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Eccellenza, Project-186866

A model of muon anomalies

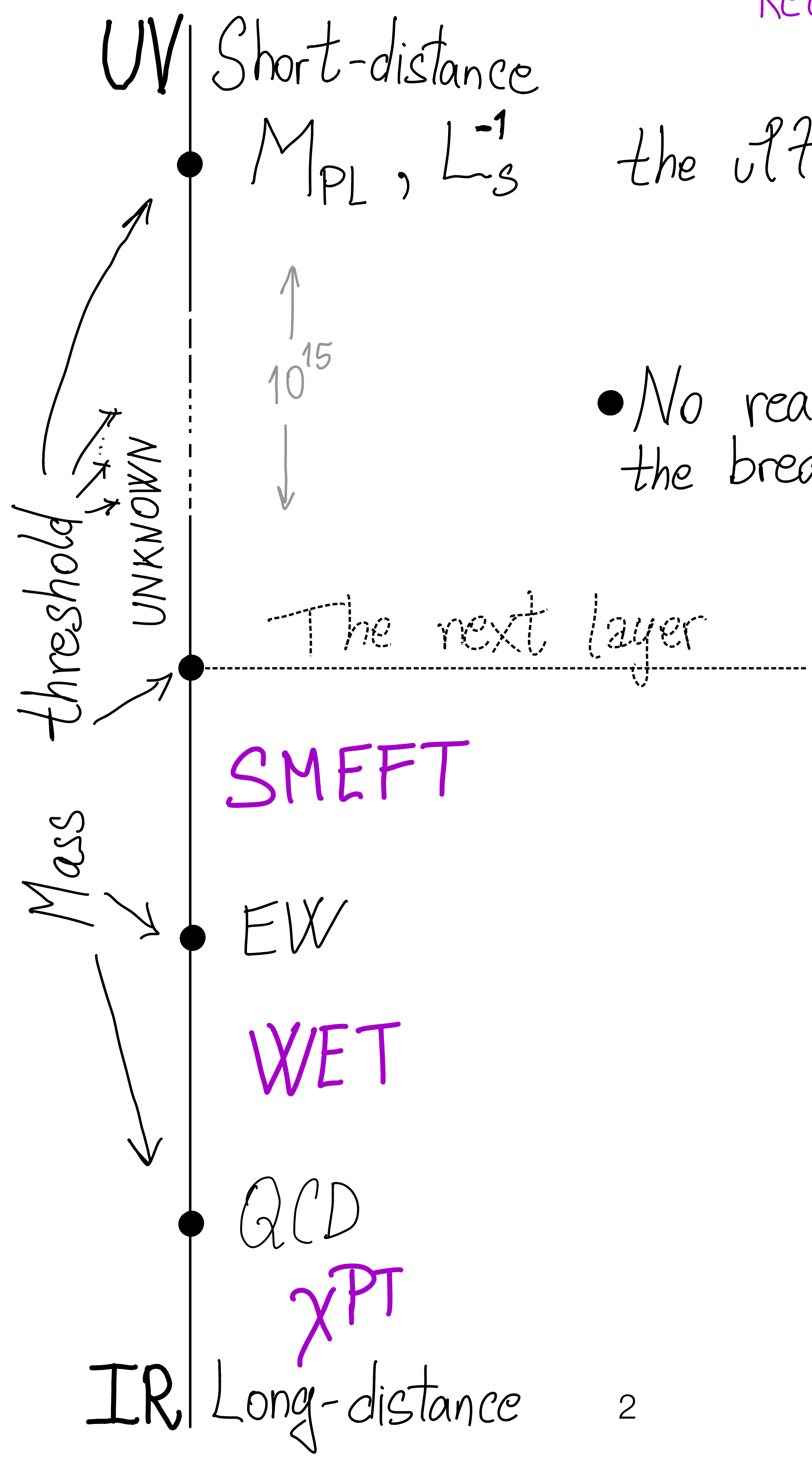
Admir Greljo

Recent R(K) update from the LHCb experiment at CERN reinforced the tension of B-meson decays into muons. The Muon g-2 experiment at Fermilab strengthened the tension in the muon anomalous magnetic moment. Can muon anomalies be coherently addressed in models beyond the SM, and if so, where else should we look for confirmation? I will discuss extensions of the SM based on 2103.13991 and some work in progress.

04.06.2021, Cambridge

Wilsonian QFT = the HEP paradigm

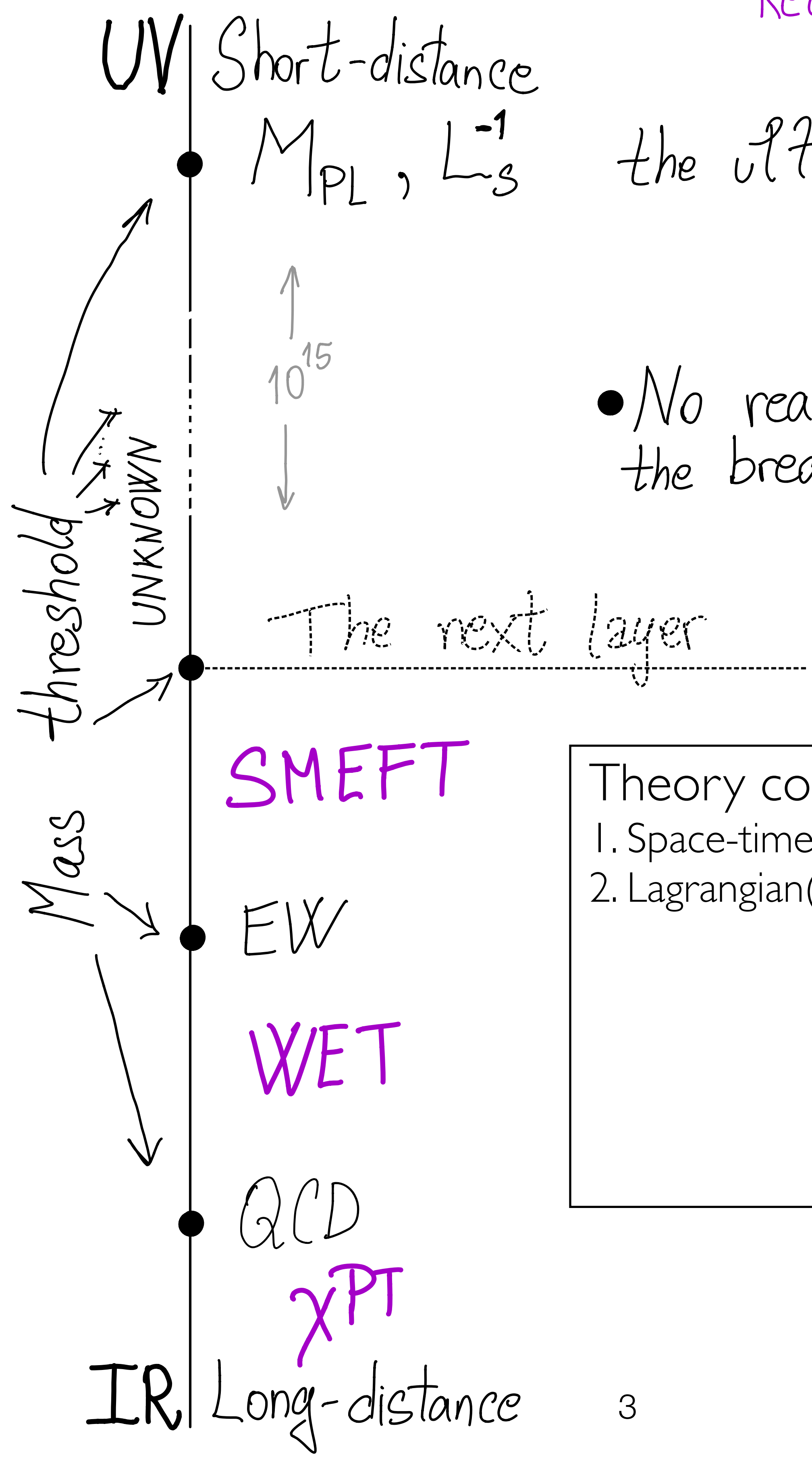
Reductionism



- No reason to expect the breakdown anytime soon

Wilsonian QFT = the HEP paradigm

Reductionism



the ultimate scale?

- No reason to expect the breakdown anytime soon

Theory construction:

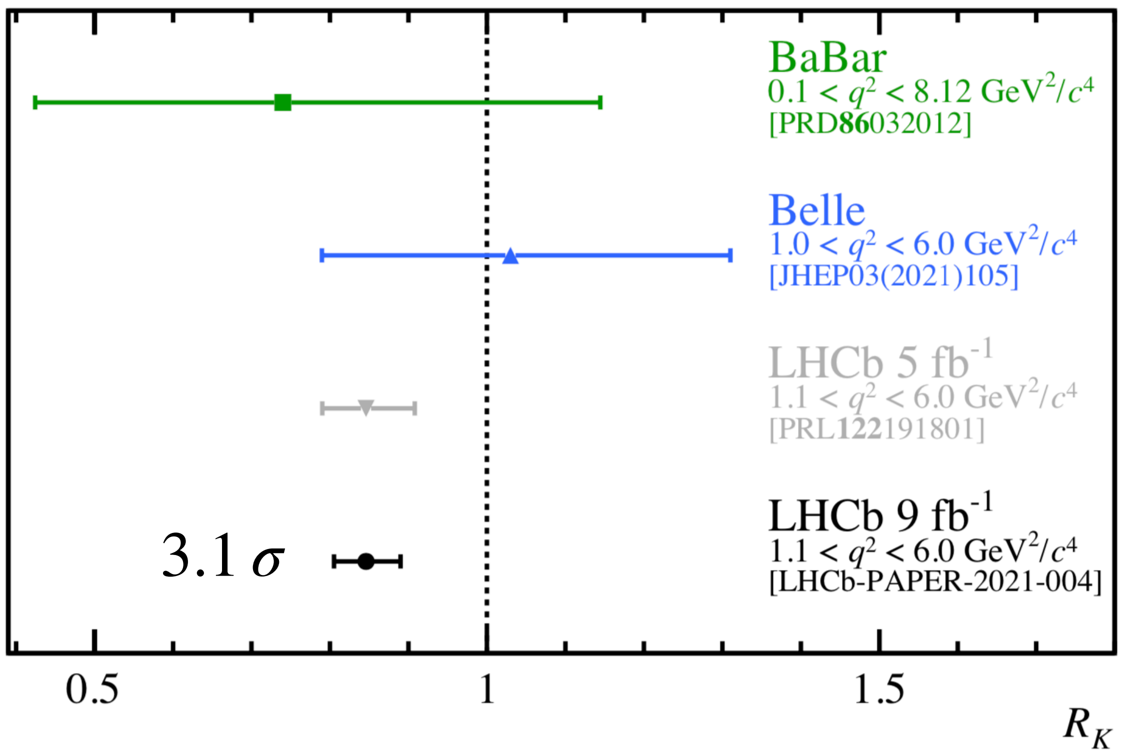
1. Space-time & gauge invariance + field content,
2. Lagrangian(x) = infinite polynomial in fields and derivatives,

$$\mathscr{L} = \sum c_{\mathcal{O}} \Lambda_{\mathcal{O}}^{4-\dim \mathcal{O}} \mathcal{O}$$

