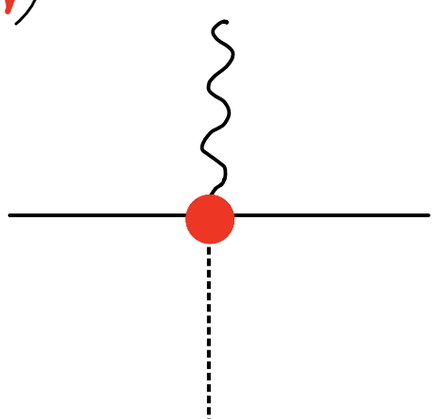


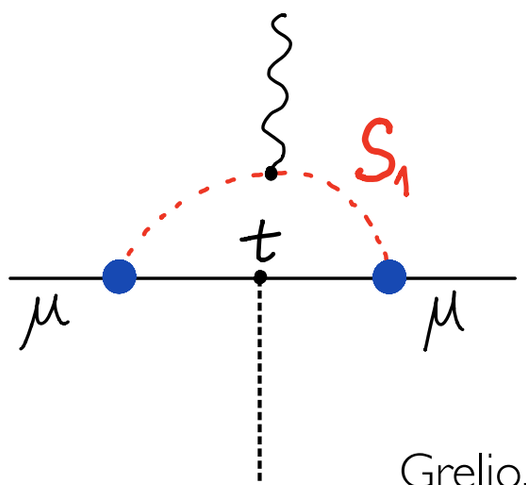


$Q = \begin{pmatrix} u_L \\ V^{CKM} d_L \end{pmatrix}$ ● = ● × V^{CKM}_{ts}

$(g-2)_\mu$:

$$\frac{g_Y y_t}{16\pi^2 (10\,\text{TeV})^2} \bar{L}_2 B_{\mu\nu} H \mu_R B^{\mu\nu}$$





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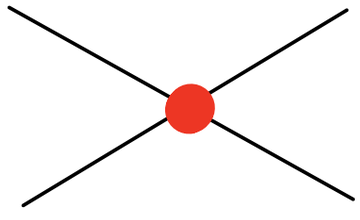
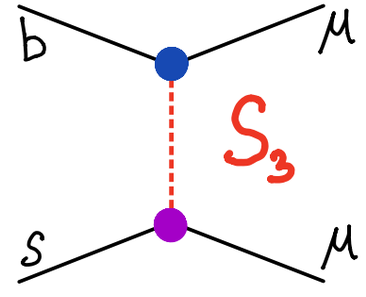
A model variation

- Add $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)_{8/3}$ muoquark for $(g-2)_\mu$. Decouple $U(1)_{B-3L_\mu}$.

$R(K)$:

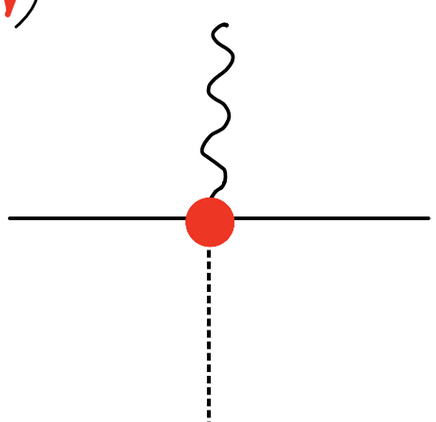
$$\frac{1}{(10\,\text{TeV})^2} Q_3 Q_3 L_2 L_2$$

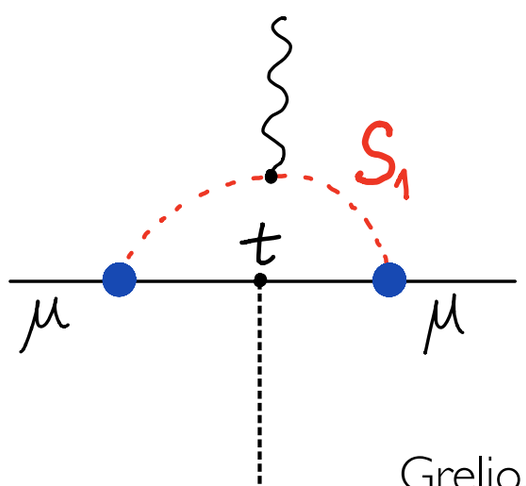




$(g-2)_\mu$:

$$\frac{g_Y\, y_t}{16\pi^2 (10\,\text{TeV})^2} \bar{L}_2 \sigma_{\mu\nu} H \mu_R B^{\mu\nu}$$





