UNIVERSITÄT BERN

SWISS NATIONAL SCIENCE FOUNDATION
Eccellenza, Project-186866

A model of muon anomalies

Admir Greljo

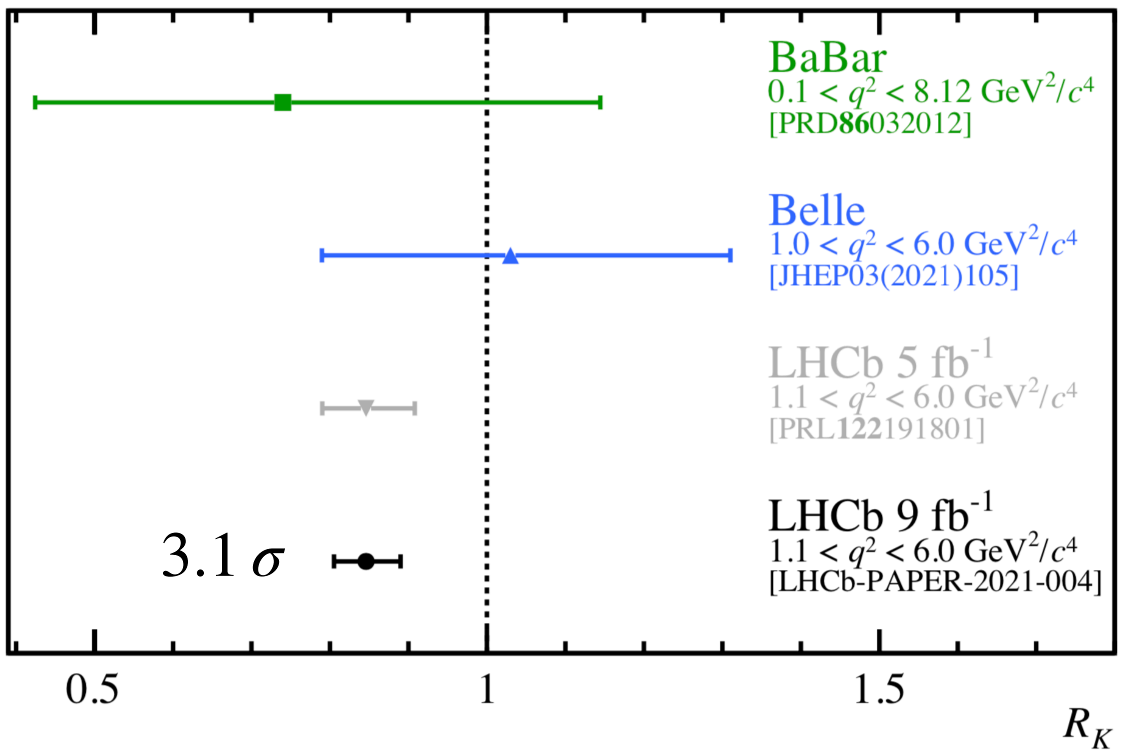
Recent R(K) update from the LHCb experiment at CERN reinforced the tension of B-meson decays into muons. Shortly after, the Muon g-2 experiment at Fermilab strengthened the tension in the muon anomalous magnetic moment. Immense theoretical and experimental work is still needed to possibly establish the existence of new physics, nonetheless, we can already ask relevant questions. Can muon anomalies be coherently addressed in models beyond the SM, and if so, where else should we look for confirmation? I will discuss minimal extensions of the SM based on 2103.13991.

04.05.2021, University of Mainz

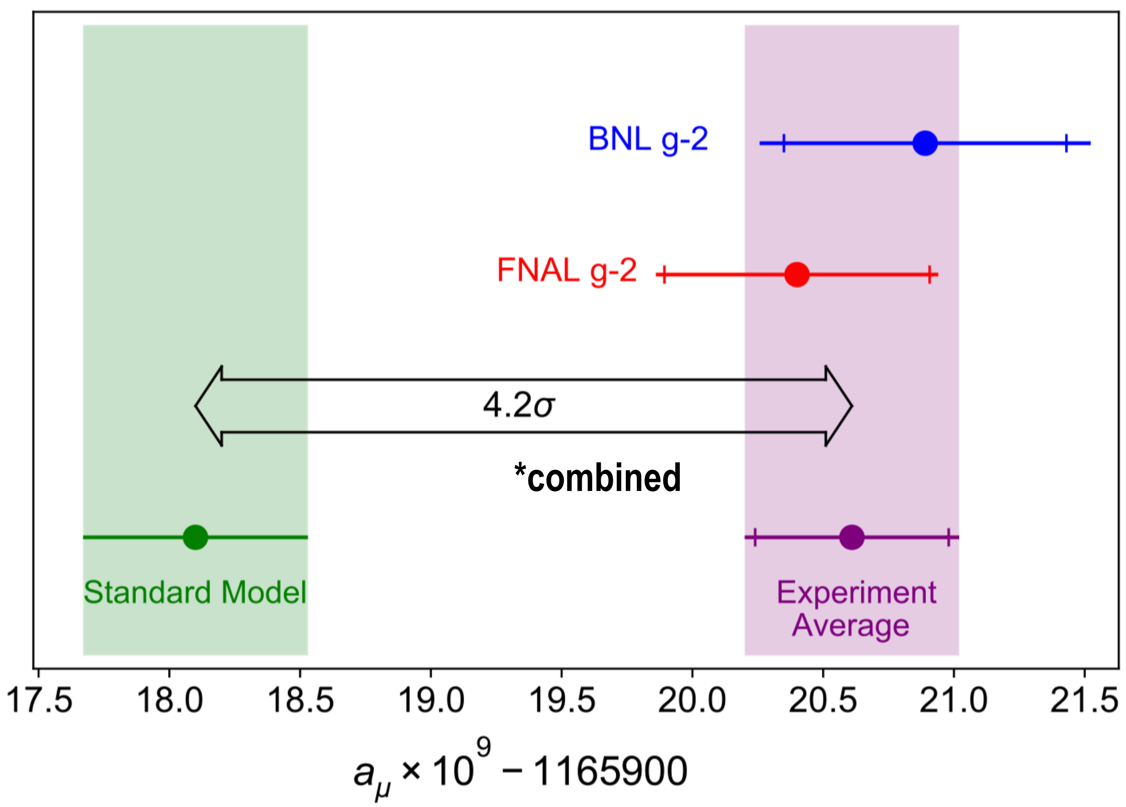
Hot topic in flavour physics: **Muon Anomalies**