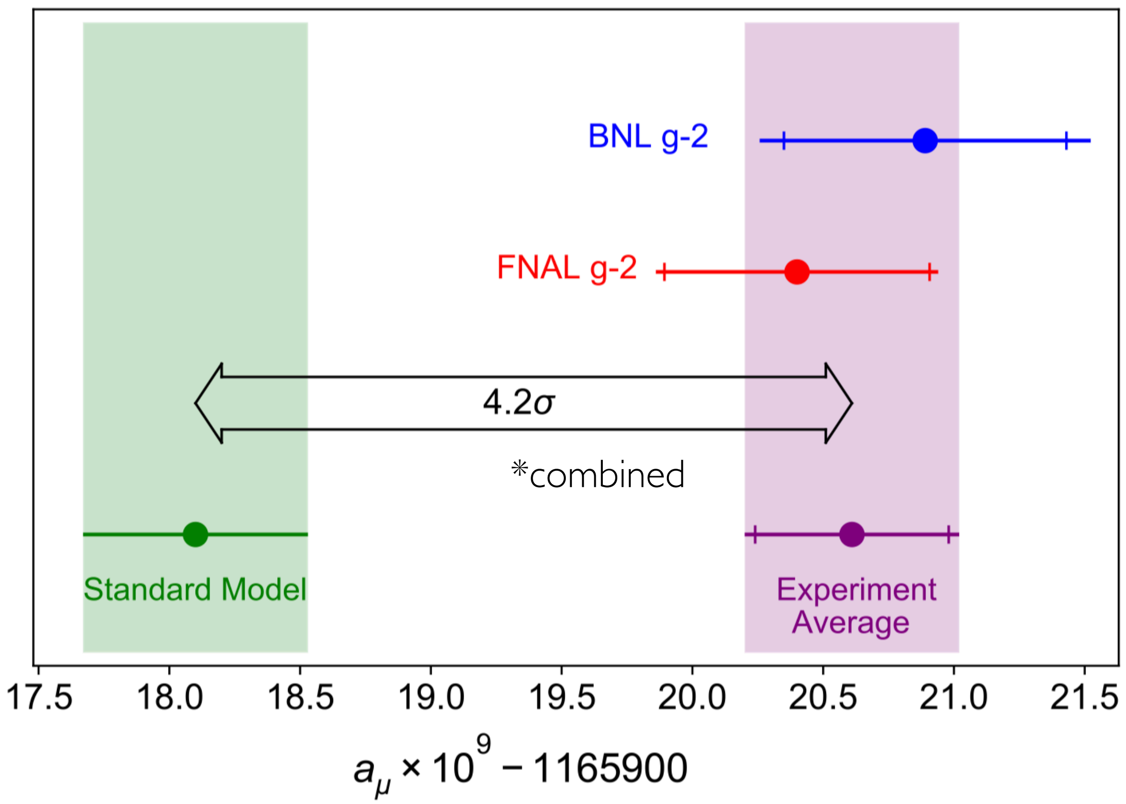
- IR relevance: $\dim[\mathcal{O}] \leq 4$
- Irrelevant couplings suppressed by $\Lambda_{\mathcal{O}}^{4-\dim \mathcal{O}}$

Muon Anomalies

Footprints of a next layer?



LHCb, CERN, 2103.11769



The Muon g-2, Fermilab, 2104.03281

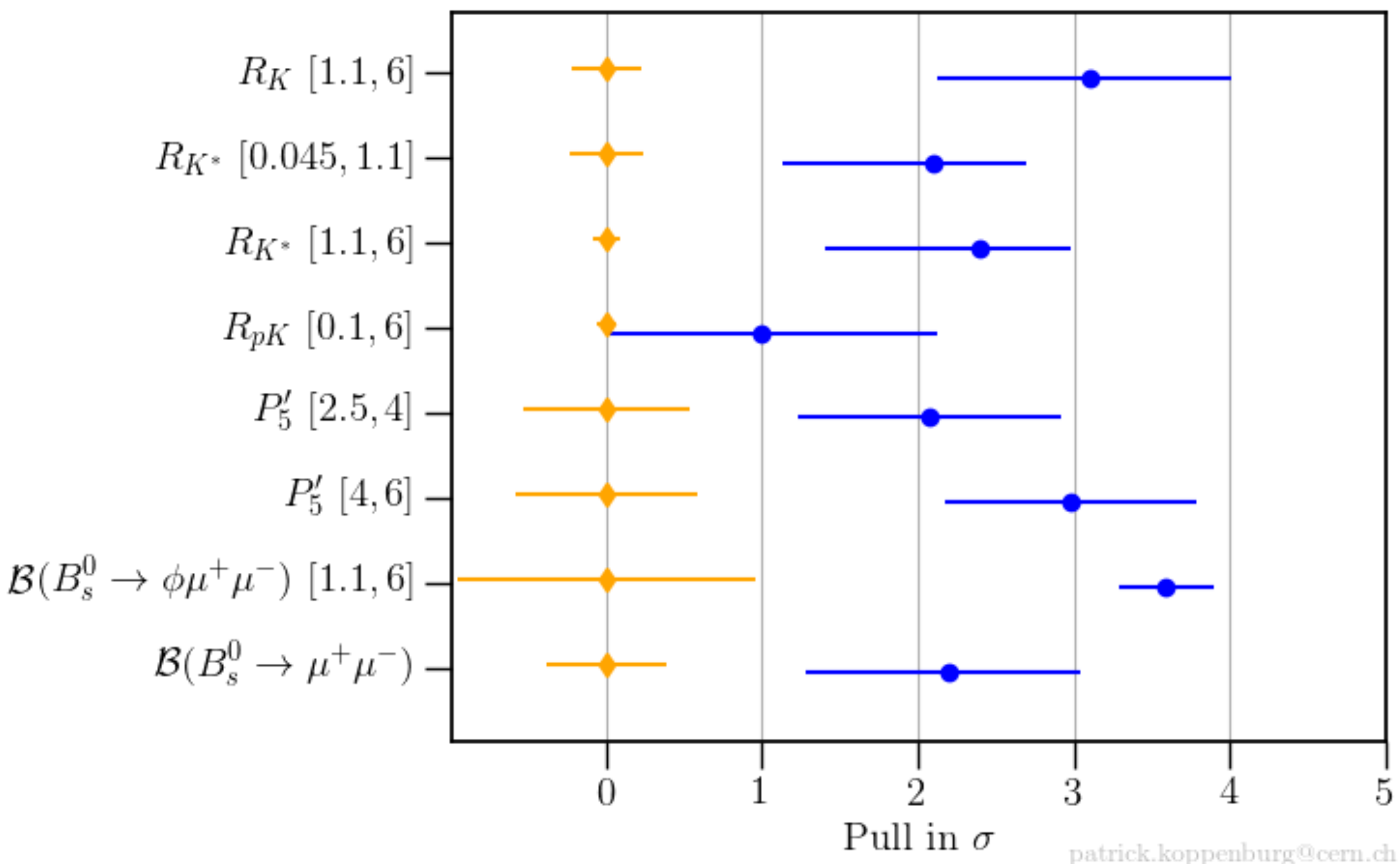
+ other $b \to s\,\mu\mu$ observables

Plan

1. Data
2. Accidental symmetries
3. Model I AG, Stangl, Thomsen, 2103.13991
4. Model II AG, Stangl, Thomsen, 2103.13991
5. wip

$b \to s\ell\ell$

Taken from @PKoppenburg



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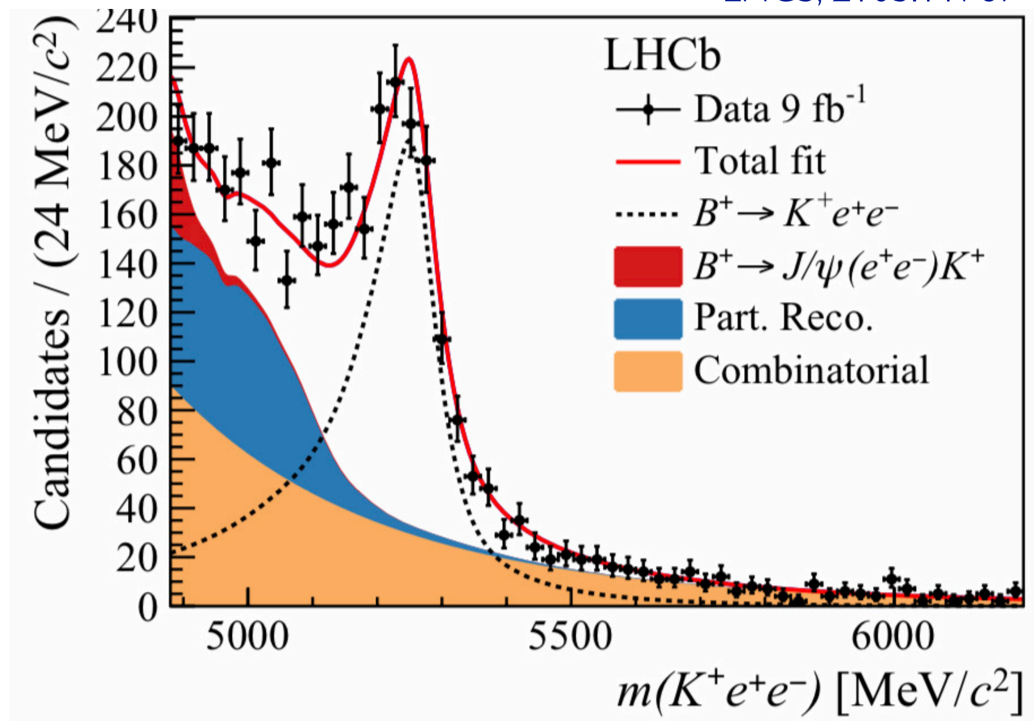
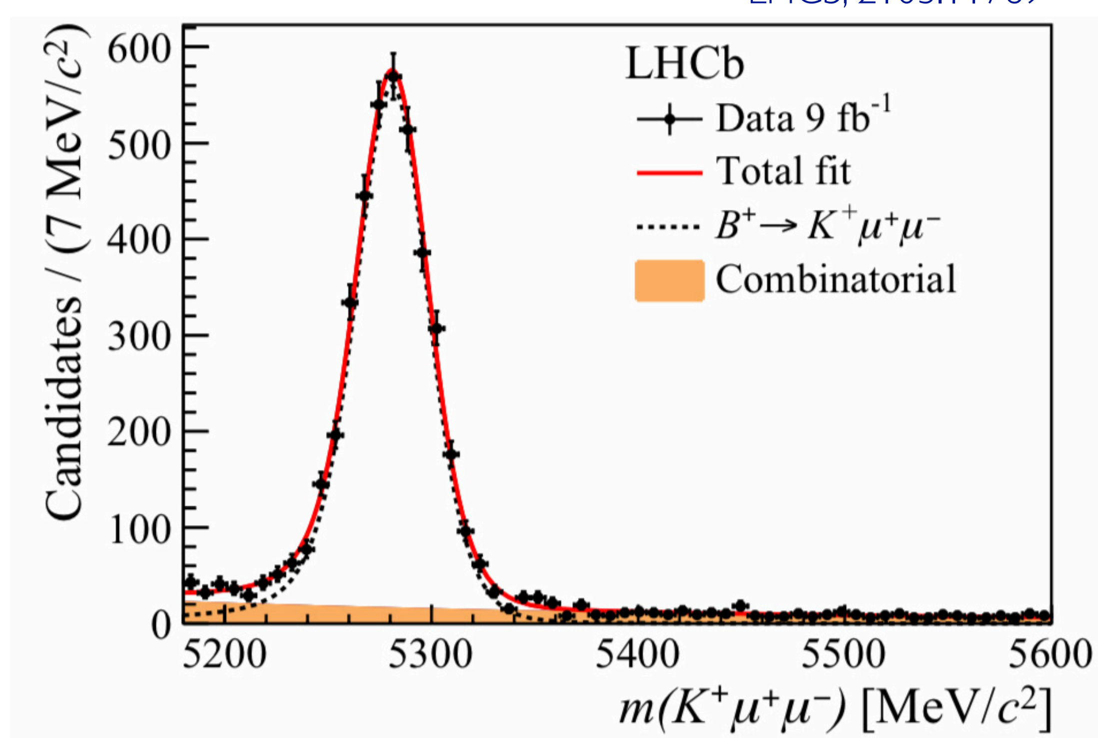