$Q = \begin{pmatrix} u_L \\ V^{CKM} d_L \end{pmatrix}$ ● = ● × V^{CKM}_{ts}

Link

● ~ $\mathcal{O}(0.1)$

M ~ $\mathcal{O}$(TeV)

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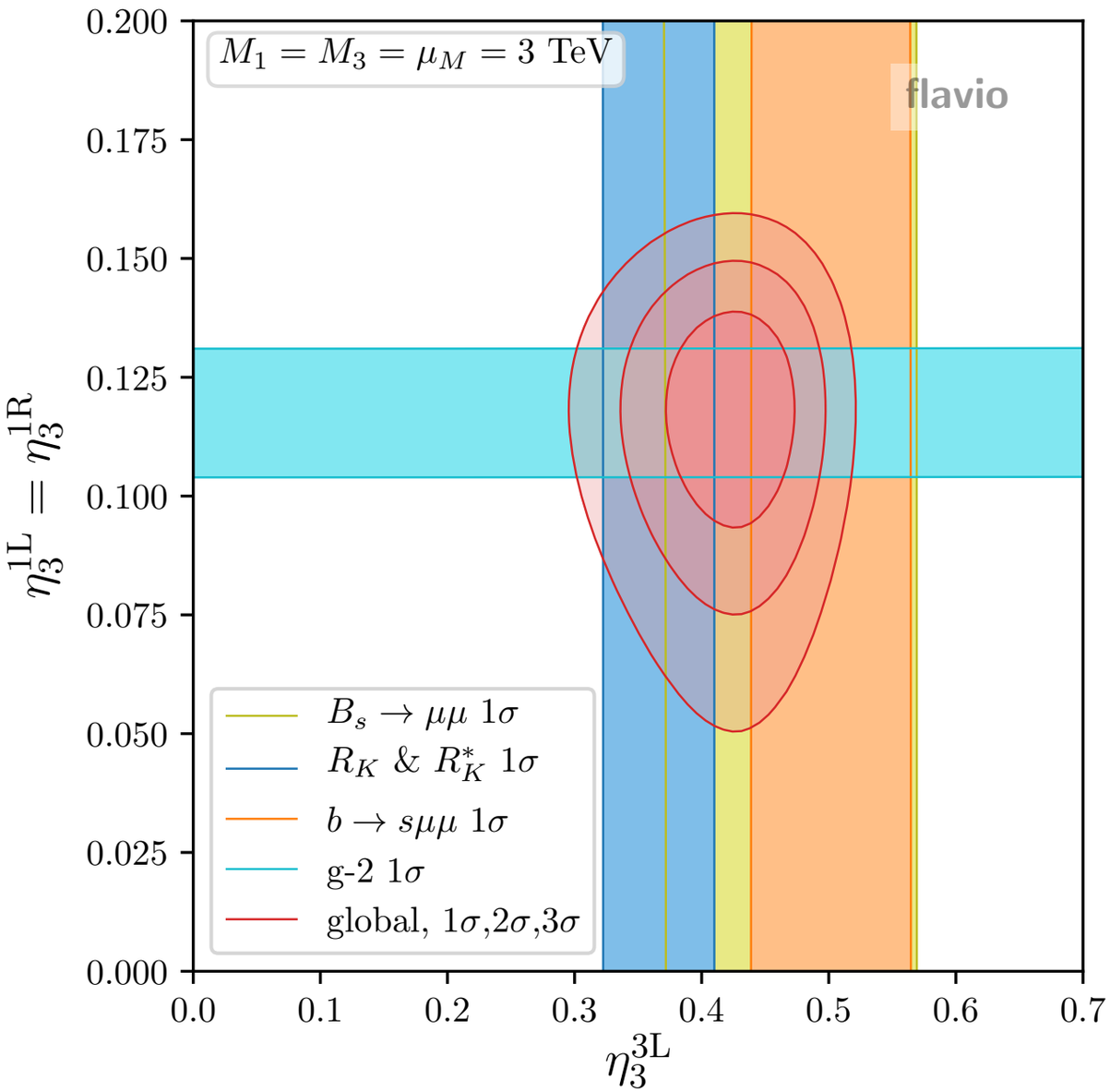
A model variation

- Add $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)_{8/3}$ muoquark for $(g-2)_\mu$. Decouple $U(1)_{B-3L_\mu}$.

$$\mathcal{L} \supset \eta_i^{3\mathrm{L}}\, \bar{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2\, S_3 + \eta_i^{1\mathrm{L}} \bar{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2 S_1 + \eta_i^{1\mathrm{R}} \bar{u}_{\mathrm{R}}^{c\,i} \mu_{\mathrm{R}} S_1$$



- Global fit
  - One-loop matching to SMEFT from 2003.12525
  - 399 observables in **smelli** 1810.07698

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A model variation

- Add $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)_{8/3}$ muoquark for $(g-2)_\mu$. Decouple $U(1)_{B-3L_\mu}$.