$$\frac{b \to s\mu\mu}{b \to see}$$

$(g-2)_\mu$



LHCb, CERN, 2103.11769



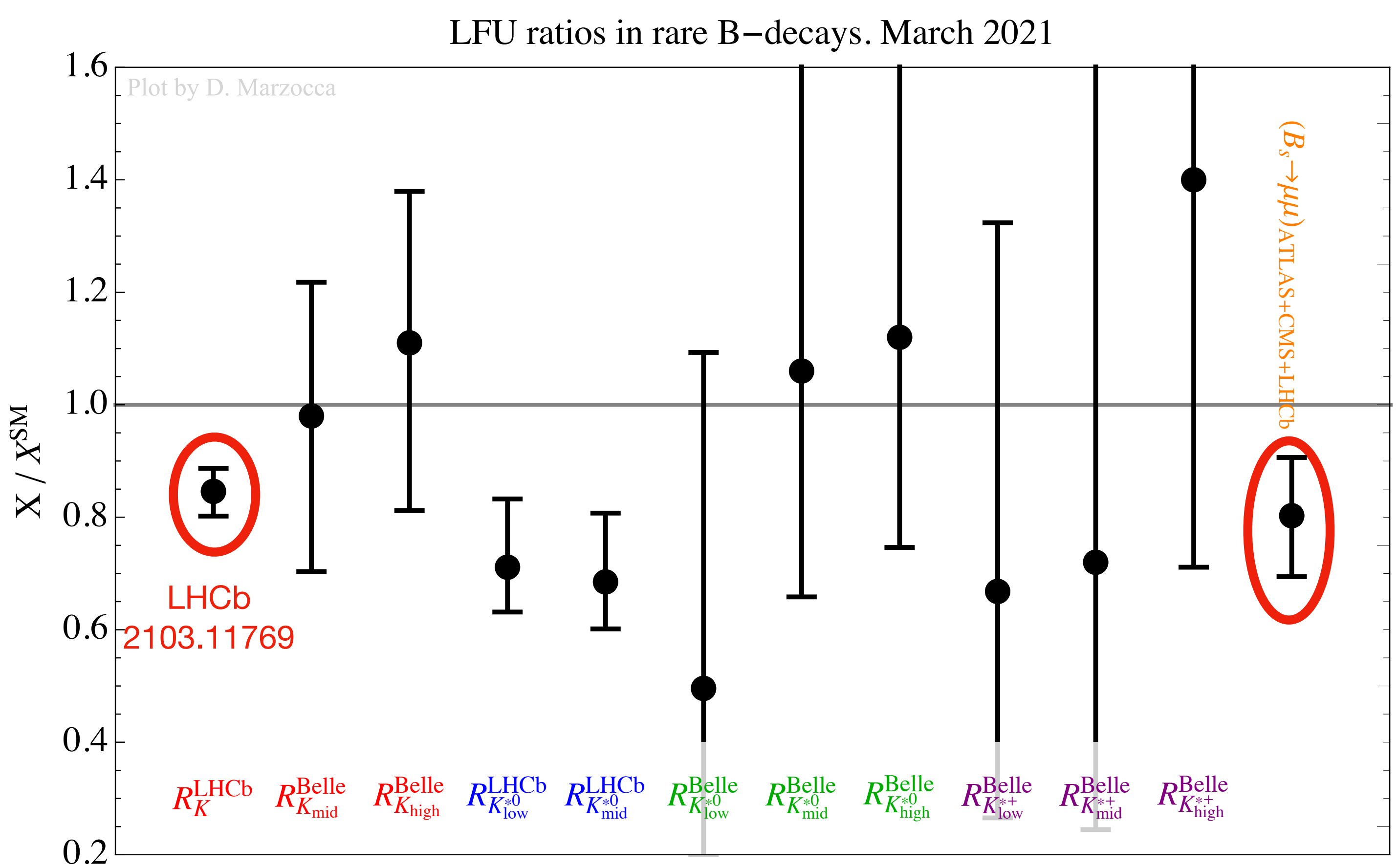
The Muon g-2, Fermilab, 2104.03281

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

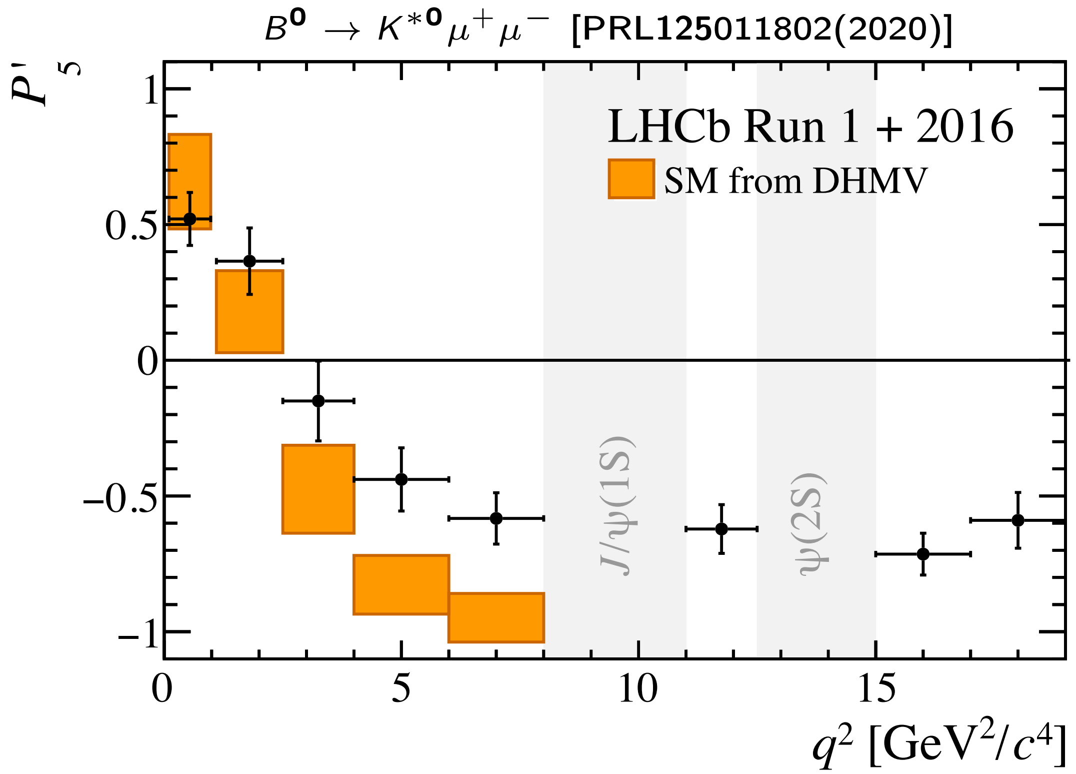
On $b \to s\,\mu\mu$

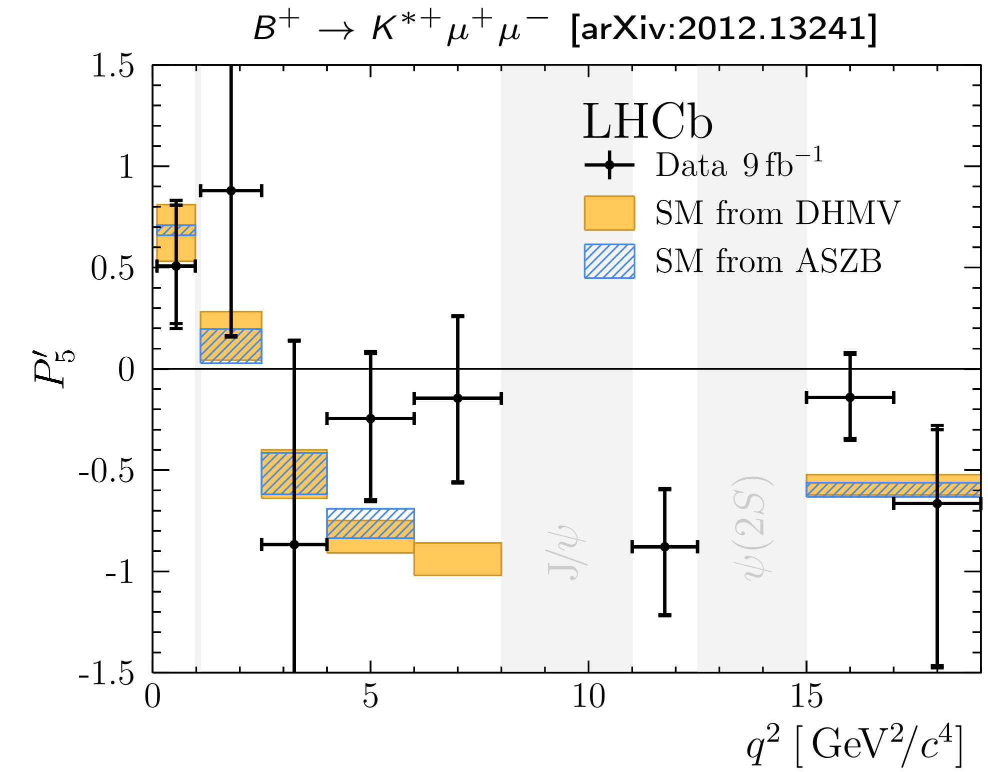
- $R(K)$ 3.1σ "evidence" for LFUV

- Global fit of TH clean observables $R(K^{(*)})$ & $B_s \to \mu^+\mu^-$ for $(\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma^\mu \mu_L)$ gives the SM pull 4.7σ 2103.13370



On $b \to s\,\mu\mu$





$B^+\to K^+$, $B\to K^0$, $B^+\to K^{*+}$, $B^0\to K^{*0}$, $B_s\to\phi$

- Branching ratios $b \to s\,\mu^+\mu^-$ and the angular observable P_5' consistent deviations but the TH prediction is under debate. (P_5' proposed as "clean", deviation $\sim 3\sigma$)

On $b \to s\,\mu\mu$

- $R(K)$ 3.1σ "evidence" for LFUV

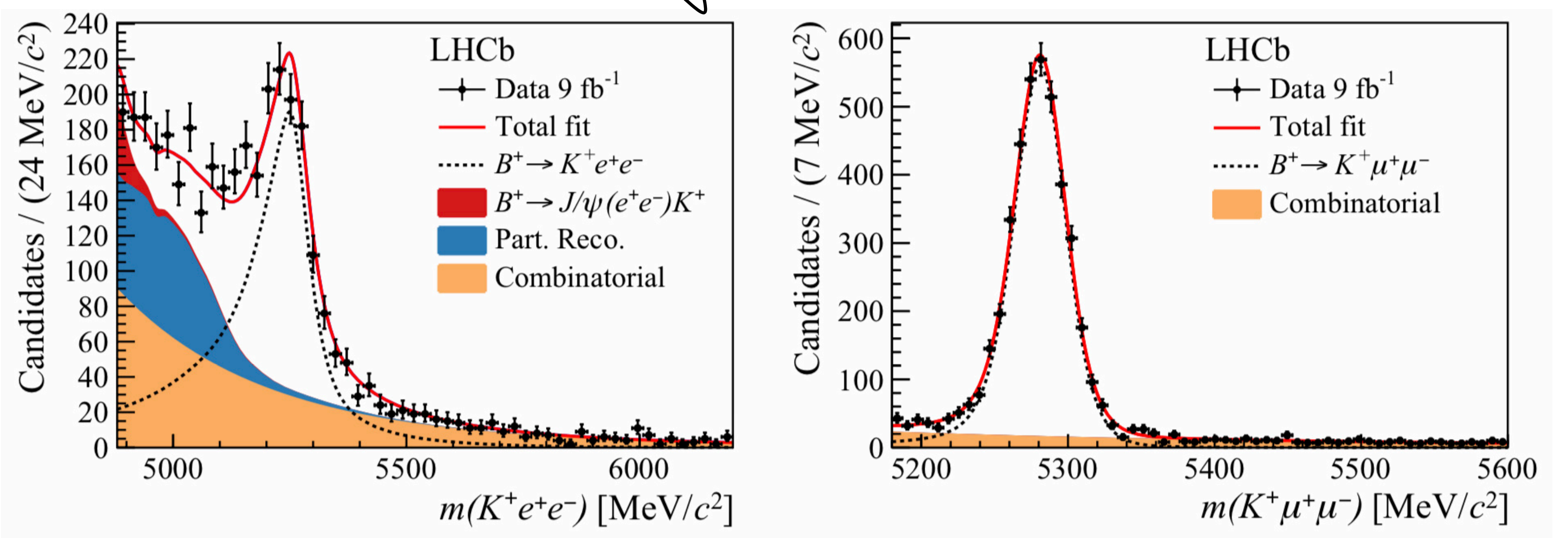
- Global fit of TH clean observables $R(K^{(*)})$ & $B_s \to \mu^+\mu^-$ for $(\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma^\mu \mu_L)$ gives the SM pull 4.7σ 2103.13370

- $B^+\to K^+$, $B\to K^0$, $B^+\to K^{*+}$, $B^0\to K^{*0}$, $B_s\to\phi$
  Branching ratios $b \to s\,\mu^+\mu^-$ and the angular observable P_5' consistent deviations but the TH prediction is under debate. (P_5' proposed as "clean", deviation ~ 3σ)

- "Dirty fit" 2103.13370 $\gtrsim 6\sigma$ **Coherent picture**

On $b \to s\mu\mu$

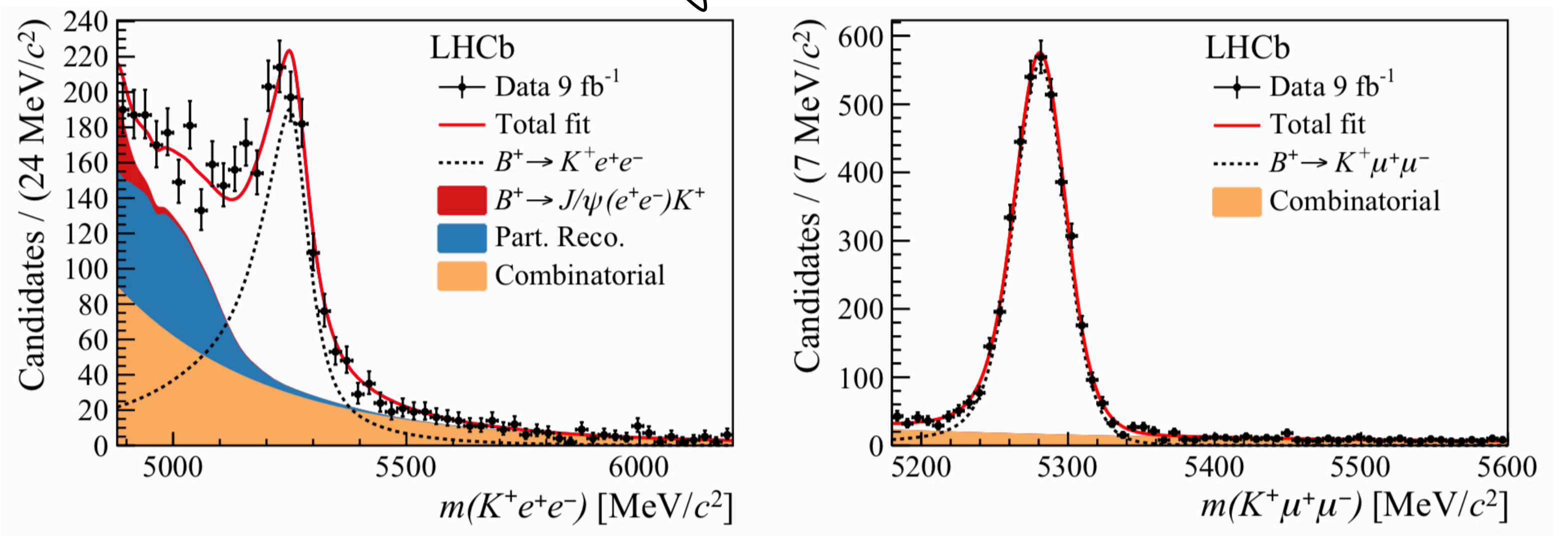
LHCb is made for muons



2103.11769

On $b \to s\,\mu\mu$

LHCb is made for muons



2103.11769

The SM #Conspiracy

- Charm loops for $b \to s\,\mu^+\mu^-$?
- Electron systematics $R(K^{(*)})$?
- 2.3σ stat. fluke $B_s \to \mu^+\mu^-$?

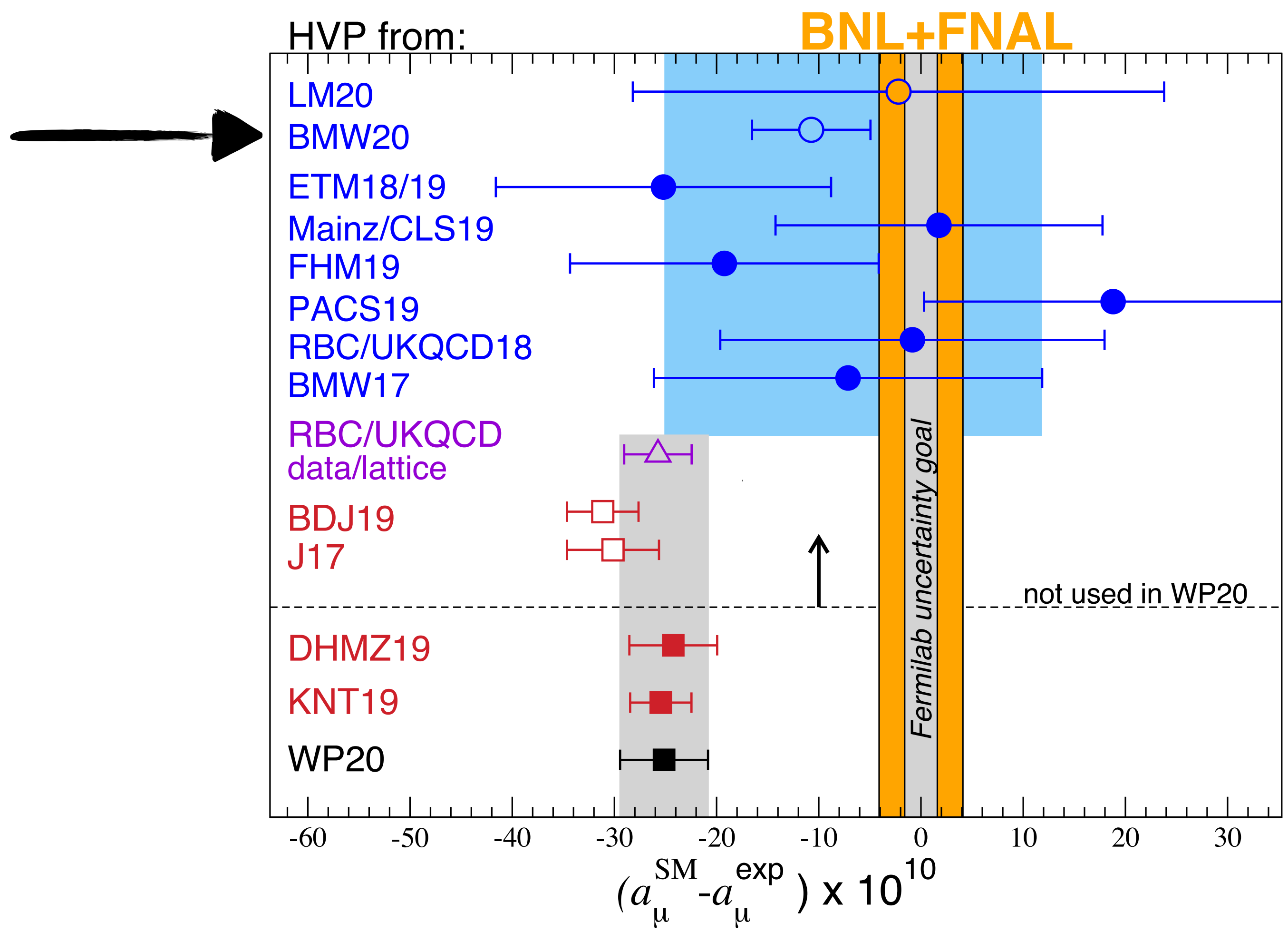
... in just right amounts to mimic NP?