Electrons

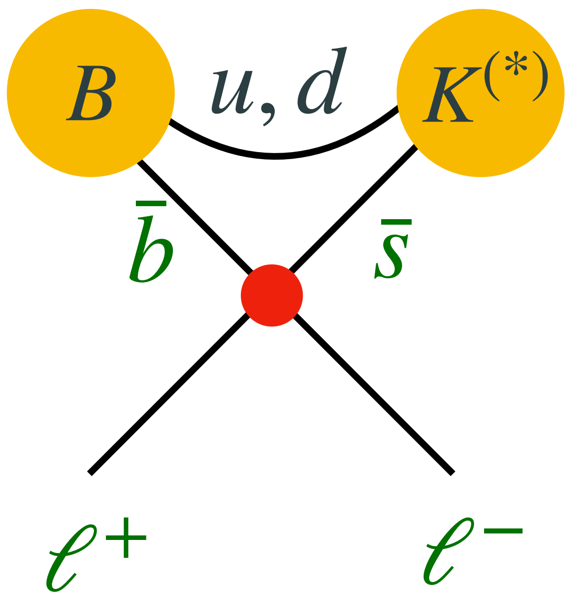
LHCb, 2103.11769



Muons

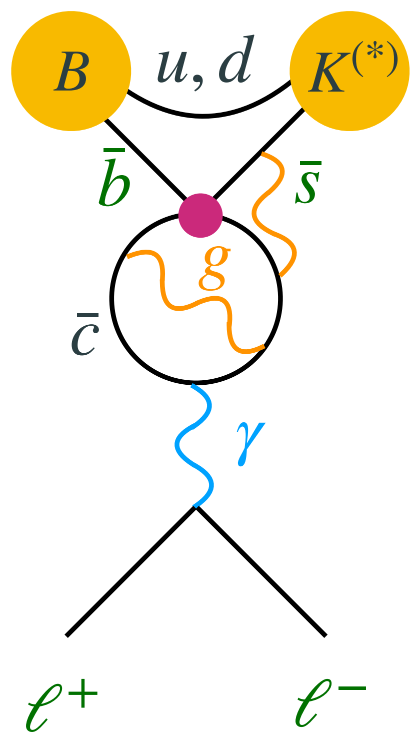
$b \to s\ell\ell$

Semileptonic operators

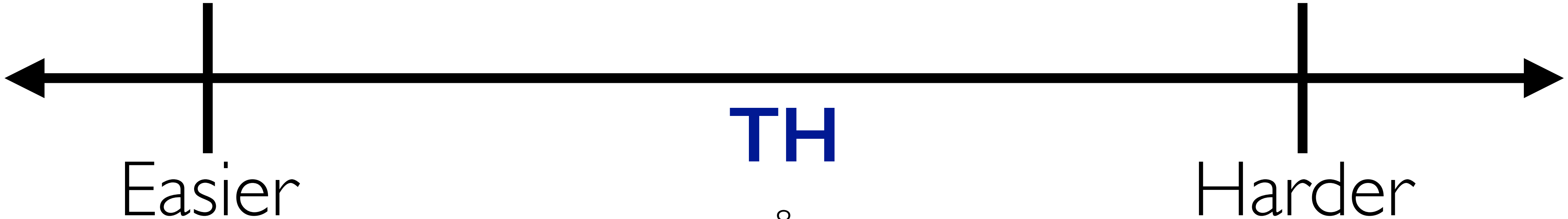


- EFT separates short-distance (Wilson Coefficients) from long-distance (Form Factors).

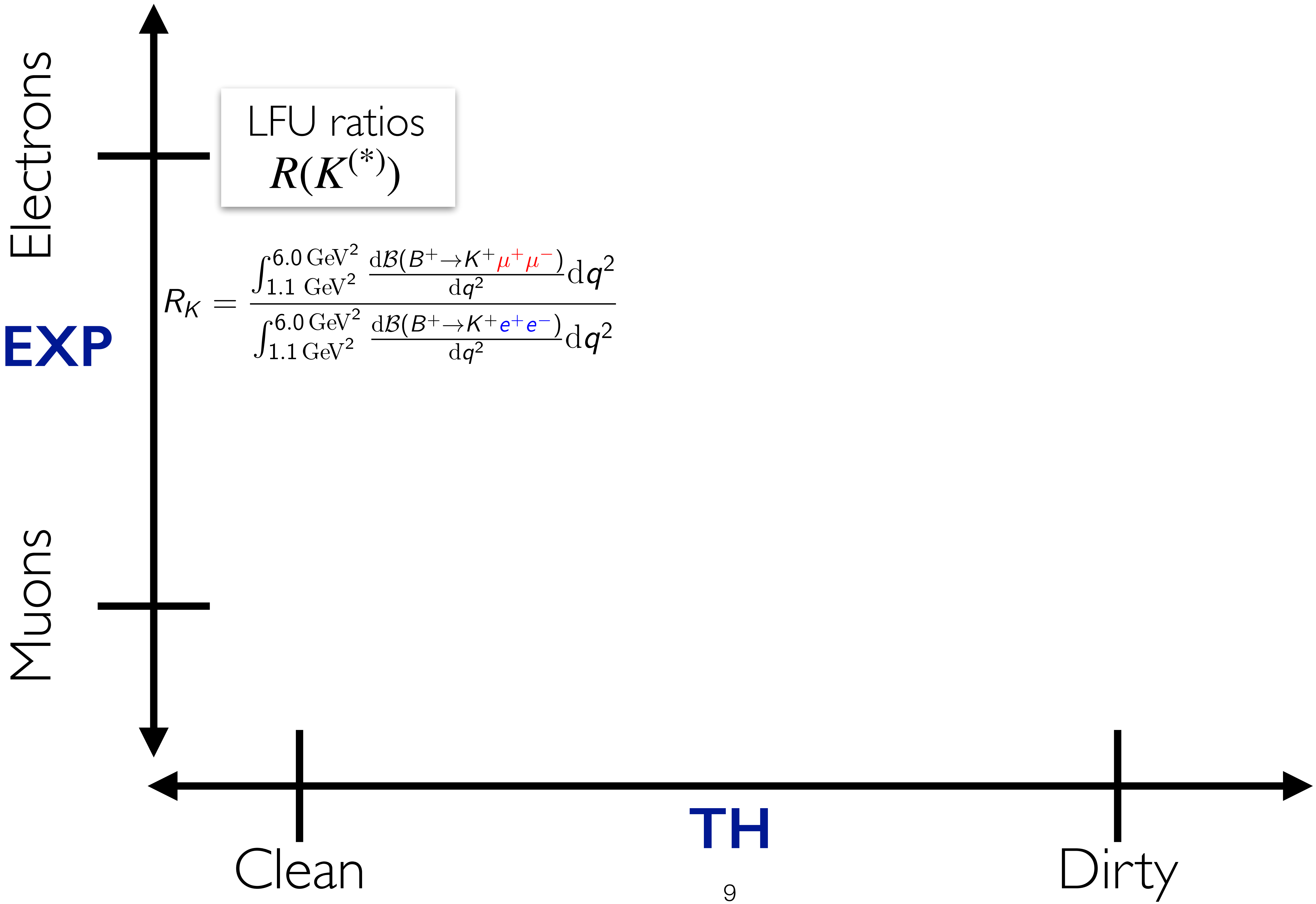
Four-quark operators



- Non-local charm effects
  1. Lepton flavor universal
  2. Vector currents $\bar{\ell}\gamma^\mu\ell$

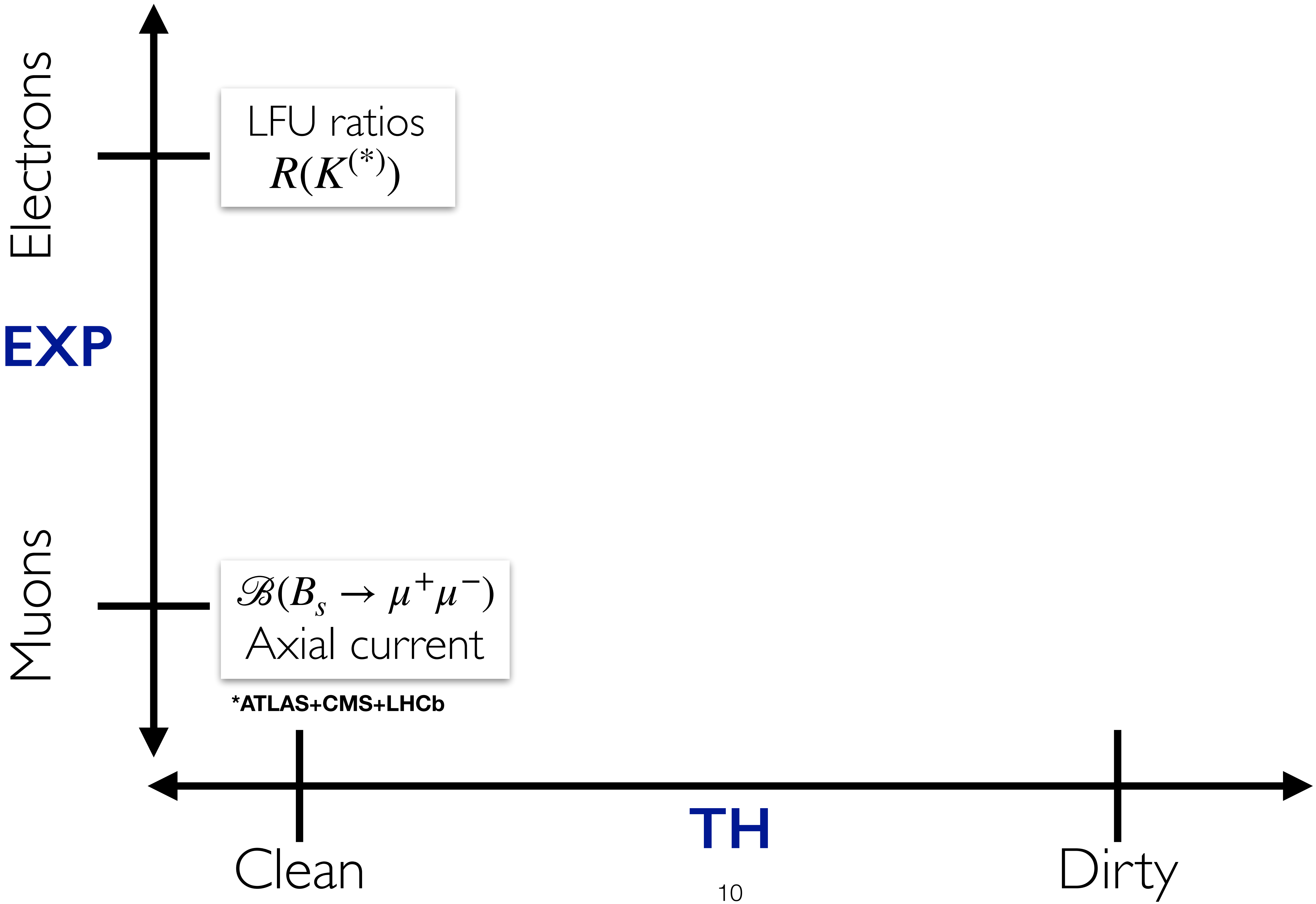


$b \to s\mu\mu$: Coherent deviations!



$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

$b \to s\mu\mu$: Coherent deviations!



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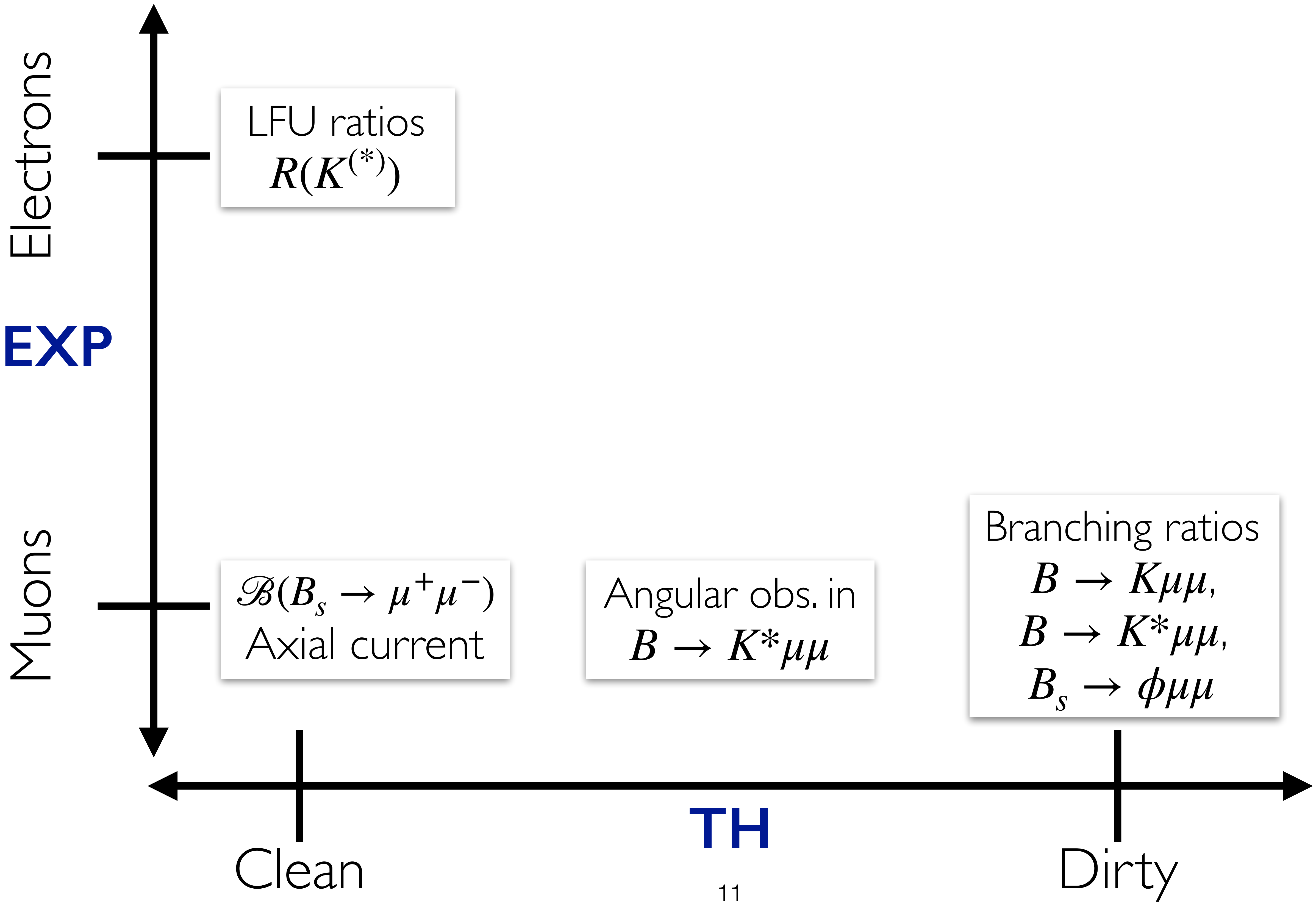

$b \to s\mu\mu$: Coherent deviations!