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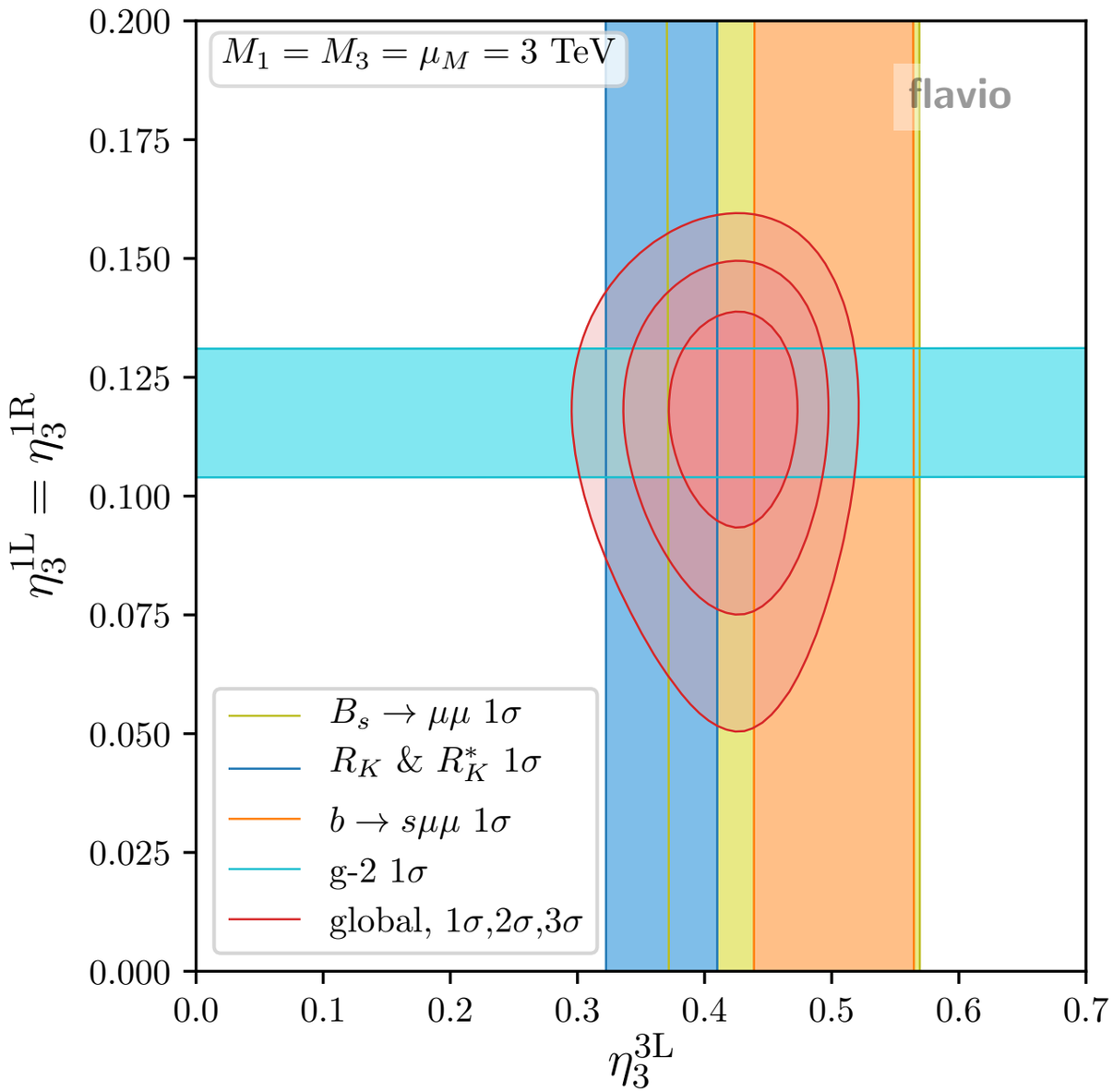

- Global fit
  - One-loop matching to SMEFT from 2003.12525
  - 399 observables in **smelli** 1810.07698

- Finite naturalness

  Higgs mass

  Muon Yukawa

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

  Interesting for collider searches.

- RGE

  The parameters of the model are radiatively stable and can be evolved to the Planck scale without inconsistencies.

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Classification of models

	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

TABLE I. Three types of *muoquark* models, which can address the muon anomalies for a variety of lepton-flavored $\mathrm{U}(1)_X$ gauge groups.

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Questions?