On $(g-2)_\mu$

- The SM prediction is a hard work:
  $(g-2)_\mu$ Theory Initiative

- BMW lattice disagrees... *Nature* (2021)

On $(g-2)_\mu$



Lattice QCD + QED

hybrid: combine data & lattice

data driven

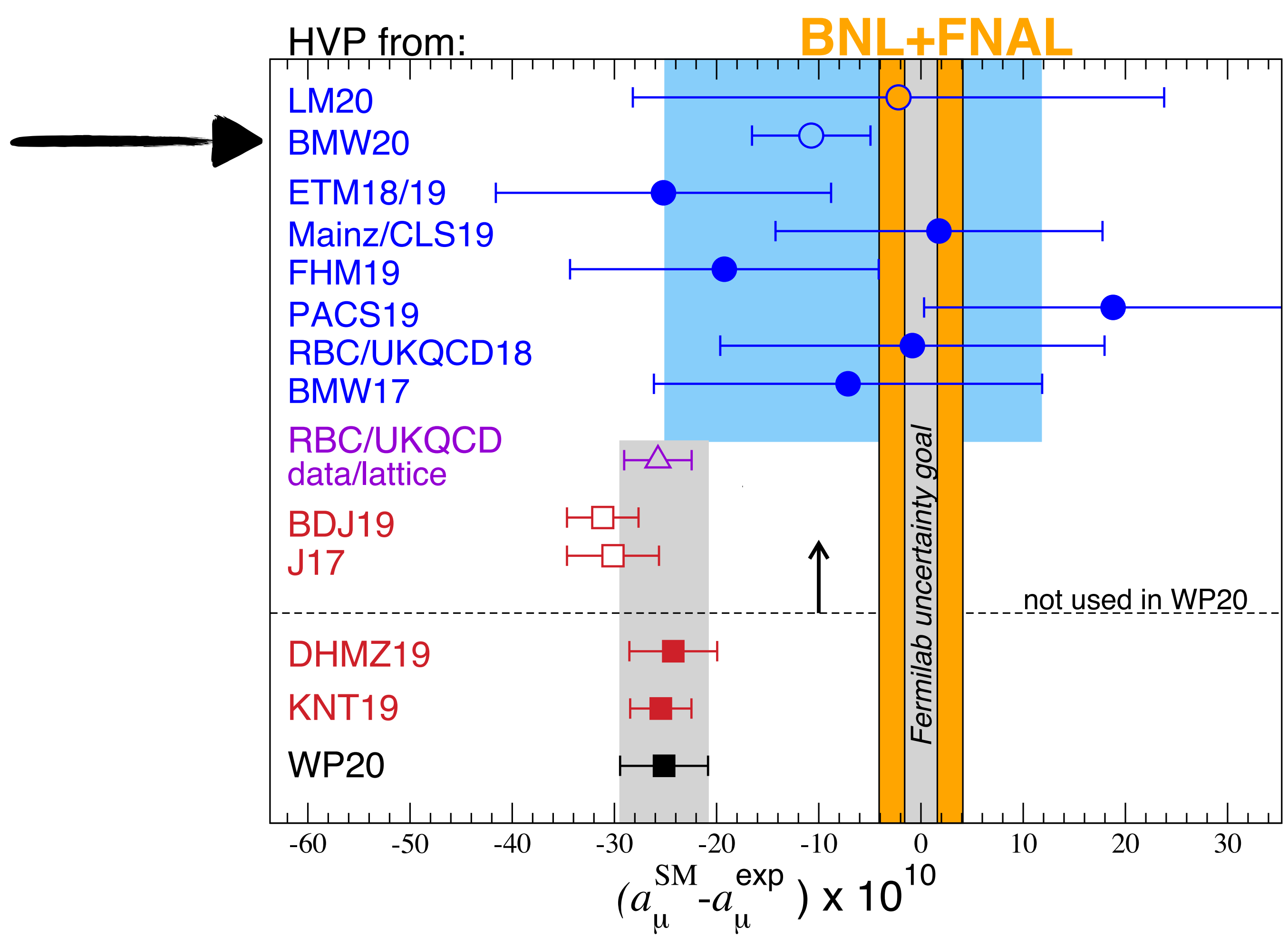
+ unitarity/analyticity constraints

Taken from A. El-Khadra

- The SM prediction is a hard work: $(g-2)_\mu$ Theory Initiative

- BMW lattice disagrees... *Nature* (2021)

On $(g-2)_\mu$



Lattice QCD + QED

hybrid: combine data & lattice

data driven

+ unitarity/analyticity constraints

Taken from A. El-Khadra

- The SM prediction is a hard work: $(g-2)_\mu$ Theory Initiative

- BMW lattice disagrees... *Nature* (2021)

Path forward

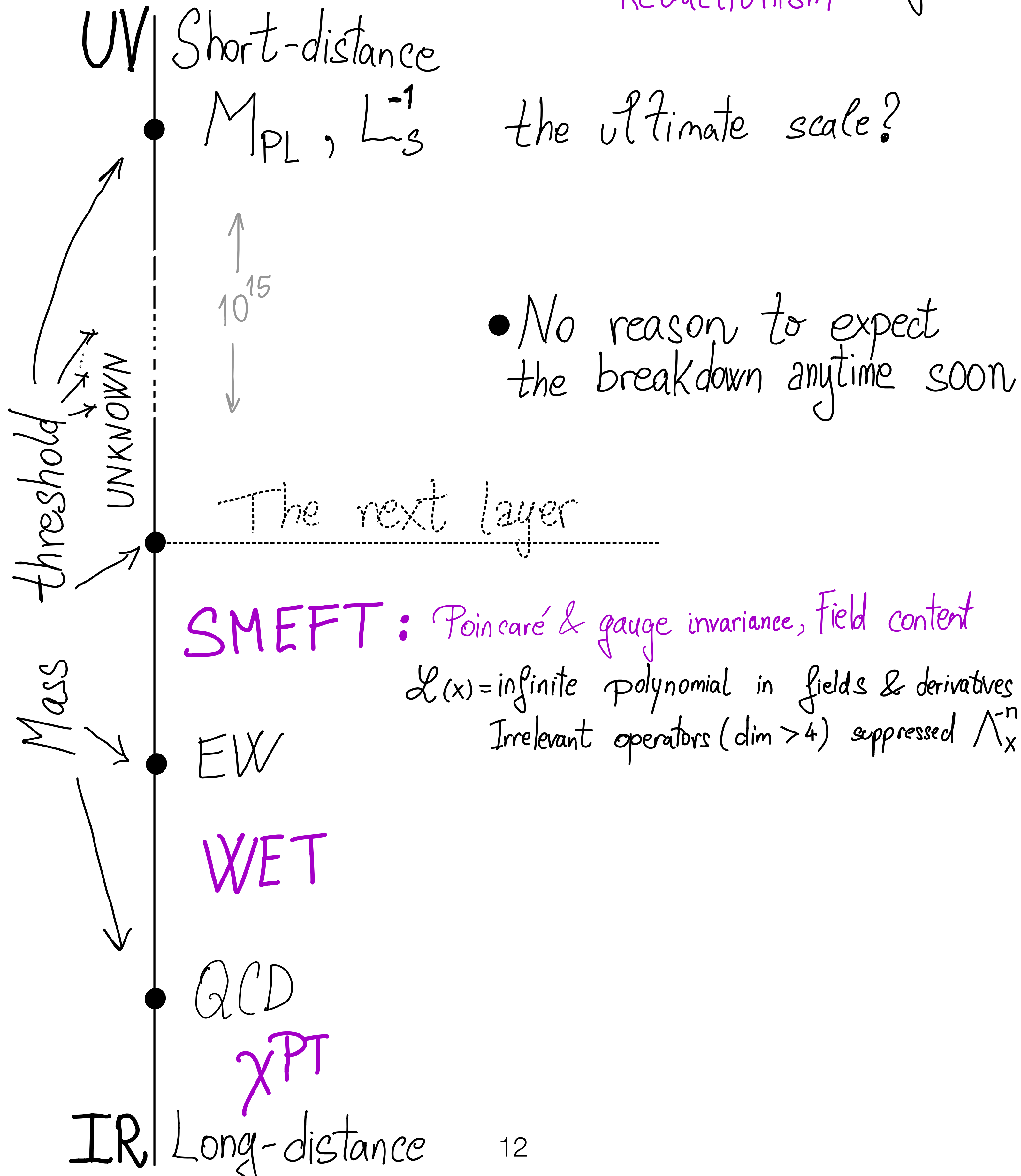
- Internal inconsistency of the $e^+e^- \to had$ data, more data is needed.
- Progress on the lattice side is crucial.

New physics?

$R(K^{(*)})$, $b \to s\mu\mu$
$+(g-2)_\mu$

Wilsonian QFT = the HEP paradigm

Reductionism



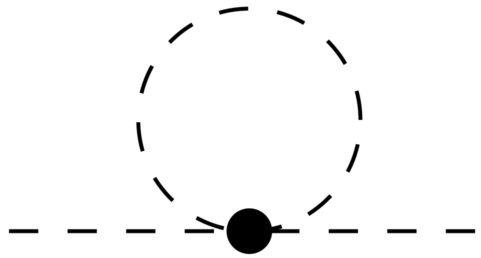
$\mathcal{L}_2$: The EW scale. $\mu^2 \ll M_{Pl}^2$.

the EW hierarchy problem

$\mathcal{L}_2$: The EW scale. $\mu^2 \ll M_{Pl}^2$.

the EW hierarchy problem

- Quadratic sensitivity to the heavy mass thresholds



$\lambda_S |H|^2 |S|^2$

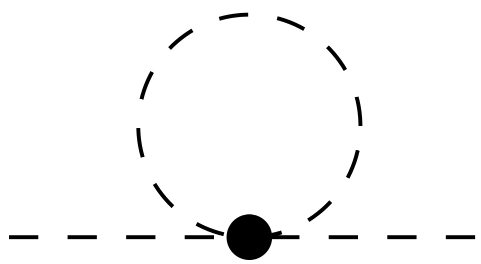
A heavy mass threshold

$$\delta\mu^2 \propto \frac{\lambda_S}{16\pi^2} M_S^2$$

$\mathcal{L}_2$: The EW scale. $\mu^2 \ll M_{Pl}^2$.

the EW hierarchy problem

- Quadratic sensitivity to the heavy mass thresholds

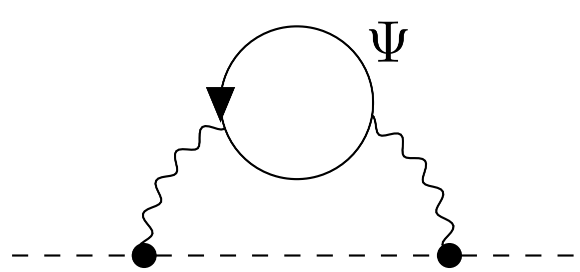


$\lambda_S |H|^2 |S|^2$

A heavy mass threshold

$$\delta\mu^2 \propto \frac{\lambda_S}{16\pi^2} M_S^2$$

- ***Highly contagious***: Something coupled to something coupled to Higgs…



$\longrightarrow$

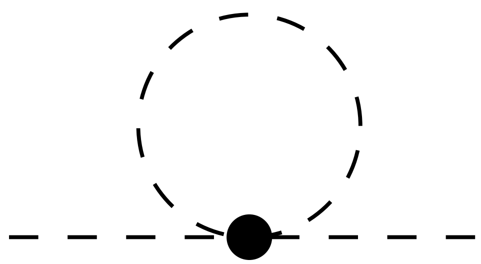
A heavy mass threshold

$$\delta\mu^2 \propto \frac{g_{SM}^4}{(16\pi^2)^2} m_\Psi^2$$

$\mathcal{L}_2$: The EW scale. $\mu^2 \ll M_{Pl}^2$.

the EW hierarchy problem

- Quadratic sensitivity to the heavy mass thresholds

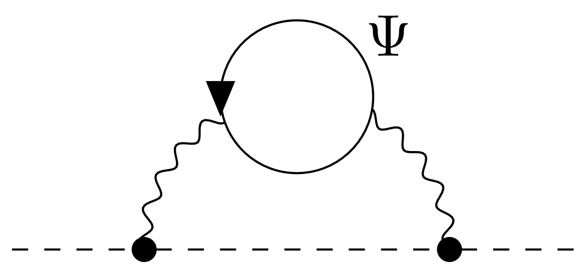


$\lambda_S |H|^2 |S|^2$

$$\delta\mu^2 \propto \frac{\lambda_S}{16\pi^2} M_S^2$$

A heavy mass threshold

- ***Highly contagious***: Something coupled to something coupled to Higgs…



$$\rightarrow \quad \delta\mu^2 \propto \frac{g_{SM}^4}{(16\pi^2)^2} m_\Psi^2$$

A heavy mass threshold

[Motivates NP; traditional solutions are TeV-scale]

$g_S \sim 1,\ g_W \sim 0.6,\ g_Y \sim 0.3,\ \lambda_H \sim 0.2$

$\mathcal{L}_4$: seen [$\theta G\tilde{G}$ exception, $\theta < 10^{-10}$; axion]

$y_e \sim 10^{-6}$ . . . $y_t \sim 1$

the flavor puzzle

$g_S \sim 1,\, g_W \sim 0.6,\, g_Y \sim 0.3,\, \lambda_H \sim 0.2$

$\mathcal{L}_4$: seen [$\theta G\tilde{G}$ exception, $\theta < 10^{-10}$; axion]