TH Clean fit with $\mathscr{L}_{NP} = G_{NP}\, \bar{b}_L \gamma^\mu s_L \, \bar{\mu}_L \gamma^\mu \mu_L$

4.6σ pull

$G_{NP} \sim 10^{-5} G_F$

Altmannshofer, Stangl; 2103.13370

Electrons

EXP

Muons

LFU ratios
$R(K^{(*)})$

$\mathscr{B}(B_s \to \mu^+\mu^-)$
Axial current

Angular obs. in
$B \to K^*\mu\mu$

Branching ratios
$B \to K\mu\mu$,
$B \to K^*\mu\mu$,
$B_s \to \phi\mu\mu$

Clean

TH

Dirty

$b \to s\mu\mu$: Coherent deviations!

TH Clean fit with $\mathscr{L}_{NP} = G_{NP}\, \bar{b}_L \gamma^\mu s_L\, \bar{\mu}_L \gamma^\mu \mu_L$

4.6σ pull

$G_{NP} \sim 10^{-5} G_F$

Altmannshofer, Stangl; 2103.13370

Dirty fit ($+P_5'$ etc) with the same NP hypothesis

5.9σ pull

EXP

Electrons

LFU ratios
$R(K^{(*)})$

Muons

$\mathscr{B}(B_s \to \mu^+\mu^-)$
Axial current

Angular obs. in
$B \to K^*\mu\mu$

Branching ratios
$B \to K\mu\mu$,
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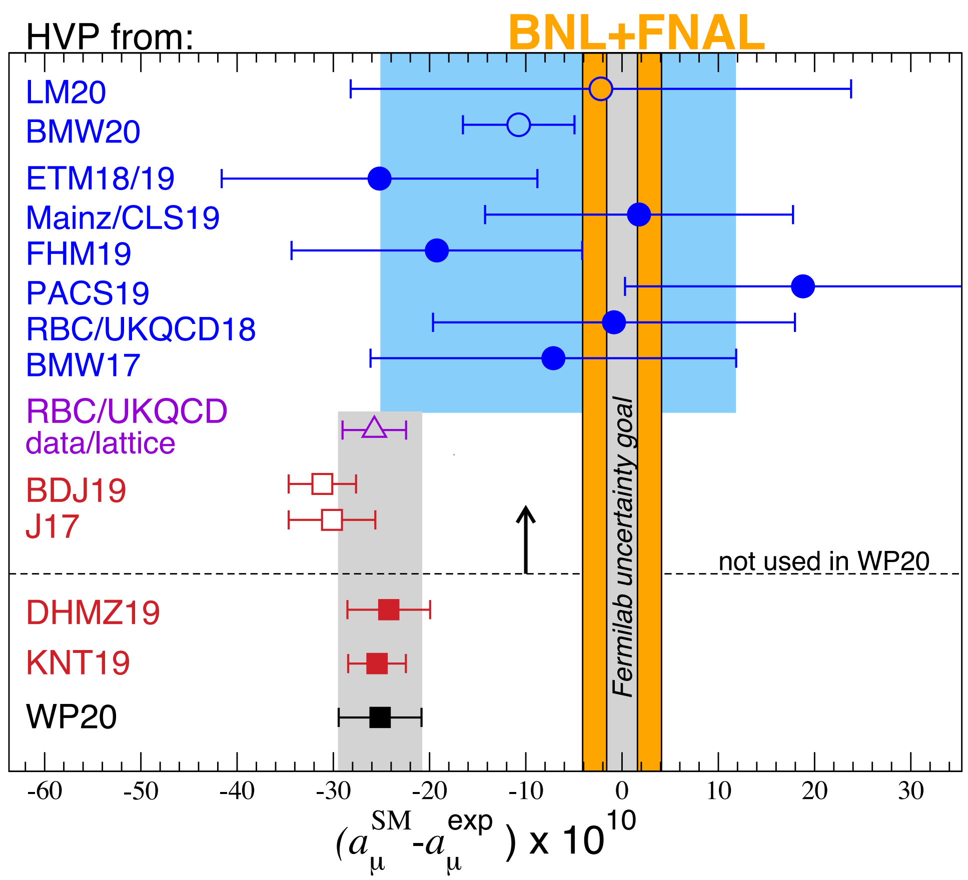
TH

Clean

Dirty

$(g-2)_\mu$



Lattice QCD + QED

hybrid: combine data & lattice

data driven

+ unitarity/analyticity constraints

Taken from A. El-Khadra

- Disagreement between the $(g-2)_\mu$ theory initiative and the BMW lattice.

2006.04822 4.2σ

2002.12347 1.6σ

$(g-2)_\mu$

- Assuming 4.2σ is correct:

Option (Light): With the chiral suppression m_μ / v_{EW}

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

Model I

Option (Heavy): No chiral suppression

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

Model II

2. Accidental symmetries

Accidental symmetries

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Accidental symmetries

- $\mathscr{L}^{SM}$ sans Yukawa

ψ : 3 generations of q_i, U_i, D_i, l_i, E_i

$$U(3)_q \times U(3)_U \times U(3)_D \times U(3)_l \times U(3)_E$$

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

$v_{EW} \ll M_P$ - The EW hierarchy problem

$\theta \lesssim 10^{-10}$ - The strong CP problem

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Accidental symmetries

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

Yukawas break $U(3)^5$

Accidental symmetries

- IR relevance $\dim[\mathscr{L}] \leq 4 \implies$ Accidental global symmetries

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

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

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

No proton decay nor cLFV

Accidental symmetries

The Yukawa puzzle

- Use $U(3)^5$ transformation and a singular value decomposition to start in a basis

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

Accidental symmetries

The Yukawa puzzle

- Use $U(3)^5$ transformation and a singular value decomposition to start in a basis

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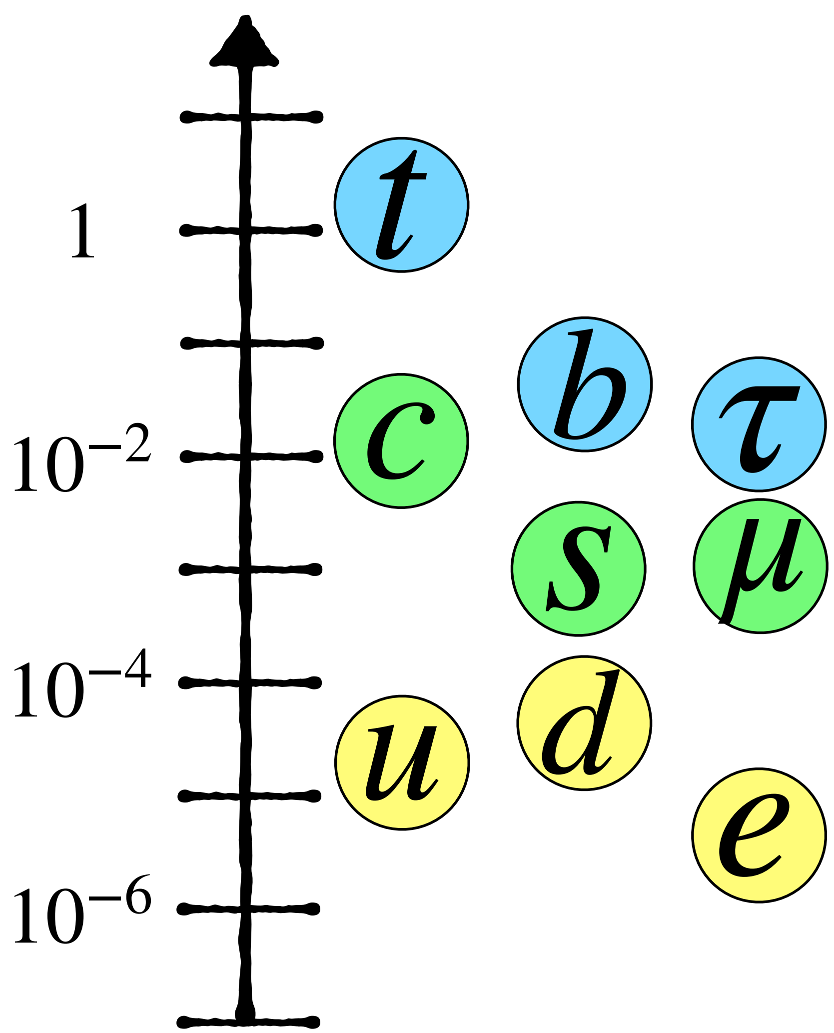


Hierarchy

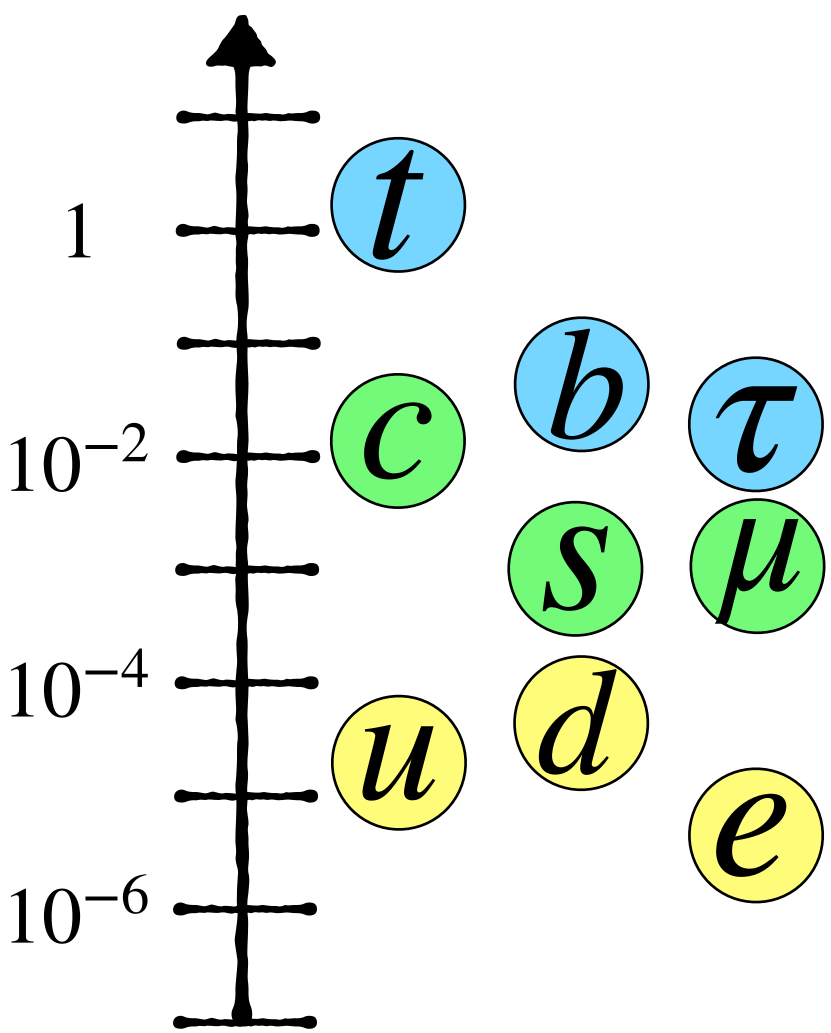
$\hat{Y}^u, \hat{Y}^d, \hat{Y}^e$

Accidental symmetries

The Yukawa puzzle

- Use $U(3)^5$ transformation and a singular value decomposition to start in a basis

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



Hierarchy

$\hat{Y}^u, \hat{Y}^d, \hat{Y}^e$

Alignment

Y^u / Y^d

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

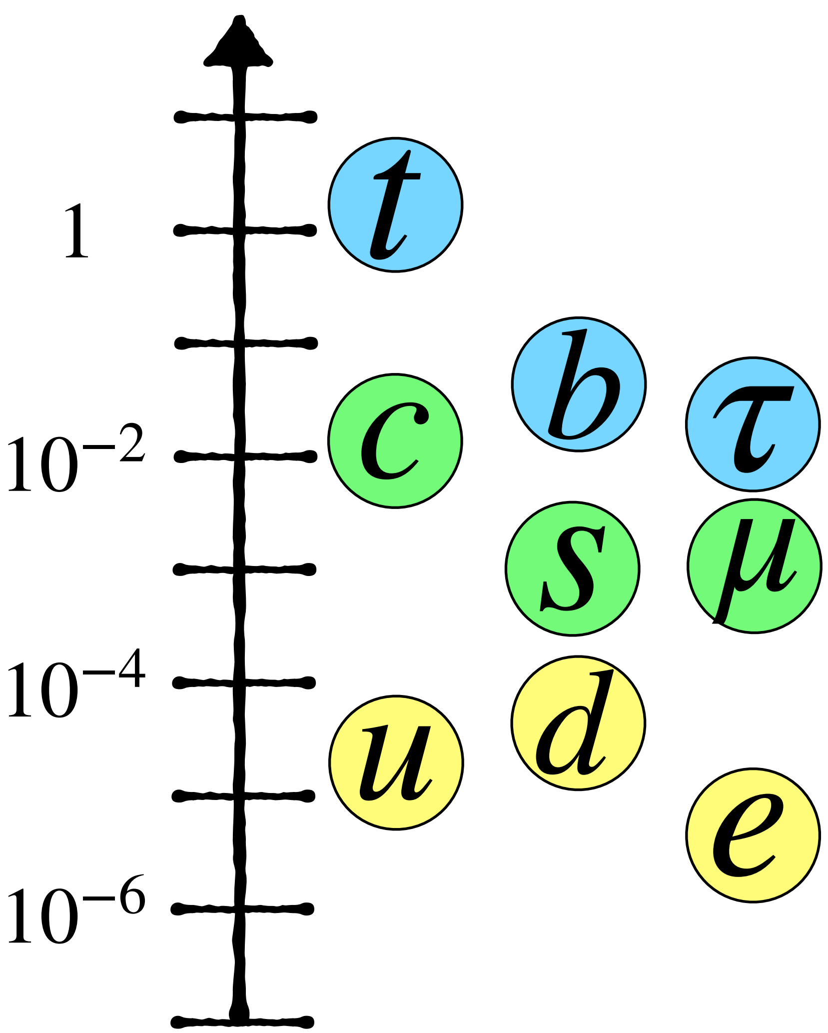
The CKM mixing

Accidental symmetries

The Yukawa puzzle

- Use $U(3)^5$ transformation and a singular value decomposition to start in a basis

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



Hierarchy

$\hat{Y}^u, \hat{Y}^d, \hat{Y}^e$

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Y^u / Y^d

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

The CKM mixing

The origin of flavor?

Approximate accidental symmetries

Peculiar structure $\Longrightarrow$ Approximate accidental symmetries

Approximate accidental symmetries

- CP is an *approximate* accidental symmetry

$$\Im(\det([Y^d Y^{d\dagger}, Y^u Y^{u\dagger}])) =$$

$$\Im \det[\hat{Y}_d^2, V^\dagger \hat{Y}_u^2 V] \approx \mathcal{O}(10^{-22})$$

Hierarchy+Alignment

Approximate accidental symmetries

- LFU is an *approximate* accidental symmetry of the $[\mathscr{L}_{\rm SM}] \leq 4$.

[LFU 123] $\quad U(3)_L \times U(3)_E$

$$\Big\downarrow \; y_\tau \neq 0 \ll g_{1,2,3}$$

[LFU 12] $\quad U(2)_L \times U(2)_E \times U(1)_\tau$

$$\Big\downarrow \; y_\mu \neq 0 \ll y_\tau$$

$$U(1)_{e_L} \times U(1)_{e_R} \times U(1)_\mu \times U(1)_\tau$$

$$\Big\downarrow \; y_e \neq 0 \ll y_\mu$$

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

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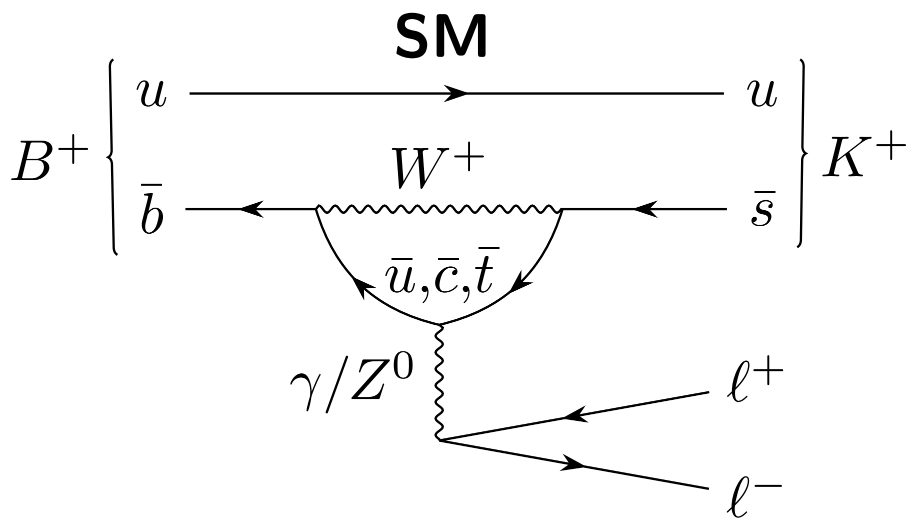
$$R_K = 1 + \mathcal{O}\left(\frac{m_\mu^2}{q^2}\right) + \mathcal{O}\left(\frac{\alpha_{EM}}{\pi}\log^2\frac{m_e^2}{m_\mu^2}\right)$$

Hiller, Kruger
hep-ph/0310219

Bordone, Isidori, Pattori
1605.07633

Approximate accidental symmetries

- No tree-level FCNC
- Quark Flavor Conservation: $\bar{q}V^\dagger \hat{Y}^u \tilde{H} U + \bar{q}\hat{Y}^d H D$
  - When $V = 1$ => $U(1)_{u+d} \times U(1)_{c+s} \times U(1)_{t+b}$
- The GIM mechanism:
  - When $\hat{Y}_d \propto 1$ implies $U(1)_u \times U(1)_c \times U(1)_t \times U(3)_{dsb}$
  - When $\hat{Y}_u \propto 1$ implies $U(1)_d \times U(1)_s \times U(1)_b \times U(3)_{uct}$



- Loop and CKM suppression
- Large GIM breaking by the top quark

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

$$C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$
$$C_{10}^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\text{SM}: \quad C_9 \approx -C_{10} \approx 4.2$$

Example: TeV-scale Leptoquarks

- Testing accidental symmetries is an opportunity.

  Accidental symmetries are broken by the irrelevant couplings.
  Efficient probe of high-energy dynamics.

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

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

- Abrupt violation of the SM accidental symmetries

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

$\cancel{U(1)_e \times U(1)_\mu \times U(1)_\tau}$ $\mu \to e \gamma$ $[i \neq j]$ probes scales up to 10^5 TeV

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

$\cancel{U(3)_L \times U(3)_E}$ LFUV, …

B-decays

$$\mathscr{L} \supset \eta\, Q_L L_L S_3$$

$$\uparrow$$

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

- 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

B-decays

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↑

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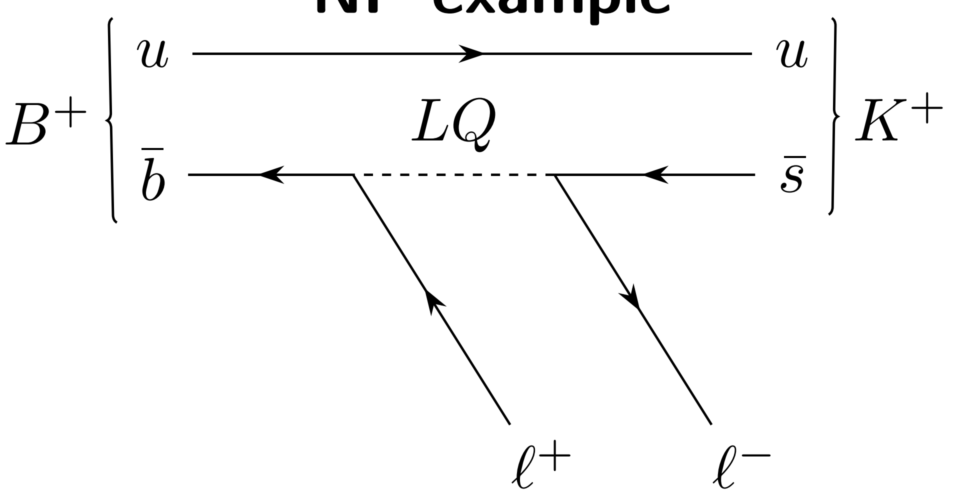
NP example



$$R(K) \implies$$

$$\frac{\eta_{b\mu}\eta_{s\mu}}{M_{LQ}^2} \sim \frac{1}{(40\ \mathrm{TeV})^2}$$

$(g-2)_\mu$

- In the SM, the breaking spurion of $U(1)_{\mu_L} \times U(1)_{\mu_R}$ is the muon Yukawa

$$y_\mu = (+1, -1)$$

- For $\mathscr{L} \supset \eta_L \, Q_L^3 L_L^2 S_1 + \eta_R \, t_R \mu_R S_1$

$$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3) \qquad \eta_L^* \eta_R = (+1, -1)$$

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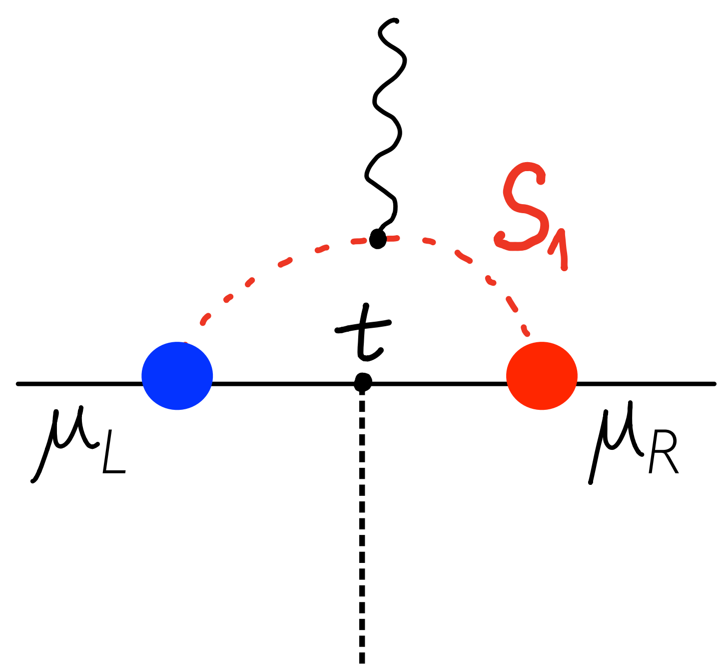

$$(g-2)_\mu \implies$$

$$\frac{\eta_L \eta_R}{M_{LQ}^2} \sim \frac{1}{(10\ \mathrm{TeV})^2}$$

$(g-2)_\mu$

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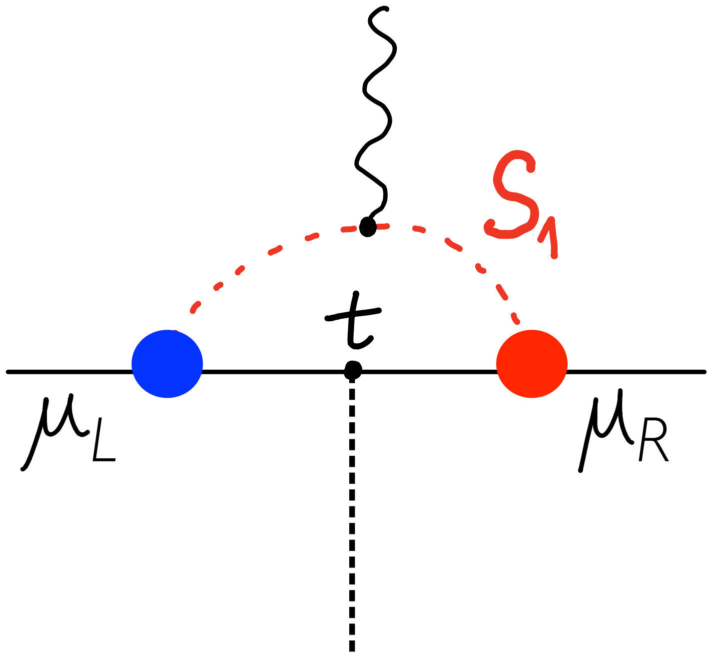