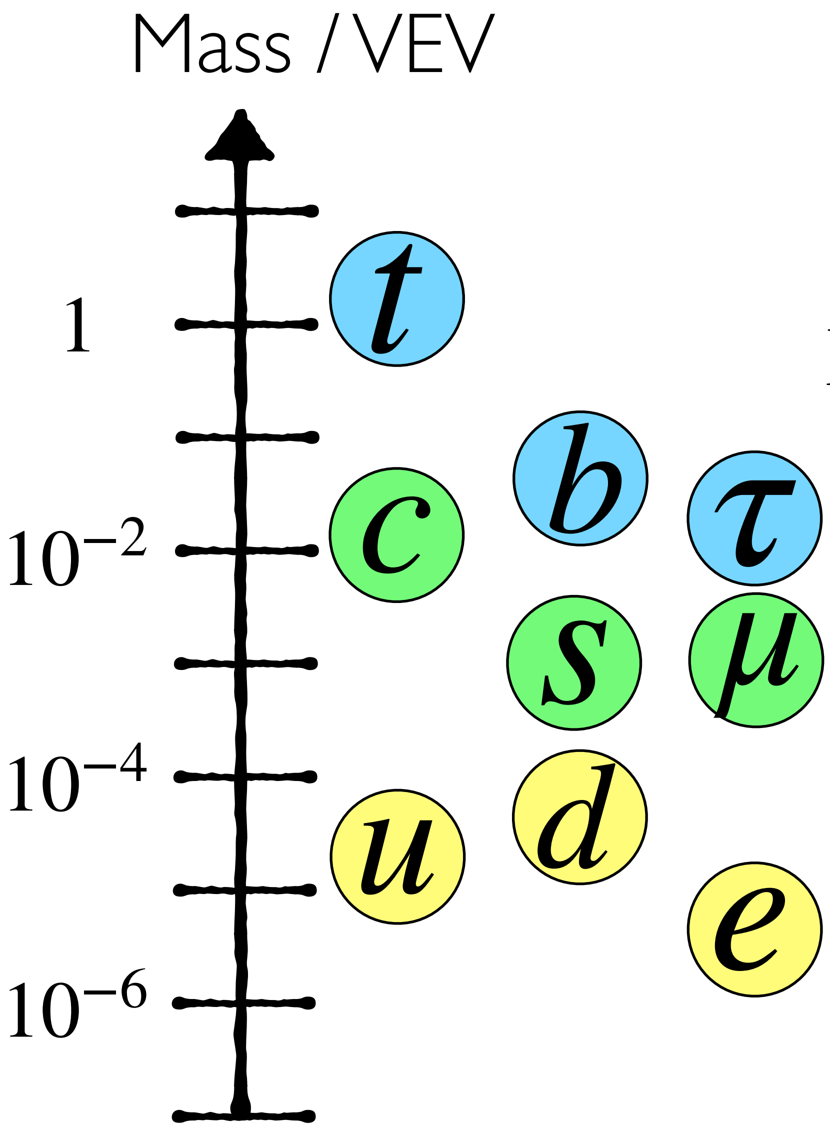
$y_e \sim 10^{-6} \quad \ldots \quad y_t \sim 1$

the flavor puzzle

- Yukawa sector

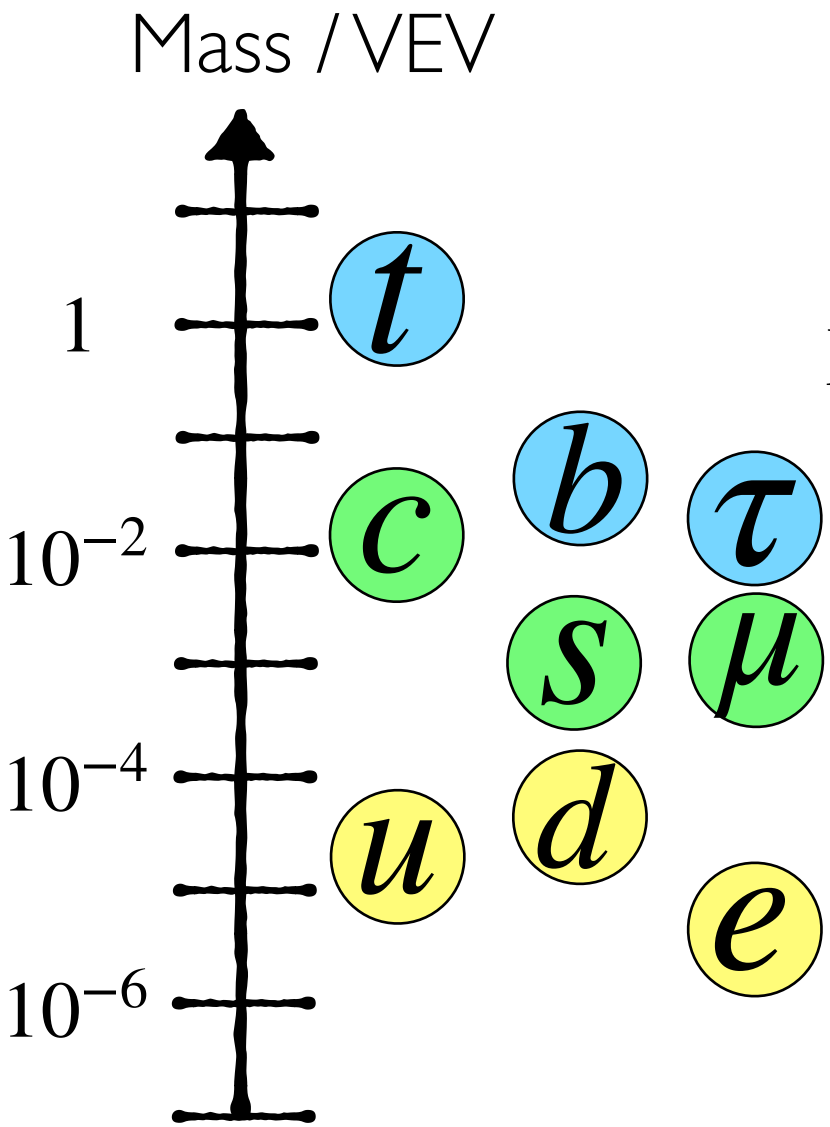
$$-\mathscr{L}_{\text{Yuk}} = \bar{q}Y^u\tilde{H}U + \bar{q}Y^dHD + \bar{l}Y^eHE$$

Flavour breaking + EWSB $\Longrightarrow$
Fermion masses and mixings



Hierarchy

Y^u, Y^d, Y^e



Hierarchy

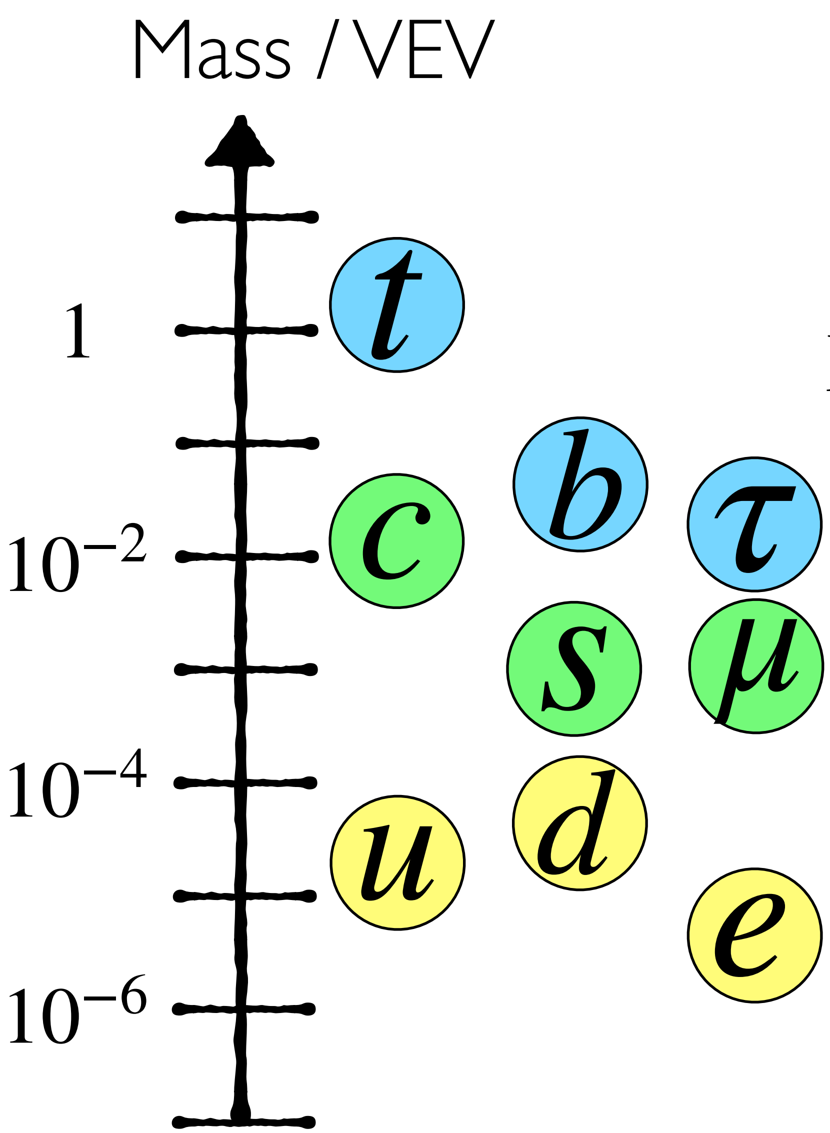
Y^u, Y^d, Y^e

The CKM mixing

$$V_{CKM} \sim \begin{bmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{bmatrix}$$

Alignment

Y^u & Y^d



Hierarchy

Y^u, Y^d, Y^e

The CKM mixing

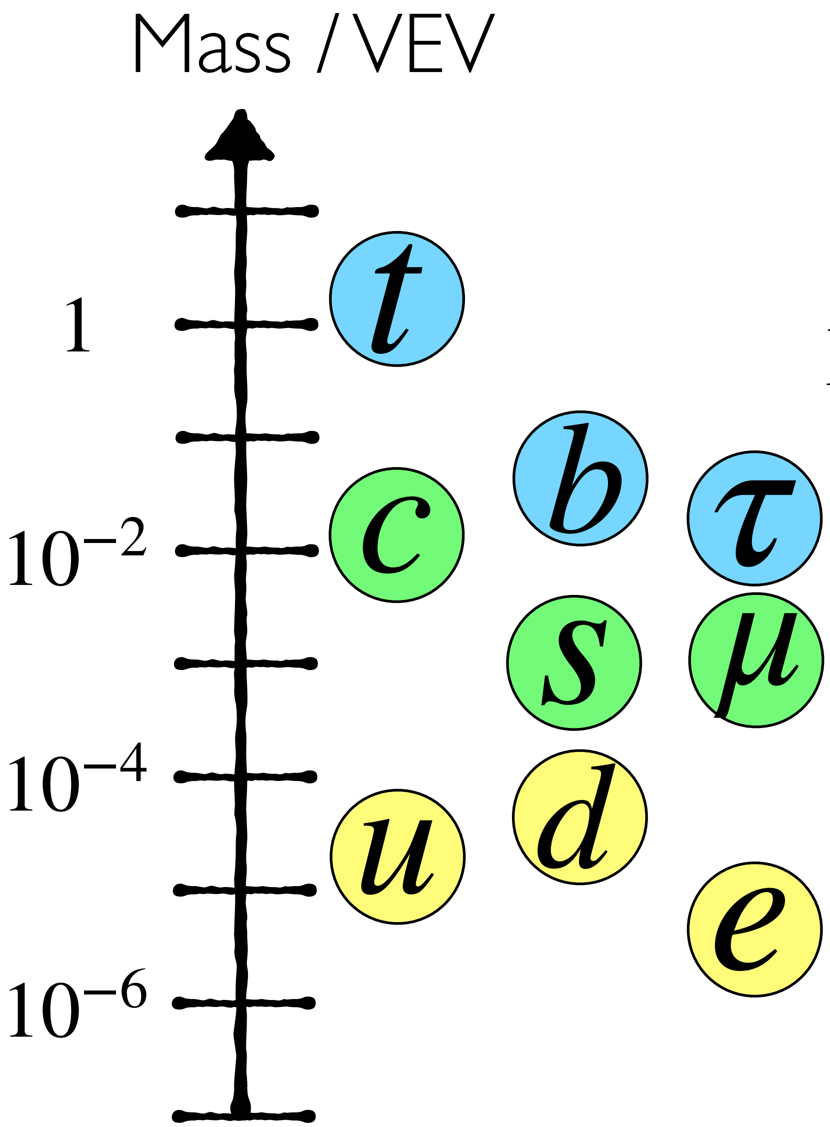
$$V_{CKM} \sim \begin{bmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{bmatrix}$$

Alignment

Y^u & Y^d

$$\det[Y^d Y^{d\dagger}, Y^u Y^{u\dagger}] \approx \mathcal{O}(10^{-22})$$

[Suppressed CPV]



Hierarchy

Y^u, Y^d, Y^e

The CKM mixing

$$V_{CKM} \sim \begin{bmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{bmatrix}$$

Alignment

Y^u & Y^d

$$\det[Y^d Y^{d\dagger}, Y^u Y^{u\dagger}] \approx \mathcal{O}(10^{-22})$$

[Suppressed CPV]

? **The SM flavour puzzle**

[Motivates NP]

The Standard Model

- Truncation at the $[\mathscr{L}_{\text{SM}}] \leq 4$. Valid for $E \ll \Lambda_{\text{Cutoff}}$.

- IR relevance $\Longrightarrow$ Accidental global symmetries

$$G^{\text{SM}}_{\text{global}}(Y^{u,d,e} \neq 0) = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

[Suppresses proton decay & charged-lepton FV]

- Accidental symmetries are broken by the irrelevant couplings.

- ***Next***: Irrelevant couplings…

$\mathcal{L}_5$: (likely)* seen

*Tiny neutrino mass explained

The first indication of new scale beyond EW ?

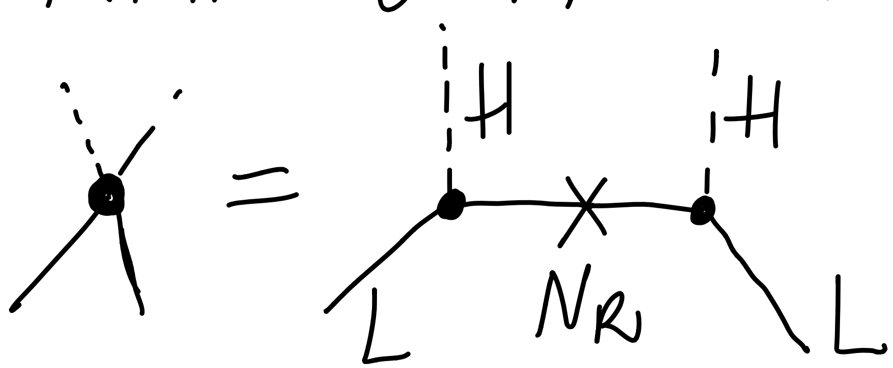
$$\frac{1}{\Lambda}(LH)^2$$

$\mathcal{L}_5$: (likely)* seen

*Tiny neutrino mass explained

The first indication of new scale beyond EW?