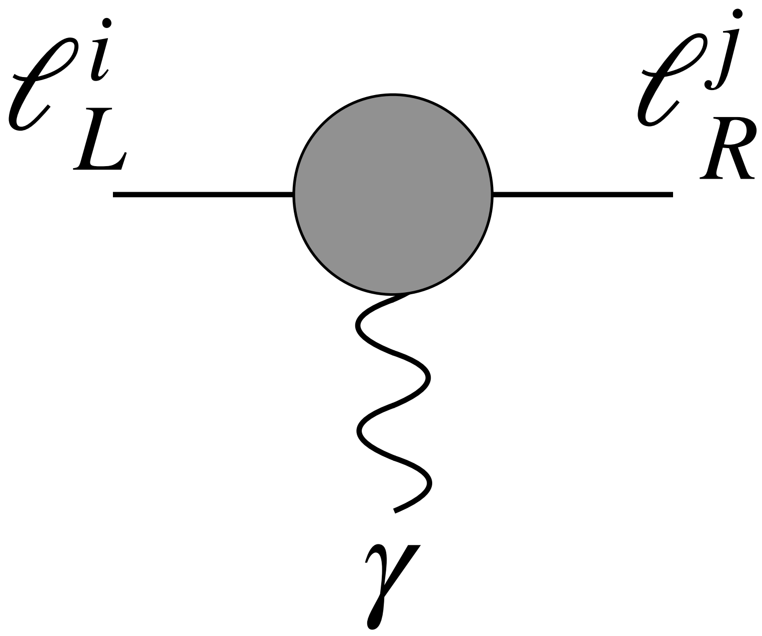
- Removing the photon → correction to the muon Yukawa

$$\delta y_\mu \sim y_\mu^{SM} \left(\frac{M_{LQ}}{3\ \mathrm{TeV}} \right)^2$$

$$(g-2)_\mu \implies \frac{\eta_L \eta_R}{M_{LQ}^2} \sim \frac{1}{(10\ \mathrm{TeV})^2}$$

LFUV but no LFV

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$



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

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

Naive BSM expectation is wrong!

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

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

$$R(K) < 1$$

Gauged lepton flavor

- $U(1)_{X_\mu}$ Gauge Symmetry & Leptoquarks:
  - Lepton flavor specific charges — the $Q\,L_i\,S$ coupling is allowed for $i=\mu$ but forbidden for $i=e,\tau$.
  - All quarks charged in the same way.
  - Diquark interactions $Q\,Q\,S^\dagger$ are forbidden.

Leptoquark $\Rightarrow$ Muoquark

Davighi, Kirk, Nardecchia, 2007.15016
AG, Stangl, Thomsen, 2103.13991

Gauged lepton flavor

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    - Lepton flavor specific charges —
      the $Q\,L_i\,S$ coupling is allowed for $i = \mu$ but forbidden for $i = e, \tau$.
    - All quarks charged in the same way.
    - Diquark interactions $Q\,Q\,S^\dagger$ are forbidden.

- Keeps the accidental symmetry
  $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Leptoquark $\Rightarrow$ Muoquark

Davighi, Kirk, Nardecchia, 2007.15016
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Model I

Light mediator for Δa_μ

Model I

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

AG, Stangl, Thomsen, 2103.13991

Model I

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

AG, 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

Model I

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

AG, 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 [Backup]

Muoquark

Model I

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

AG, Stangl, Thomsen, 2103.13991

SM

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

Muon force

Muoquark

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

Model I

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

AG, 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			
S_3	$\bar{3}$			

Muon force

- No proton decay up to dim-6

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

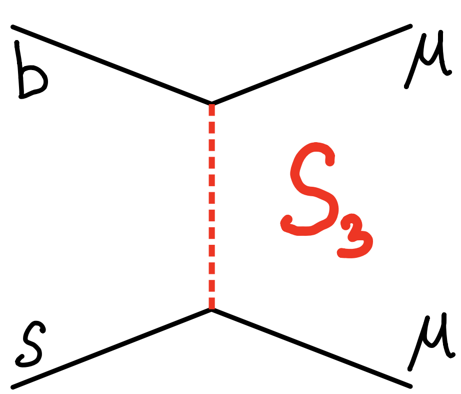
Muoquark

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

Model I

Muoquark

$R(K)$:



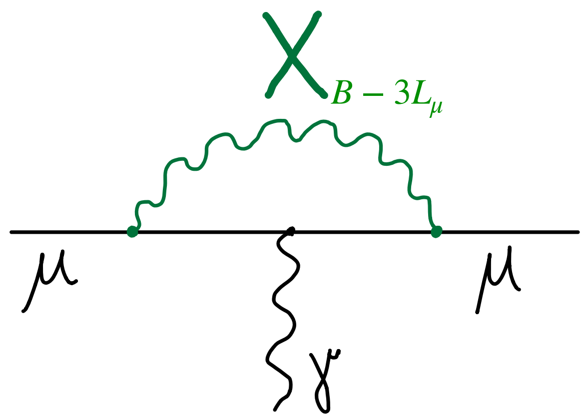
* V-A solution

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

Model I

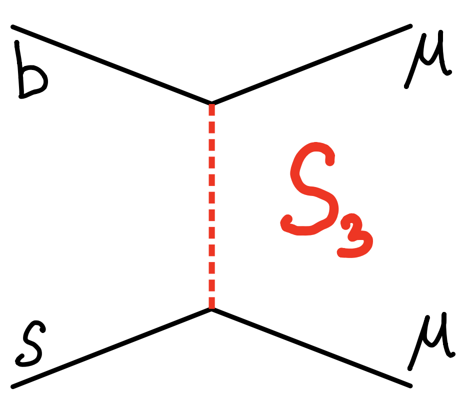
Muon force

$(g-2)_\mu$:



Muoquark

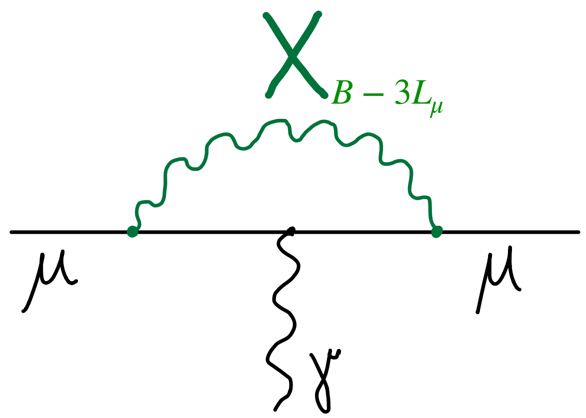
$R(K)$:



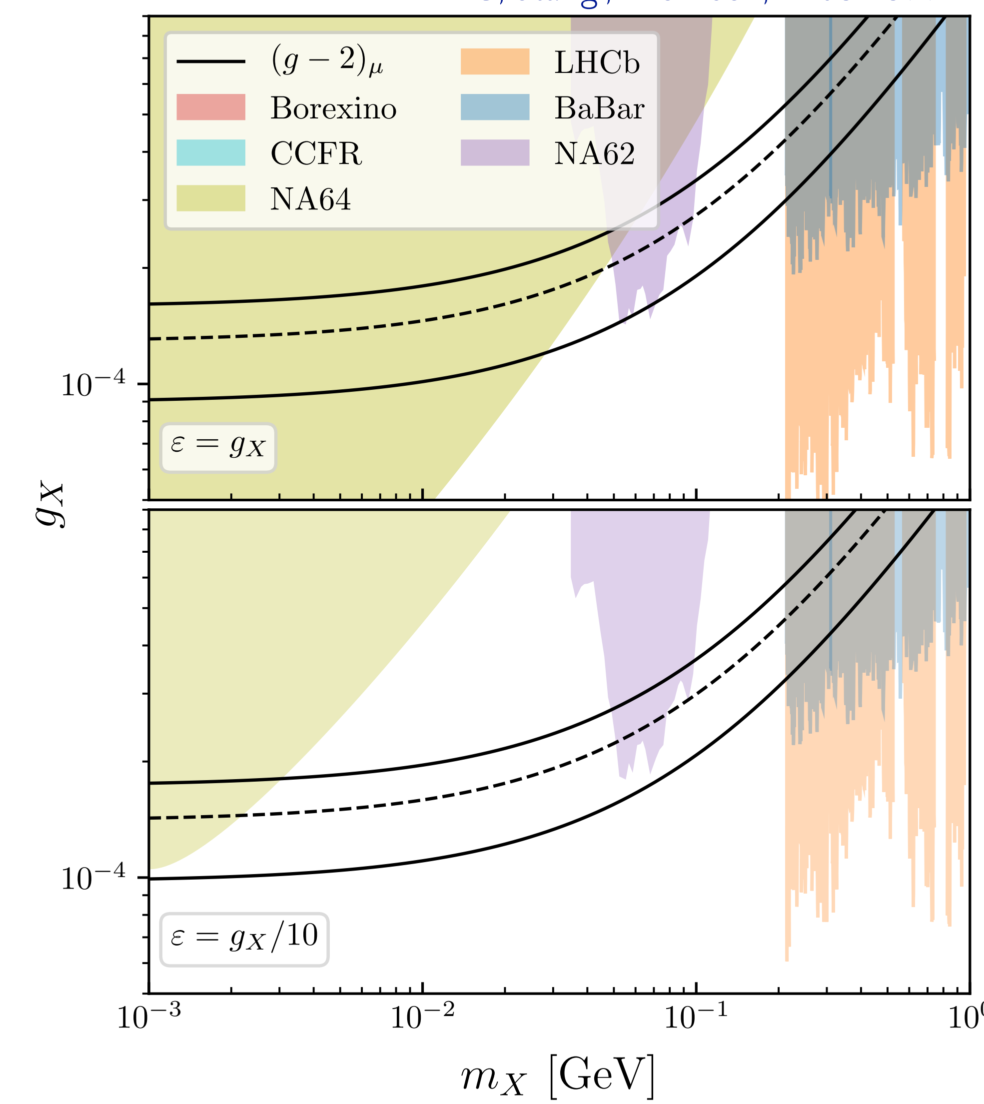
Model I

Muon force

$(g-2)_\mu$:



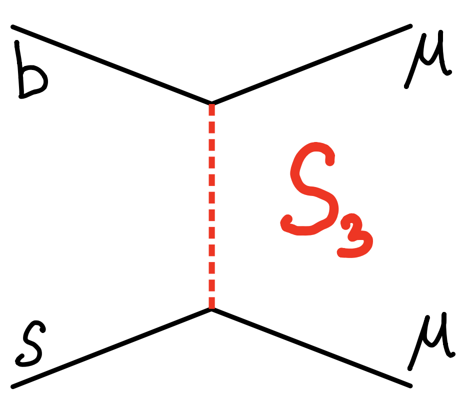
AG, Stangl, Thomsen, 2103.13991



- A robust 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.
- DarkCast constraints 1801.04847.