Minimal model:



$$m_\nu \sim Y_\nu^2 \frac{v^2}{M_R} \quad \text{type-I}$$

$$Y_\nu \sim y_e \Rightarrow M_R \sim 10 \text{ TeV}$$

$$Y_\nu \sim y_t \Rightarrow M_R \sim 10^{12} \text{ TeV}$$

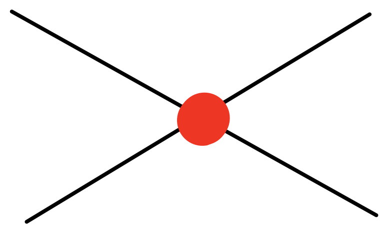
$\mathcal{L}_6$: Muon anomalies

The first indication of a new scale after neutrino oscillations ?

Muon anomalies: **SMEFT picture**

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

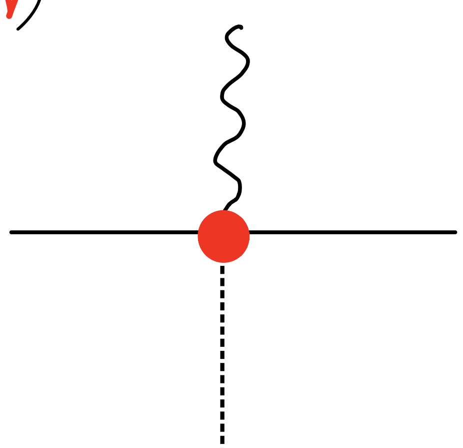
$R(K)$:



*super-weak/irrelevant couplings

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

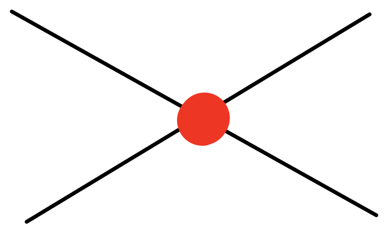
$(g-2)_\mu$:



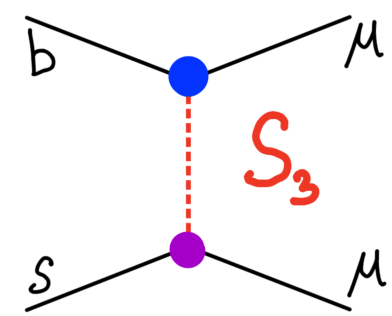
Muon anomalies: **Leptoquarks**

$R(K)$:

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



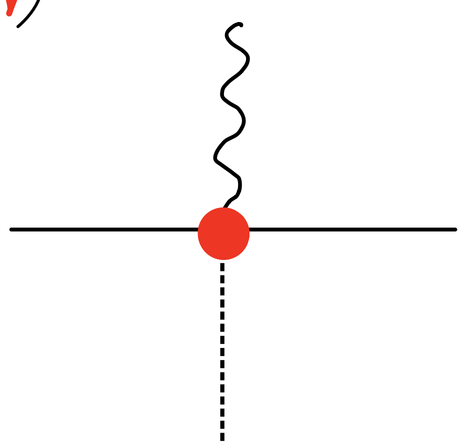
$\longleftarrow$



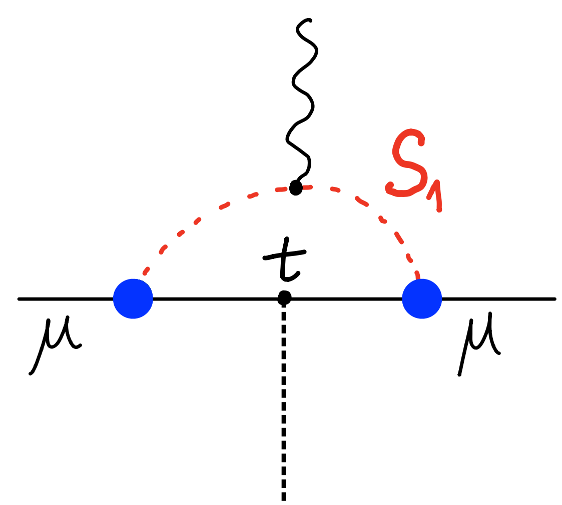
$Q = \begin{pmatrix} u_L \\ V^{CKM} d_L \end{pmatrix}$ $= \times V_{ts}^{CKM}$

$(g-2)_\mu$:

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



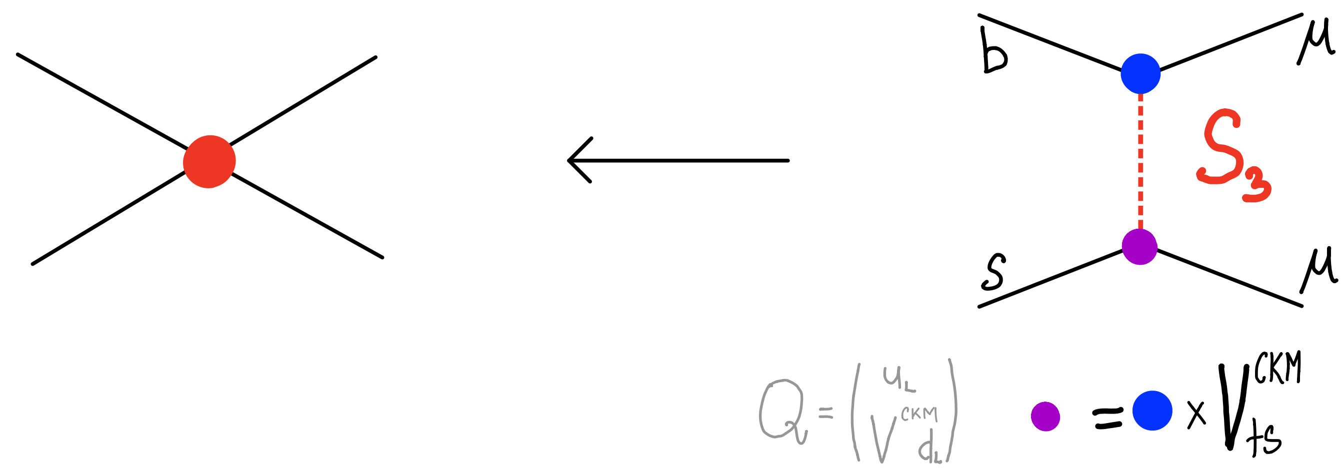
$\longleftarrow$

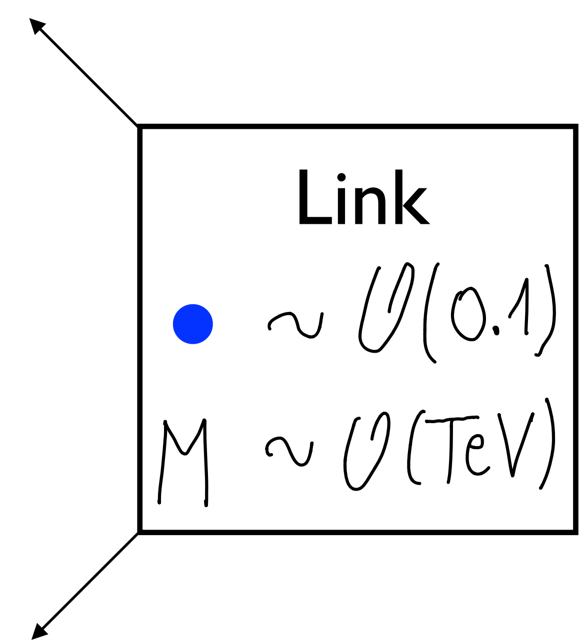


Muon anomalies: **Leptoquarks**

$R(K)$:

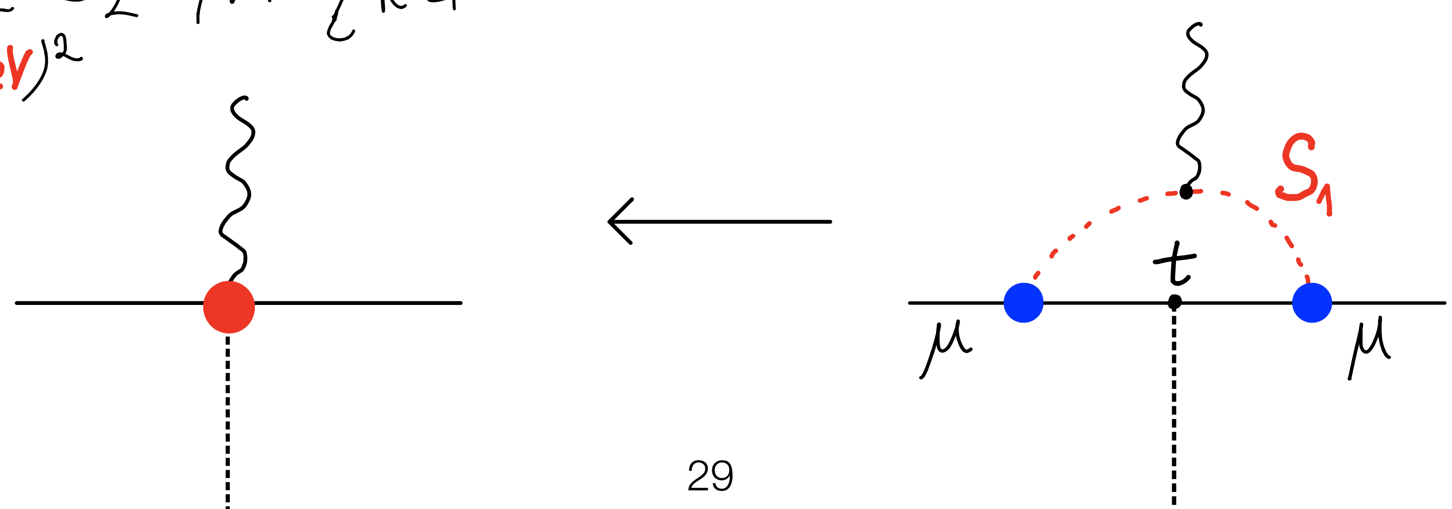
$$\frac{1}{(10\,\text{TeV})^2}\, Q_3 Q_3 L_2 L_2$$





$(g-2)_\mu$:

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



Why people object about TeV-scale Leptoquarks?

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

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

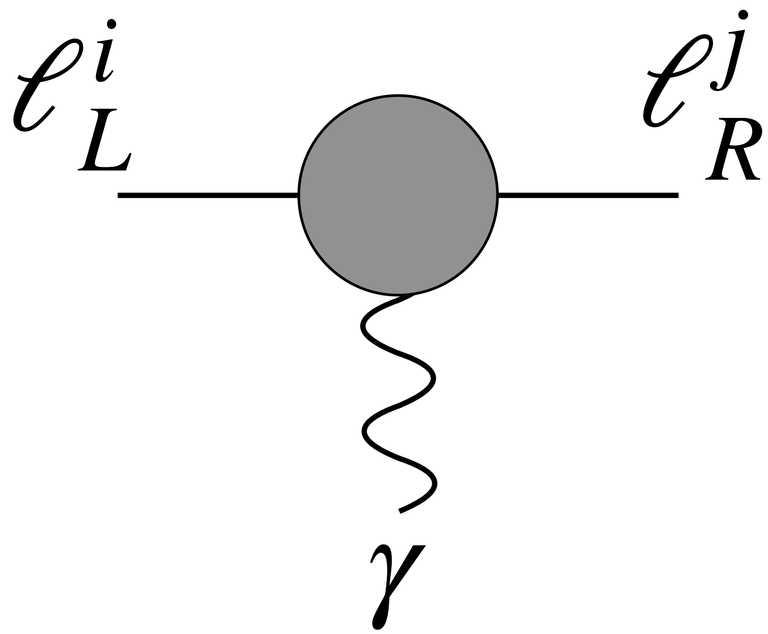
- Abrupt violation of the SM accidental symmetries $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Proton decay $[z \cdot y]$ probes scales up to 10^{13} TeV

$\mu \to e \gamma$ $[i \neq j]$ probes scales up to 10^{5} TeV

Electron EDM $[\mathrm{Im}\, y]$ probes scales up to 10^{6} TeV

Charged-lepton flavor violation



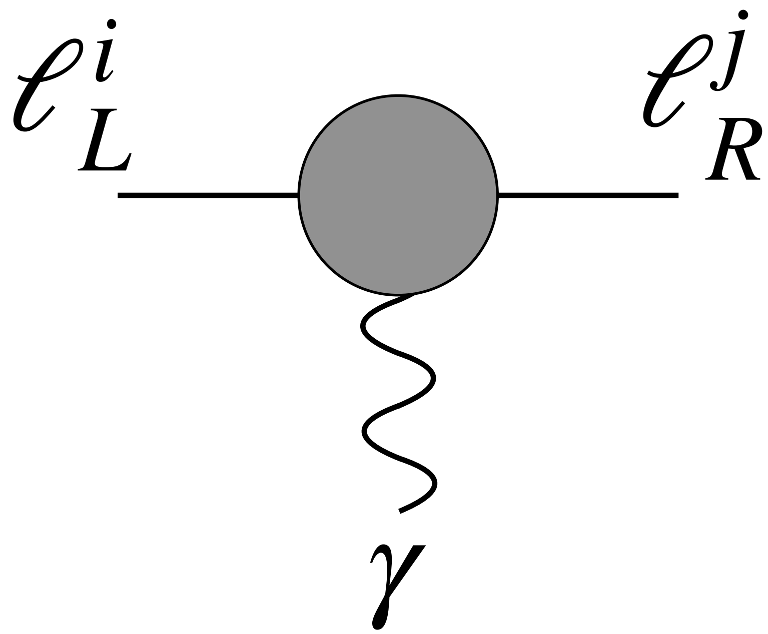
$$\frac{Br(\mu \to e\gamma)}{3 \times 10^{-13}} \approx \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{12}}{10^{-5}}\right)^2$$

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

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

Almost exact lepton flavor symmetry

Charged-lepton flavor violation



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

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

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

[AG, Stangl, Thomsen; 2103.13991]

- Lepton-flavor gauged $U(1)_X$:

Leptoquark ⇒ Muoquark

[AG, Stangl, Thomsen; 2103.13991]

- Scalar leptoquarks are charged under $U(1)_{X_\mu}$ gauge symmetry such that they interact with muons but not with electrons or taus.
- This ensures the accidental symmetries of the SM, even though the leptoquark is present.

[AG, Stangl, Thomsen; 2103.13991]

- Scalar leptoquarks are charged under $U(1)_{X_\mu}$ gauge symmetry such that they interact with muons but not with electrons or taus.

- This ensures the accidental symmetries of the SM, even though the leptoquark is present.

$$\mathcal{L} = - \eta_i^{3\mathrm{L}}\, \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2\, S_3 - \eta_i^{1\mathrm{L}} \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2 S_1 - \eta_i^{1\mathrm{R}} \overline{u}_{\mathrm{R}}^{c\,i} \mu_{\mathrm{R}} S_1$$

e.g. gauged $U(1)_{B-3L_\mu}$

- Accidental B-number, cLFC, no eEDM

The quark flavor structure

- The gauge symmetry fixes the lepton couplings of $S_{1,3}$ but not the quark.

The quark flavor structure

- The gauge symmetry fixes the lepton couplings of $S_{1,3}$ but not the quark.
- The SM has an approximate $U(2)_q \times U(2)_U \times U(2)_D$ quark flavor symmetry.
- The first two generations form a doublet while the third is a singlet.

The quark flavor structure

- The gauge symmetry fixes the lepton couplings of $S_{1,3}$ but not the quark.
- The SM has an approximate $U(2)_q \times U(2)_U \times U(2)_D$ quark flavor symmetry.
- The first two generations form a doublet while the third is a singlet.
- In the limit of an exact $U(2)$, only the top and the bottom quarks are massive and the CKM matrix is identity - an excellent starting point.

The quark flavor structure

- The gauge symmetry fixes the lepton couplings of $S_{1,3}$ but not the quark.
- The SM has an approximate $U(2)_q \times U(2)_U \times U(2)_D$ quark flavor symmetry.
- The first two generations form a doublet while the third is a singlet.
- In the limit of an exact $U(2)$, only the top and the bottom quarks are massive and the CKM matrix is identity - an excellent starting point.
- The minimal breaking needed to fit the quark masses and mixing consists of spurions: $V = (\mathbf{2}, \mathbf{1}, \mathbf{1})$, $\Delta_u = (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})$ and $\Delta_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$

$$V = (V_{td}, V_{ts})^{\mathrm{T}}$$

See PRISMA+ Colloquium by Fuentes-Martin

The quark flavor structure

- The gauge symmetry fixes the lepton couplings of $S_{1,3}$ but not the quark.
- The SM has an approximate $U(2)_q \times U(2)_U \times U(2)_D$ quark flavor symmetry.
- The first two generations form a doublet while the third is a singlet.
- In the limit of an exact $U(2)$, only the top and the bottom quarks are massive and the CKM matrix is identity - an excellent starting point.
- The minimal breaking needed to fit the quark masses and mixing consists of spurions: $V = (\mathbf{2}, \mathbf{1}, \mathbf{1})$, $\Delta_u = (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})$ and $\Delta_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$

$$V = (V_{td}, V_{ts})^{\mathrm{T}}$$

See PRISMA+ Colloquium by Fuentes-Martin

- Let's assume the muoquark interactions $\mathscr{L} \supset \eta_i Q^i \mu S$ respect the same rules:

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

A muoquark solution of muon anomalies

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

- Global fit
  - 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.

Greljo, Stangl, Thomsen, 2103.13991

A muoquark solution of muon anomalies

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

- Global fit
  - 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.

FIG. 1. The preferred muoquark Yukawa couplings from the global fit to low-energy data. Here we choose $\eta_i^{3\mathrm{L}} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{3\mathrm{L}}$, $\eta_i^{1\mathrm{L}} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{1\mathrm{L}}$, and $\eta_i^{1\mathrm{R}} = (0,\, 0,\, 1)\, \eta_3^{1\mathrm{R}}$. The muoquark masses are set to $M_1 = M_3 = 3\,\mathrm{TeV}$.

Greljo, Stangl, Thomsen, 2103.13991

A muoquark solution of muon anomalies

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

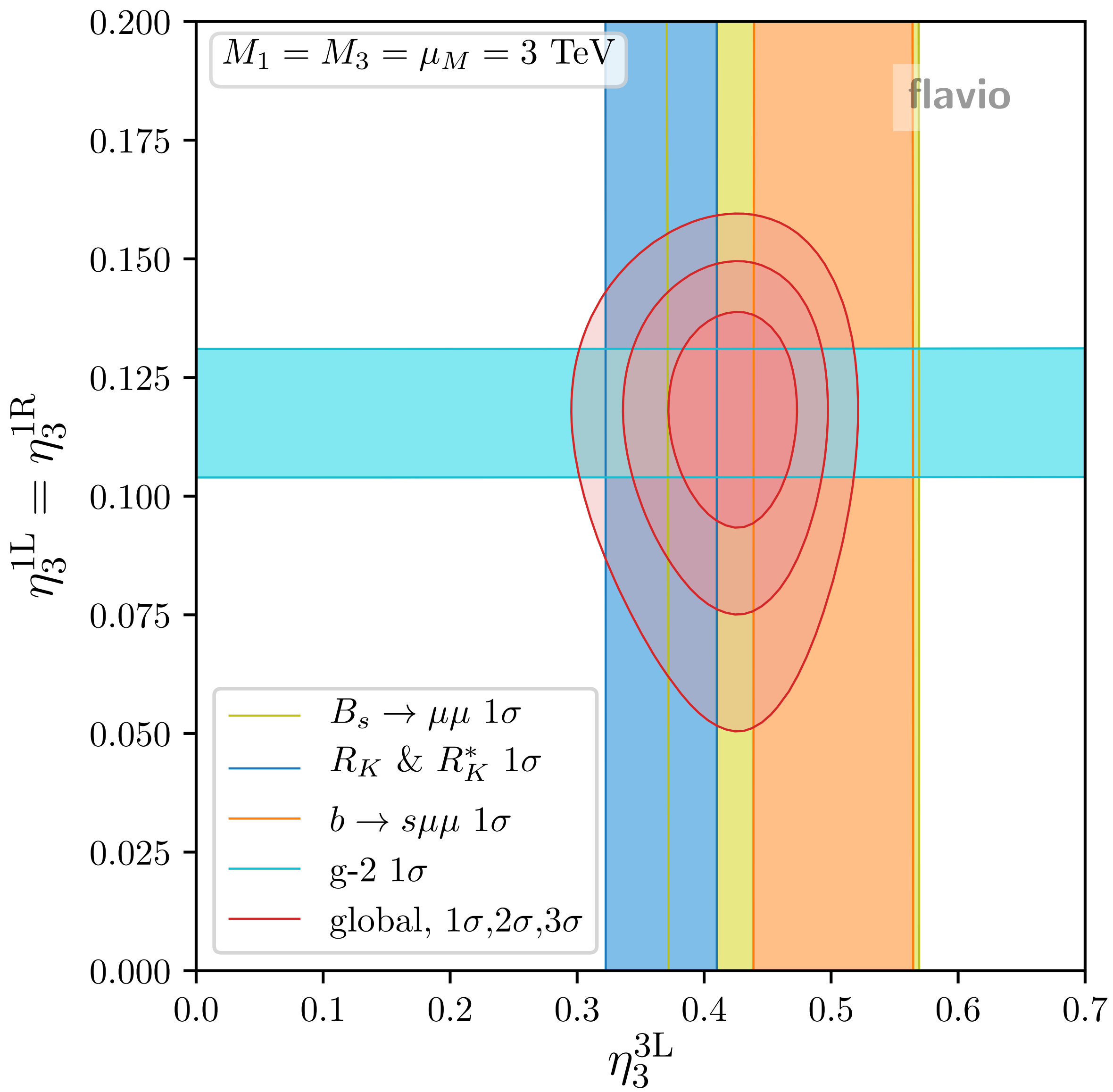


FIG. 1. The preferred muoquark Yukawa couplings from the global fit to low-energy data. Here we choose $\eta_i^{3\mathrm{L}} = (V_{td}, V_{ts}, 1)\,\eta_3^{3\mathrm{L}}$, $\eta_i^{1\mathrm{L}} = (V_{td}, V_{ts}, 1)\,\eta_3^{1\mathrm{L}}$, and $\eta_i^{1\mathrm{R}} = (0, 0, 1)\,\eta_3^{1\mathrm{R}}$. The muoquark masses are set to $M_1 = M_3 = 3$ TeV.

- Global fit
  - 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.

Greljo, Stangl, Thomsen, 2103.13991

A muoquark solution of muon anomalies

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

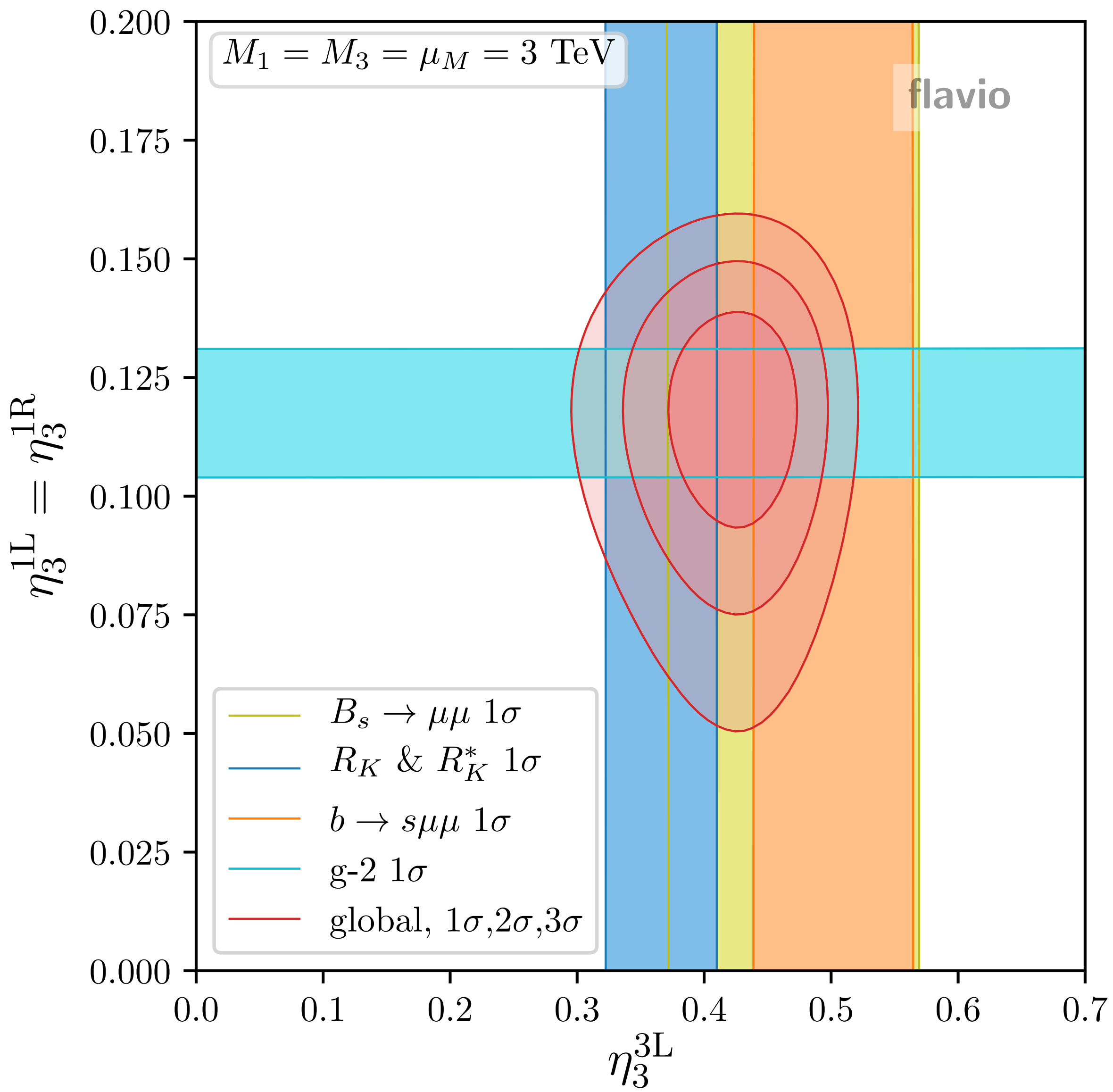


FIG. 1. The preferred muoquark Yukawa couplings from the global fit to low-energy data. Here we choose $\eta_i^{3\mathrm{L}} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{3\mathrm{L}}$, $\eta_i^{1\mathrm{L}} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{1\mathrm{L}}$, and $\eta_i^{1\mathrm{R}} = (0,\, 0,\, 1)\, \eta_3^{1\mathrm{R}}$. The muoquark masses are set to $M_1 = M_3 = 3\,\mathrm{TeV}$.