Muoquark

$R(K)$:



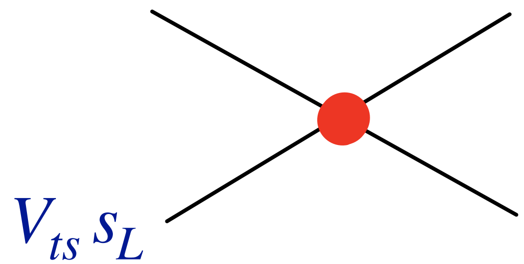
Model II

Heavy mediator for Δa_μ

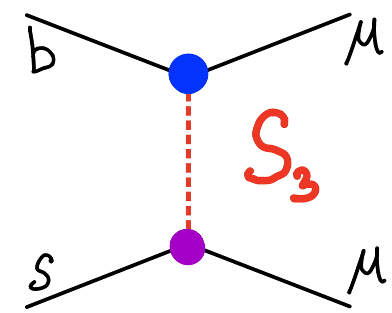
Model II

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

$R(K)$:



$\longleftarrow$



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

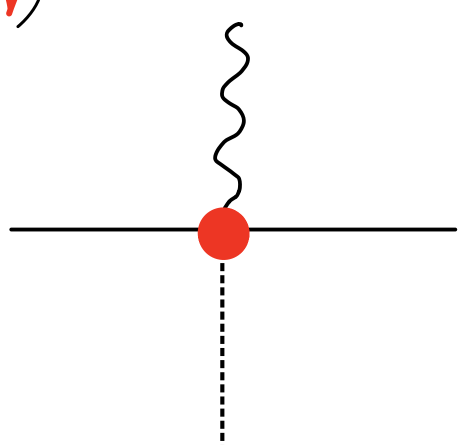
Link

● $\sim \mathcal{O}(0.1)$

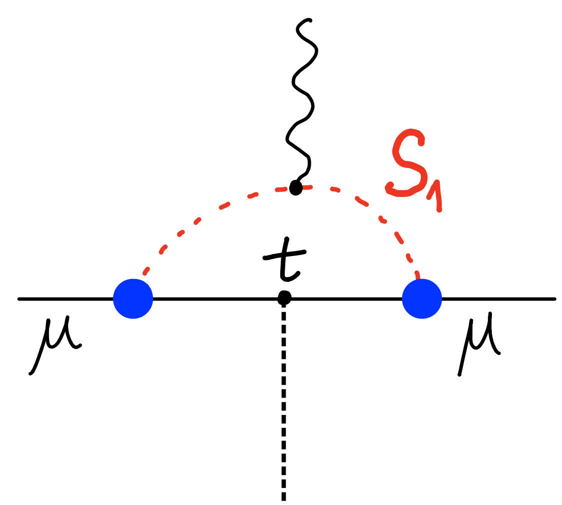
$M \sim \mathcal{O}(\mathrm{TeV})$

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

$(g-2)_\mu$:



$\longleftarrow$



Model II

Field content: Model I + $S_1 \equiv (\bar{\mathbf{3}}, \mathbf{1}, 1/3)_{8/3}$

- $\mathscr{L} \supset \eta_i Q^i \mu S$ - Assume the quark flavour structure is **CKM-like**

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

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

- $V = (\mathbf{2}, \mathbf{1}, \mathbf{1})$,
  $\Delta_u = (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})$ and
  $\Delta_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$ under
  $U(2)_q \times U(2)_U \times U(2)_D$

Model II

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

- 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.

Model II

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AG, Stangl, Thomsen, 2103.13991

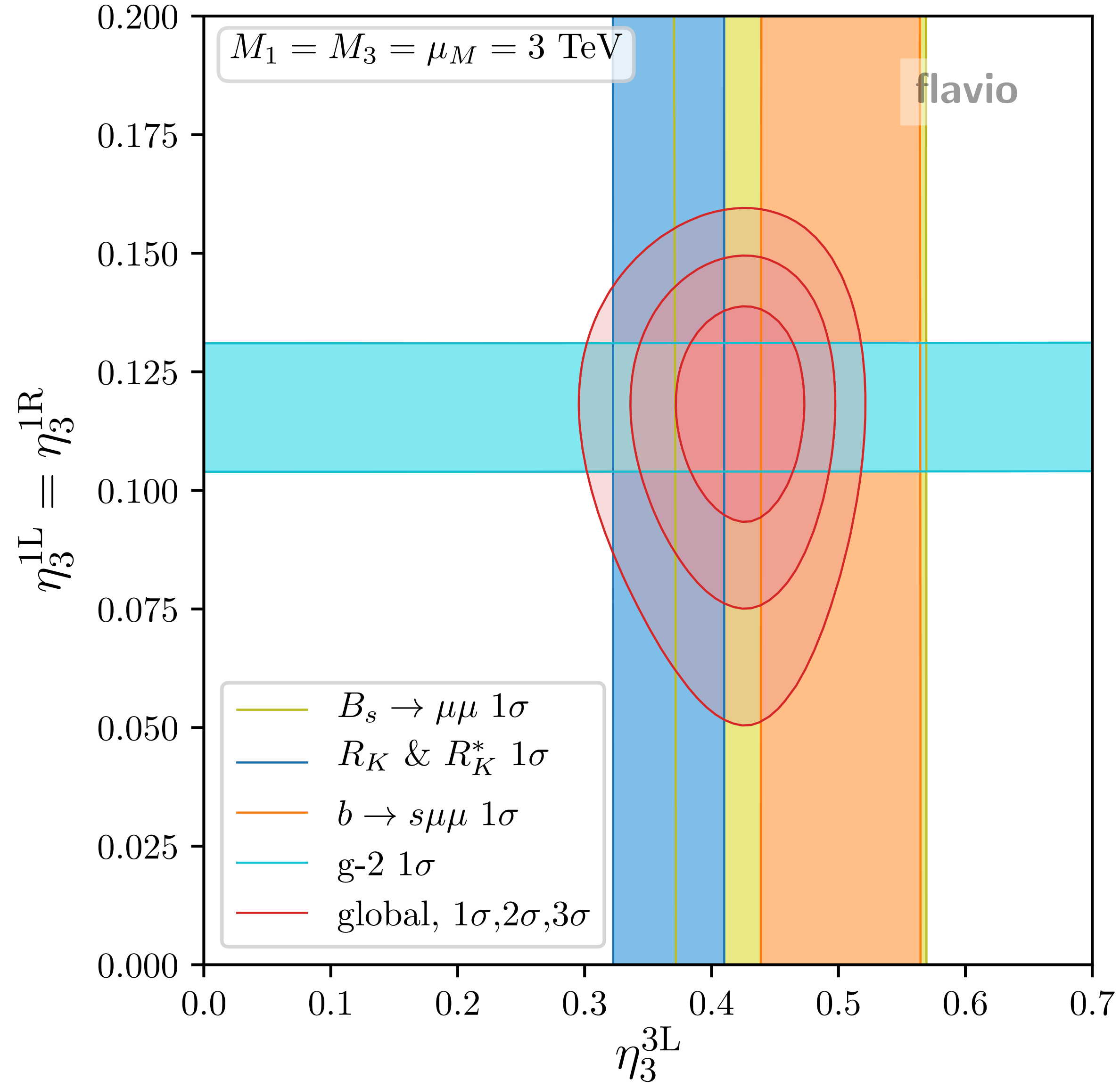


FIG. 1. The preferred muoquark Yukawa couplings from the global fit to low-energy data. Here we choose $\eta_i^{3\mathrm{L}} = (V_{td}, V_{ts}, 1)\, \eta_3^{3\mathrm{L}}$, $\eta_i^{1\mathrm{L}} = (V_{td}, V_{ts}, 1)\, \eta_3^{1\mathrm{L}}$, and $\eta_i^{1\mathrm{R}} = (0, 0, 1)\, \eta_3^{1\mathrm{R}}$.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

Model II

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

- 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.