- Global fit
  - 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.

- $\Delta\chi^2 = 62$

- No tension with complementary data
  - When varying $\mathcal{O}(1)$ in front of the spurions
  - Linear coupling vs mass rescaling

- Collider constraints

  $M_1 > 1.4\,\mathrm{TeV}$ ATLAS $\quad M_3 > 1.7\,\mathrm{TeV}$ ATLAS

Greljo, Stangl, Thomsen, 2103.13991

The scalar potential

- The spontaneous symmetry breaking

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

- H break EW, while the SM singlet Φ breaks $U(1)_X$.

The scalar potential

- The spontaneous symmetry breaking

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

- H break EW, while the SM singlet Φ breaks $U(1)_X$.
- In the limit $g_X \to 0$ and/or $v_\Phi \to \infty$ is the decoupling of $U(1)_X$ sector.

The scalar potential

- The spontaneous symmetry breaking

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

- H break EW, while the SM singlet Φ breaks $U(1)_X$.
- In the limit $g_X \to 0$ and/or $v_\Phi \to \infty$ is the decoupling of $U(1)_X$ sector.
- The rest of the potential:

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

The scalar potential

- The spontaneous symmetry breaking

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

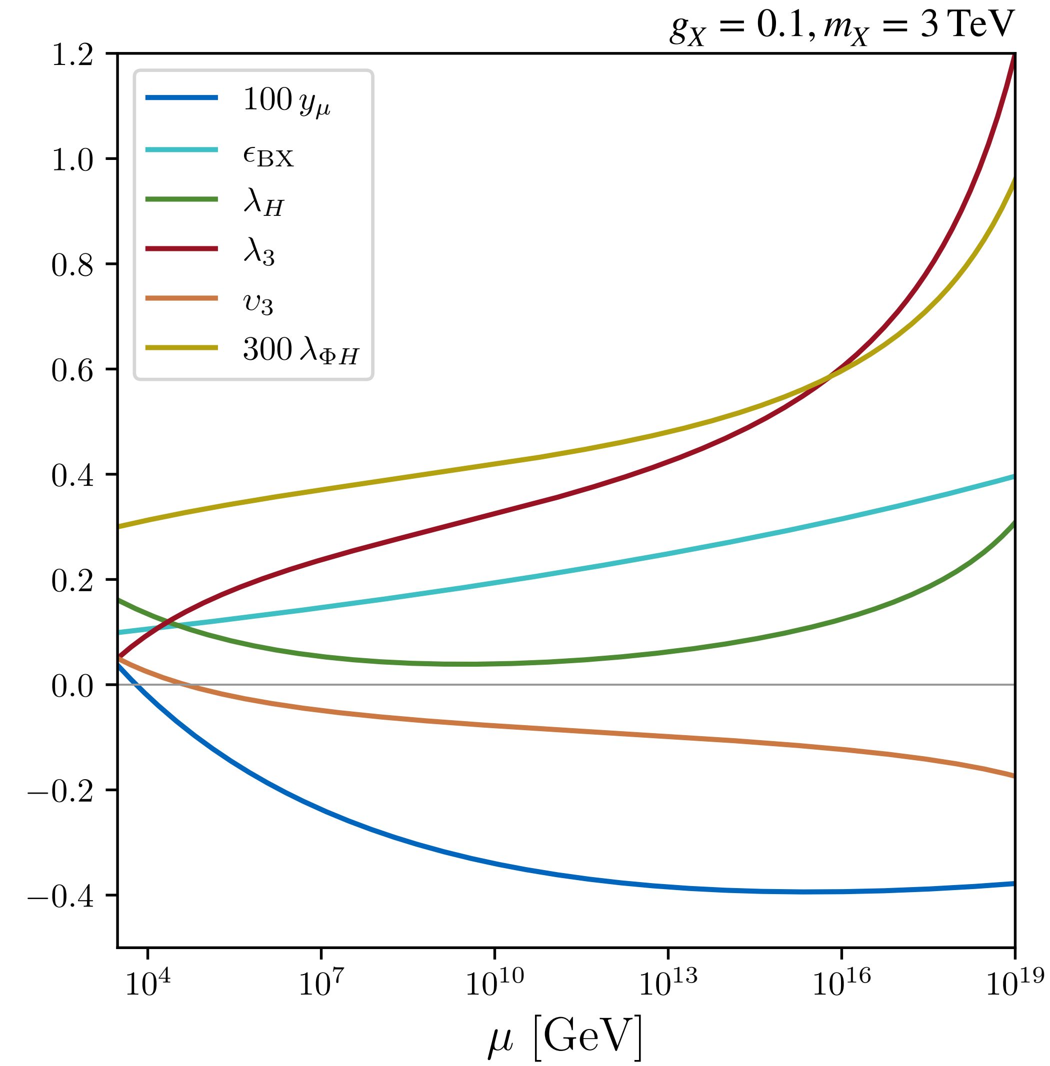
- H break EW, while the SM singlet Φ breaks $U(1)_X$.
- In the limit $g_X \to 0$ and/or $v_\Phi \to \infty$ is the decoupling of $U(1)_X$ sector.
- The rest of the potential:

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

- The RGE of the benchmark point

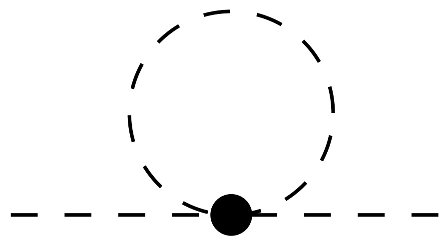
  - Two loop Yukawa and quartic, three loop gauge (**RGBeta** 2101.08265)

- In this benchmark
  - No Landau poles up to the Planck
  - The potential is stable - ll-



Finite naturalness

- The Higgs mass

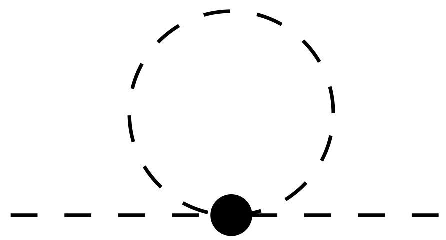


$$\delta\mu_H^2 = -\frac{9(\lambda_{H3}+\kappa_{H3})}{(4\pi)^2} M_3^2 \left(1 + \ln\frac{\mu_M^2}{M_3^2}\right) + \frac{3\lambda_{H1}}{(4\pi)^2} M_1^2 \left(1 + \ln\frac{\mu_M^2}{M_1^2}\right) + \mathcal{O}(\mu^4/M_{1,3}^2)$$

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

Finite naturalness

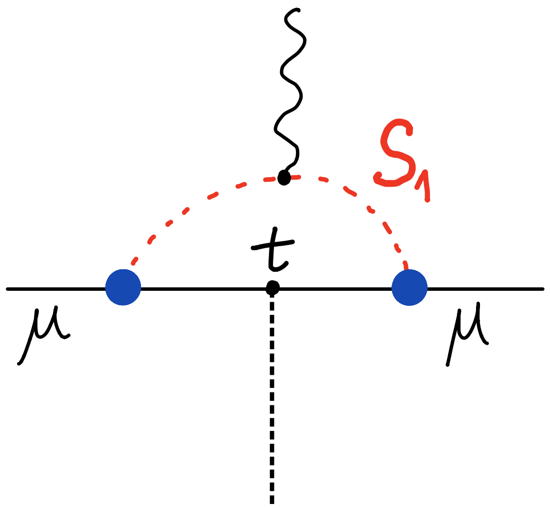
- The Higgs mass



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

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

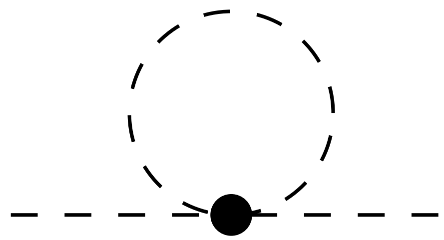
$$\delta y_\mu = -\frac{3}{(4\pi)^2}\left(1+\ln\frac{\mu_M^2}{M_1^2}\right)\eta_i^{1L*}y_u^{ij}\eta_j^{1R}$$

- $(g-2)_\mu$ requires larger couplings for heavier leptoquark

- No tuning only if $M_{1,3} \lesssim$ a few TeV, see also the RG flow

Finite naturalness

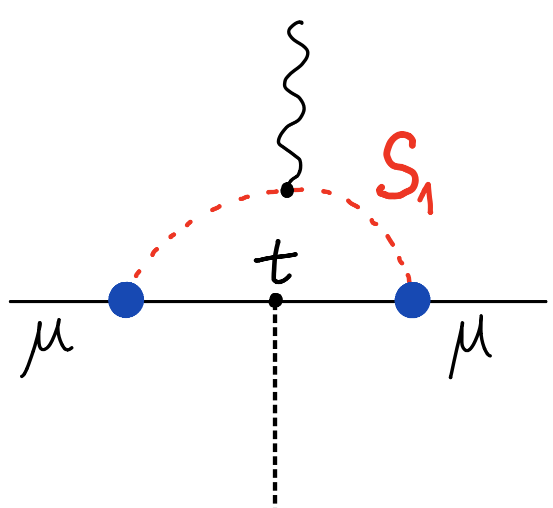
- The Higgs mass



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

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

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.

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

    $$\cancel{QQS_3^\dagger} \quad \cancel{QQS_3^\dagger \phi^\dagger}$$

- 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.

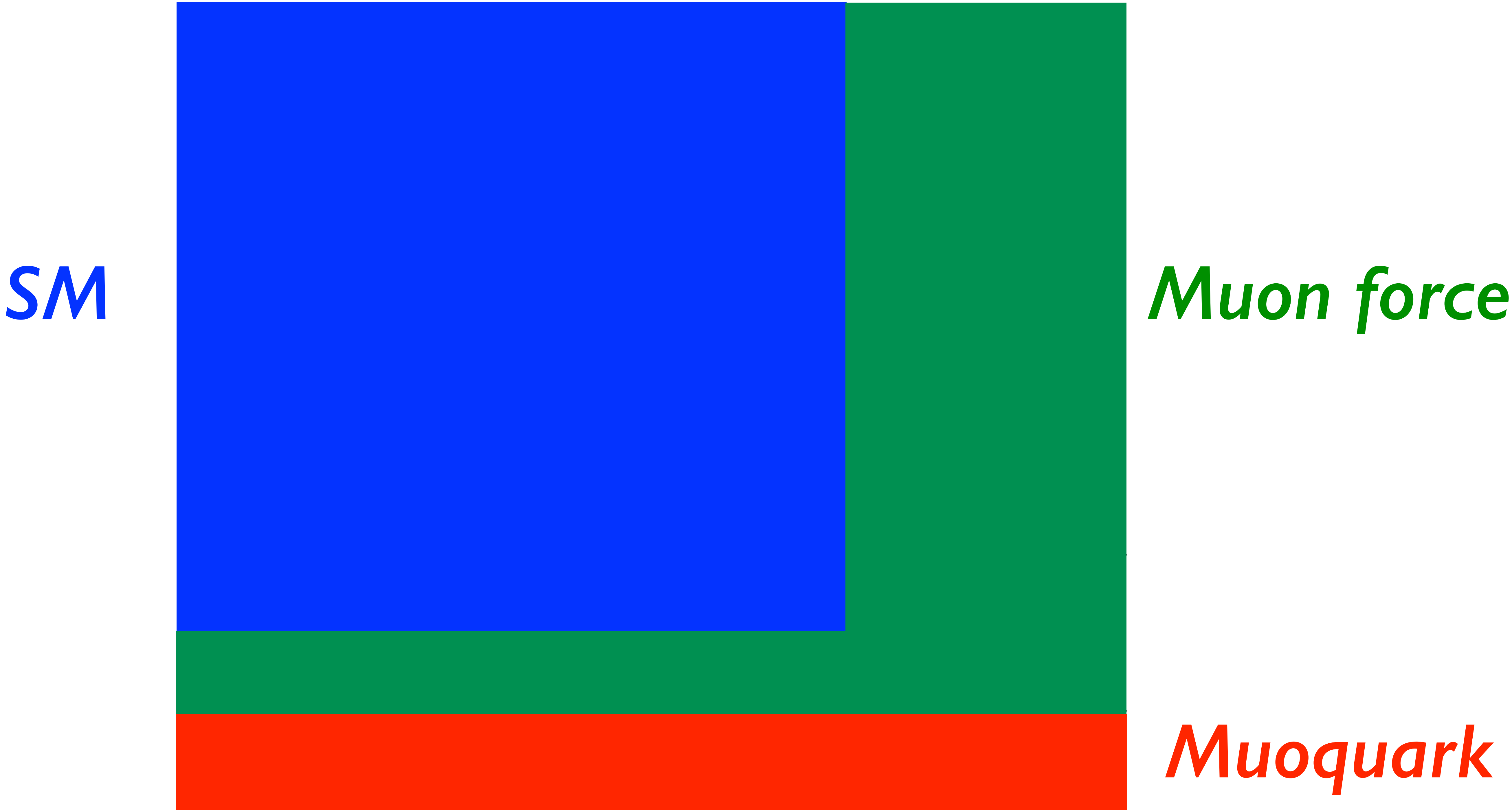
Do we have to decouple $U(1)_{X_\mu}$?

No!

A **minimal** model example

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

Greljo, Stangl, Thomsen, 2103.13991



A **minimal** model example

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

Greljo, Stangl, Thomsen, 2103.13991

SM

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
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

Muon force

Muoquark

A **minimal** model example

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

Greljo, Stangl, Thomsen, 2103.13991

SM

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-3L_\mu}$
Q_L	**3**	**2**	$1/6$	$1/3$
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

A **minimal** model example

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

Greljo, Stangl, Thomsen, 2103.13991

SM

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-3L_\mu}$
Q_L	**3**	**2**	$1/6$	$1/3$
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
S_3	$\bar{\mathbf{3}}$	**3**	$1/3$	$8/3$

Muon force

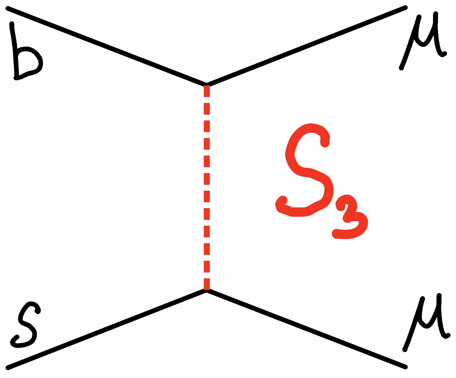
Muoquark

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

A **minimal** model example

Muoquark

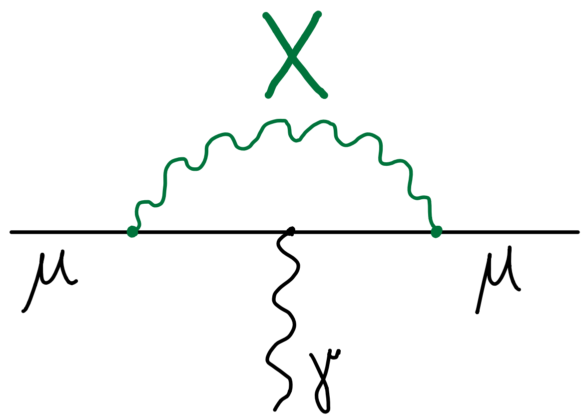
$R(K)$:



A **minimal** model example

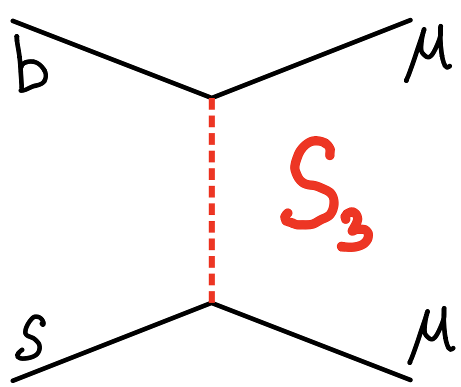
Muon force

$(g-2)_\mu$:



Muoquark

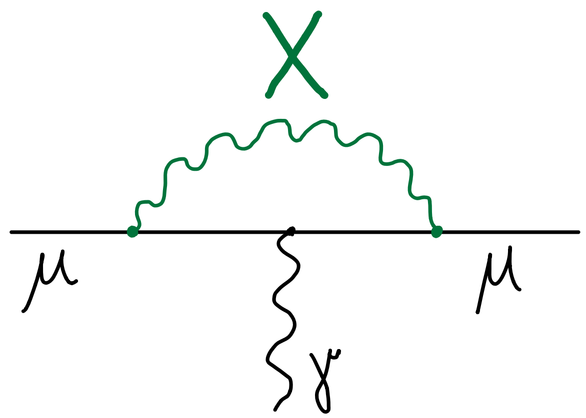
$R(K)$:



A **minimal** model example

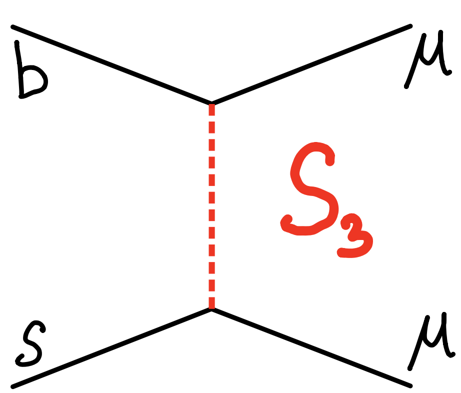
Muon force

$(g-2)_\mu$:

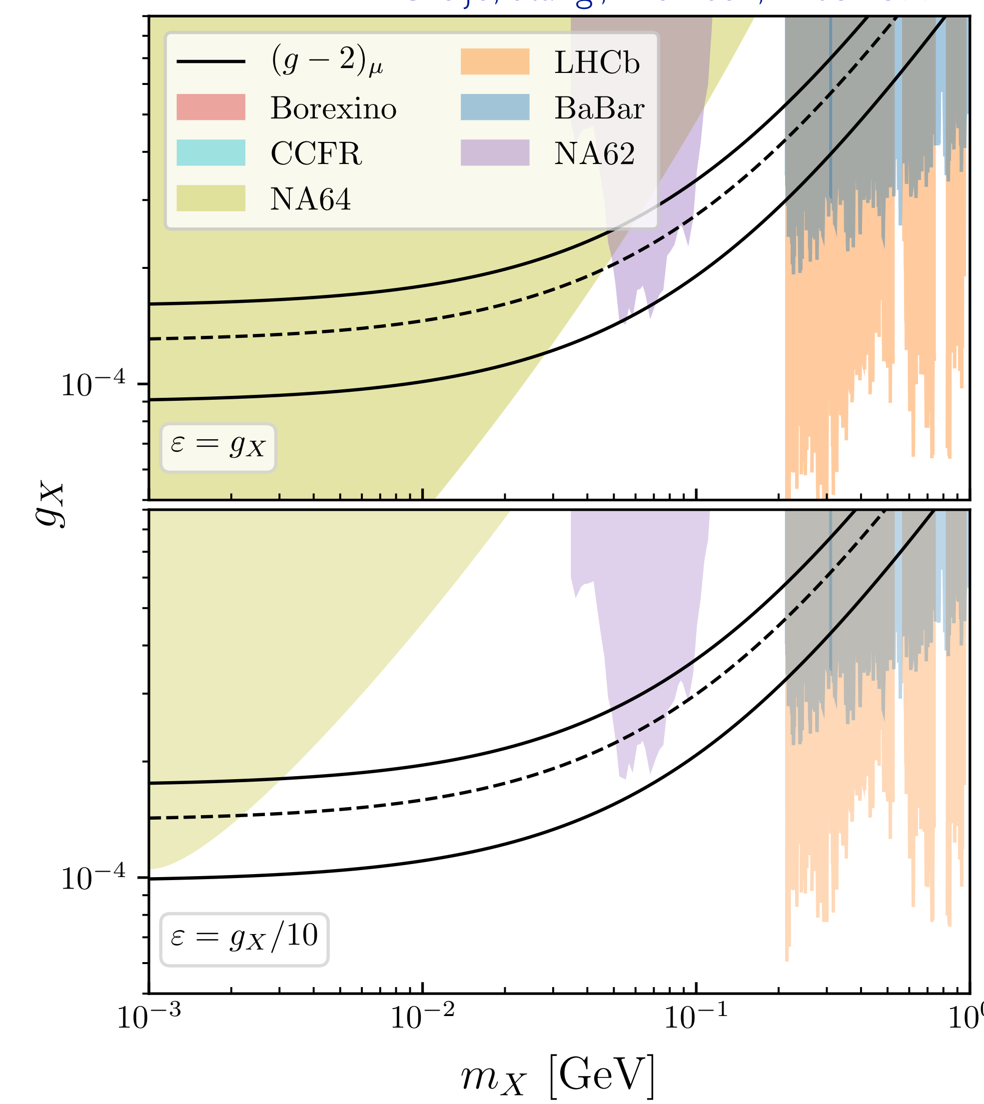


Muoquark

$R(K)$:



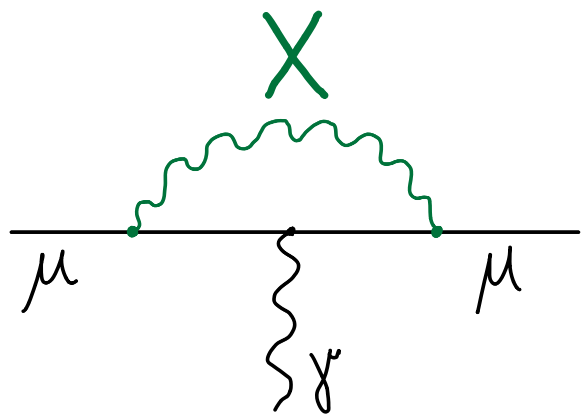
Greljo, Stangl, Thomsen, 2103.13991



A **minimal** model example

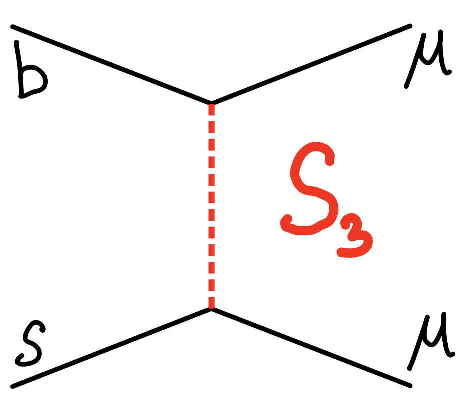
Muon force

$(g-2)_\mu$:

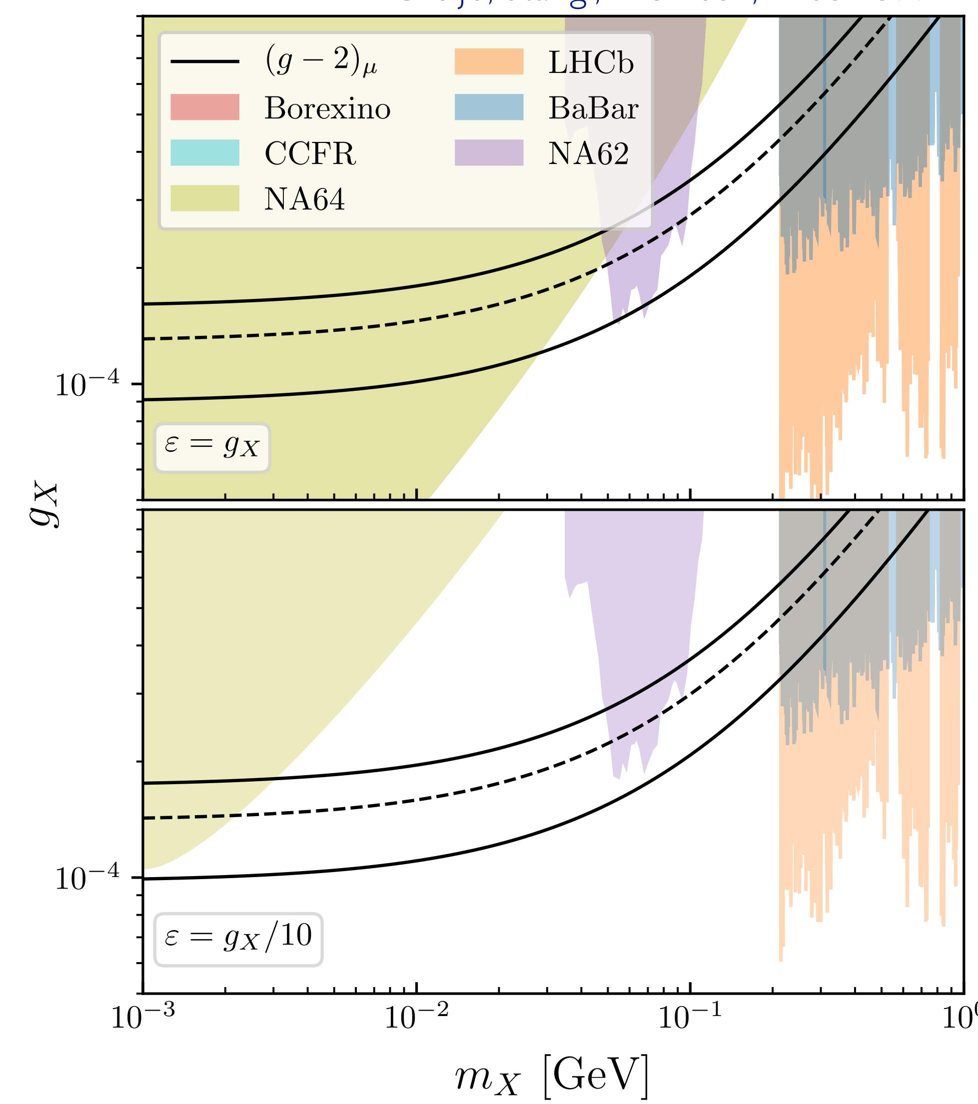


Muoquark

$R(K)$:



Greljo, Stangl, Thomsen, 2103.13991



- A robust muon bound:
  $N\nu_\mu \to N\nu_\mu\mu\mu$ (CCFR) $m_X \lesssim 0.5\,\mathrm{GeV}$
- Electron bounds (Borexino, NA64):
  - From the running of a small kinetic mixing we observe $\epsilon \sim \mathcal{O}(g_X)$. Can be tuned away.
- Other constraints from **DarkCast** 1801.04847.
- The full $U(1)_{X_\mu}$ atlas, work in progress [AG,Stangl,Thomsen,Soreq,Zupan]

Implications for **Higgs physics: Muon force**

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

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

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

Implications for **Higgs physics: Muon force**

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

- 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.

Summary: Muoquark and a muon force

A sketch of a minimal structure:

		Type A	Type B	Type C
Tree-level	$R_{K^{(*)}}$, $b \to s\mu\mu$	S_3	S_3	heavy X
One-loop	$(g-2)_\mu$	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 $U(1)_X$ gauge groups.

Greljo, Stangl, Thomsen, 2103.13991

- Why is the muon special?
  I don't know.
  The model is an attempt to follow data, i.e., it is bottom-up motivated…