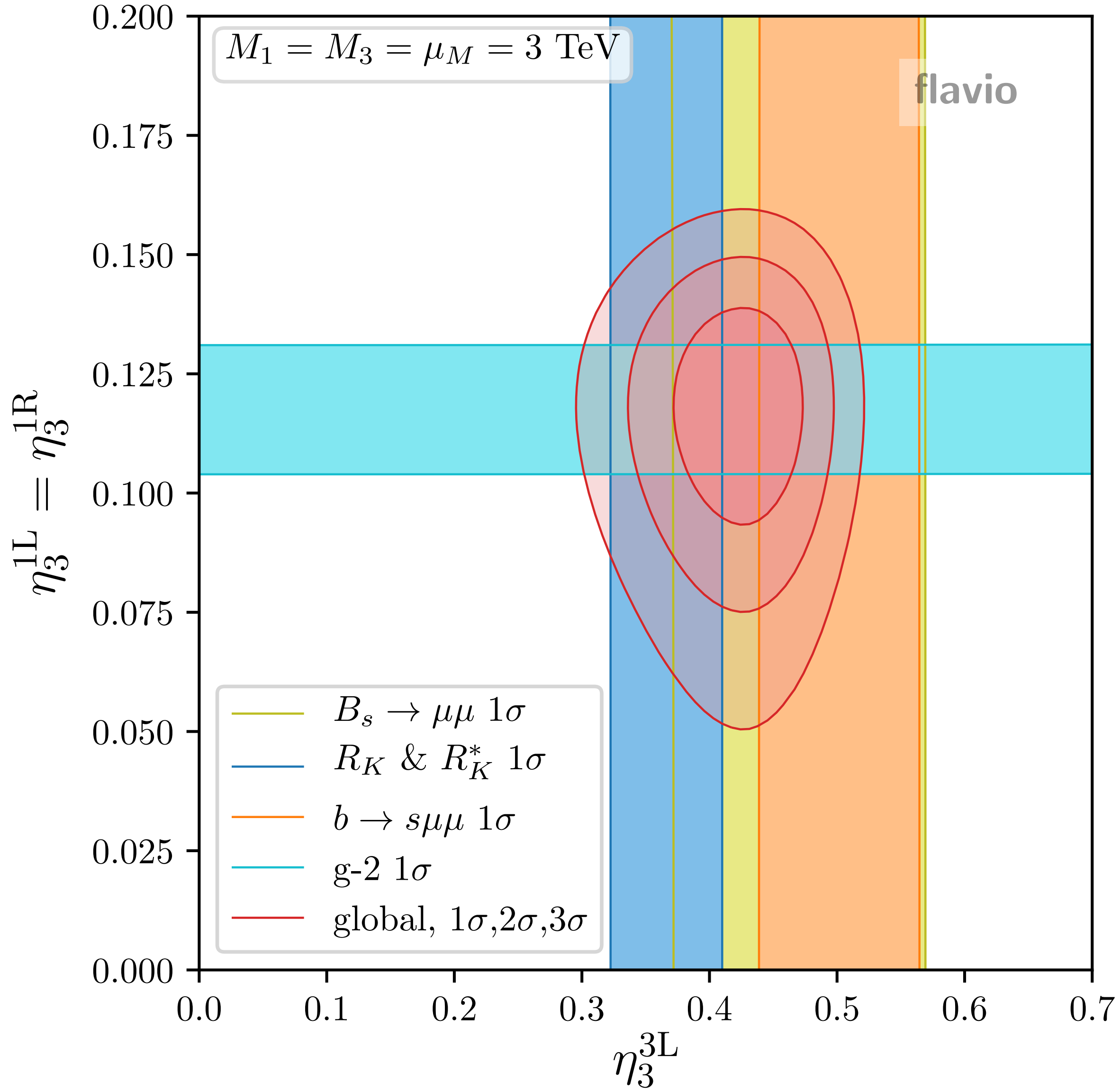
- $\Delta\chi^2 = 62$

- 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

AG, Stangl, Thomsen, 2103.13991



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The scalar potential

- The spontaneous symmetry breaking

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

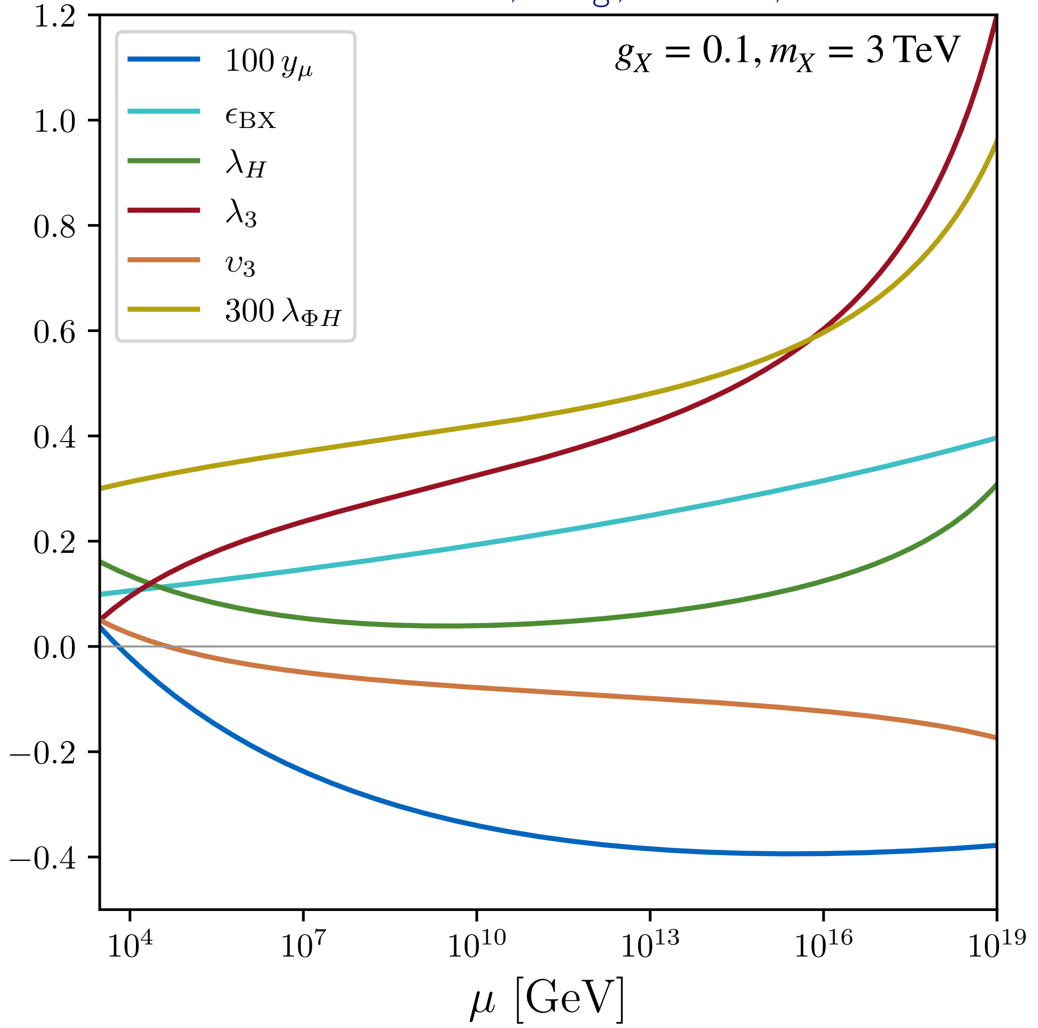
- H break EW, while the SM singlet Φ breaks $U(1)_X$.
- In the limit $g_X \to 0$ and/or $v_\Phi \to \infty$ is the decoupling of $U(1)_X$ sector.

- The 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-

AG, Stangl, Thomsen, 2103.13991



wip

Conclusions

1. Muon anomalies might be a footprints of physics beyond the SM
2. Testing accidental symmetries of the SM is a clever strategy to search for NP
3. Gauged lepton flavor is an interesting direction

Backup

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 $\mathrm{U}(1)_X$ gauge groups.

AG, Stangl, Thomsen, 2103.13991

The scalar potential

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

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The scalar potential

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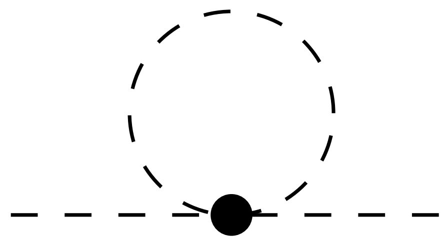
- H break EW, while the SM singlet Φ breaks $U(1)_X$.
- In the limit $g_X \to 0$ and/or $v_\Phi \to \infty$ is the decoupling of $U(1)_X$ sector.
- The rest of the potential:

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

Finite naturalness

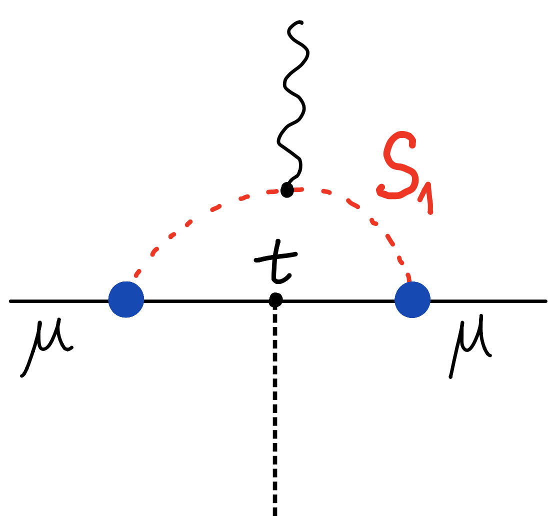
- The Higgs mass



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

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

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

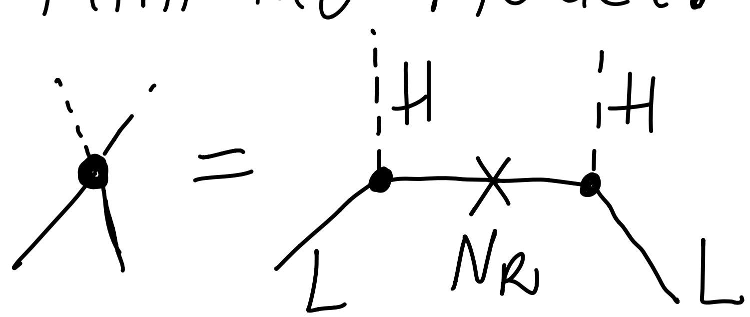
- $(g-2)_\mu$ requires larger couplings for heavier leptoquark
- No tuning only if $M_{1,3} \lesssim$ a few TeV, see also the RG flow

- Finite naturalness provides argument for direct searches at colliders

$\mathscr{L}_5$: Neutrino masses?

- The first indication of a new scale beyond EW
- Lepton number violation $\Lambda^{-1}(LH)^2$, a tiny m_ν from a heavy Λ

Minimal model:



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

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

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

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.

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

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

- 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 $\dfrac{1}{M_P} q S^\dagger \phi^\dagger q$, together with $q\ell S$ needed for the muon anomalies and TeV-scale S mass, leads to dangerous proton decay.

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 $m_X \in [10,200]\,\mathrm{MeV}$.

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

- Mixing between real scalars h and ϕ.

$$g_X : X \to \nu_\mu \bar{\nu}_\mu \qquad \lambda_\Phi : \phi \to XX \qquad \xrightarrow{\lambda_{\Phi H},\, \lambda_\Phi} \qquad h \to inv$$

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

Implications for **Higgs physics: Muoquarks**

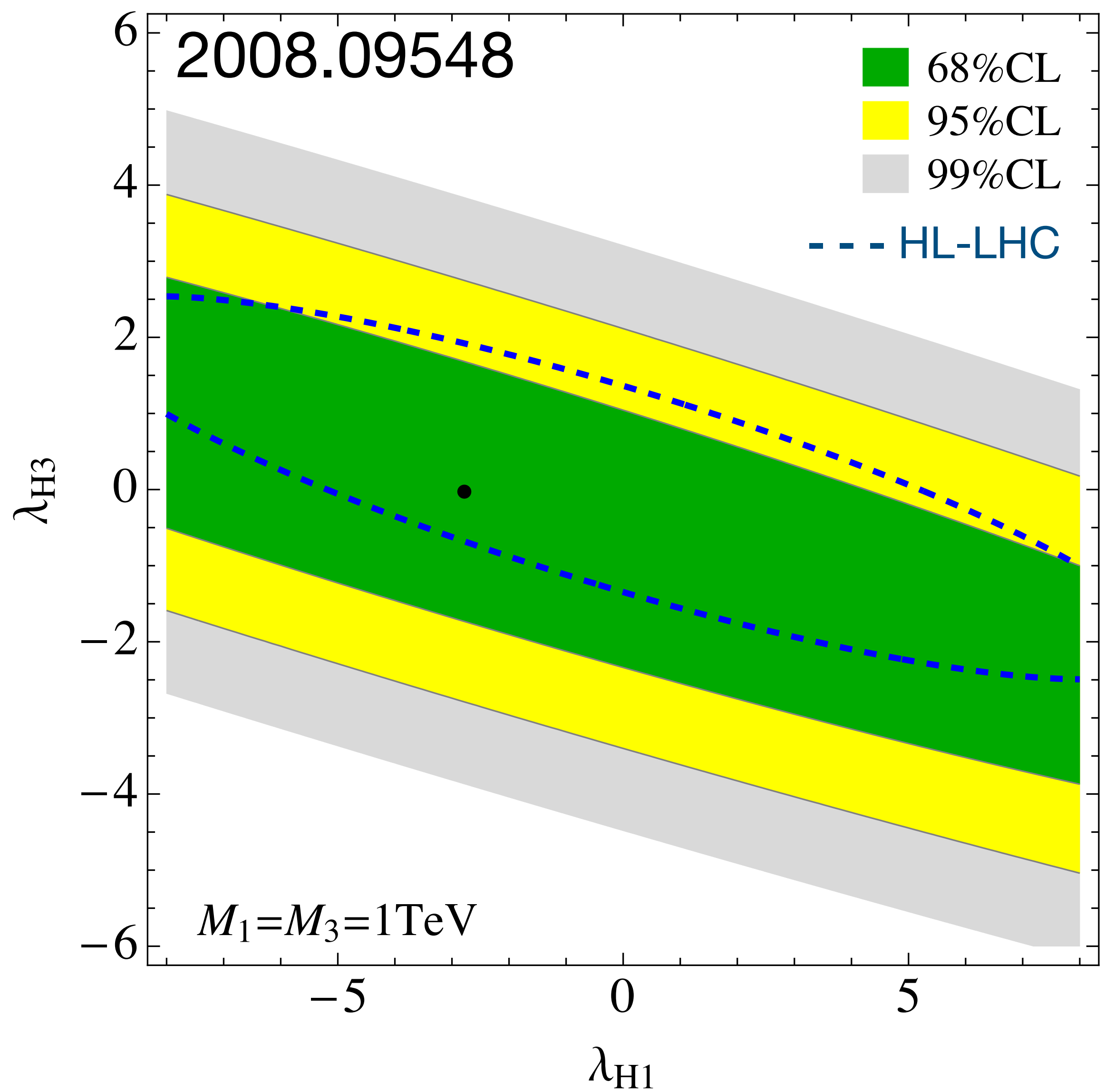
- The Higgs portal

$$\mathcal{L}_{\mathrm{LQ}} = -\lambda_{H1}|H|^2|S_1|^2 - \lambda_{H3}|H|^2|S_3^I|^2$$

- At one-loop

$$h \to gg$$
$$h \to \gamma\gamma$$

- Rather weak constraints for a TeV-scale LQ



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.
  1105.2296
- 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 $\Delta_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$

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

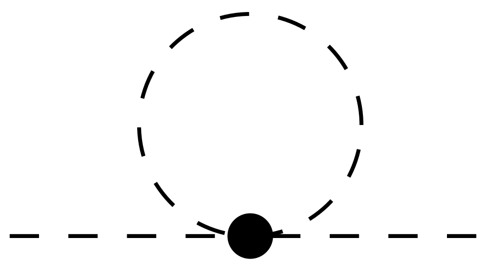
- Let's assume the muoquark interactions $\mathscr{L} \supset \eta_i Q^i \mu S$ respect the same rules:

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

$\mathscr{L}_2$: The EW scale

The EW hierarchy $\mu^2 \ll M_P^2$

- Quadratic sensitivity to a heavy mass threshold

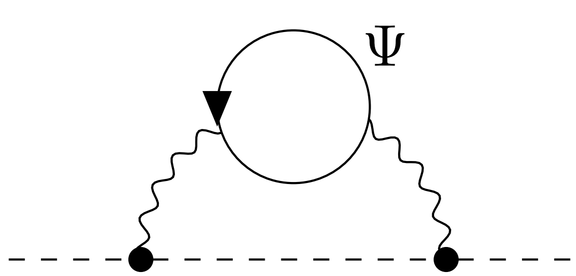


$\lambda_S |H|^2 |S|^2$

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

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

Next layer at the TeV scale?