UNIVERSITÄT BERN

Higgs and Flavour

Admir Greljo

27.04.2021, Standard Model at the LHC 2021

Outline

- Part I: ***Flavor physics of the Higgs Boson*** (2/3)

- Part II: ***Implications of flavor anomalies for the Higgs Boson*** (1/3)

Part I

The SM flavours

- Consider $\mathscr{L}_{\mathrm{SM}}$ *sans* Yukawa

$$G_{\mathrm{global}}^{\mathrm{SM}}(Y^{u,d,e}=0) = SU(3)^3 \times SU(3)^2 \times U(1)^5$$

Three identical copies of five gauge representations: q, U, D, l, E

The SM flavours

- Consider $\mathscr{L}_{\rm SM}$ *sans* Yukawa

$$G^{\rm SM}_{\rm global}(Y^{u,d,e}=0) = SU(3)^3 \times SU(3)^2 \times U(1)^5$$

Three identical copies of five gauge representations: q, U, D, l, E

- Yukawa sector

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

Flavour breaking + EWSB $\Longrightarrow$

Fermion masses and mixings

The SM flavours

- Consider $\mathscr{L}_{\rm SM}$ *sans* Yukawa

$$G^{\rm SM}_{\rm global}(Y^{u,d,e}=0) = SU(3)^3 \times SU(3)^2 \times U(1)^5$$

Three identical copies of five gauge representations: q, U, D, l, E

- Yukawa sector

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

- The breaking spurions

$$Y^u = (3,\bar{3},1,1,1) \qquad Y^d = (3,1,\bar{3},1,1) \qquad Y^e = (1,1,1,3,\bar{3})$$

The SM flavours

- Consider $\mathscr{L}_{\mathrm{SM}}$ *sans* Yukawa

$$G^{\mathrm{SM}}_{\mathrm{global}}(Y^{u,d,e}=0) = SU(3)^3 \times SU(3)^2 \times U(1)^5$$

Three identical copies of five gauge representations: q, U, D, l, E

- Yukawa sector

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

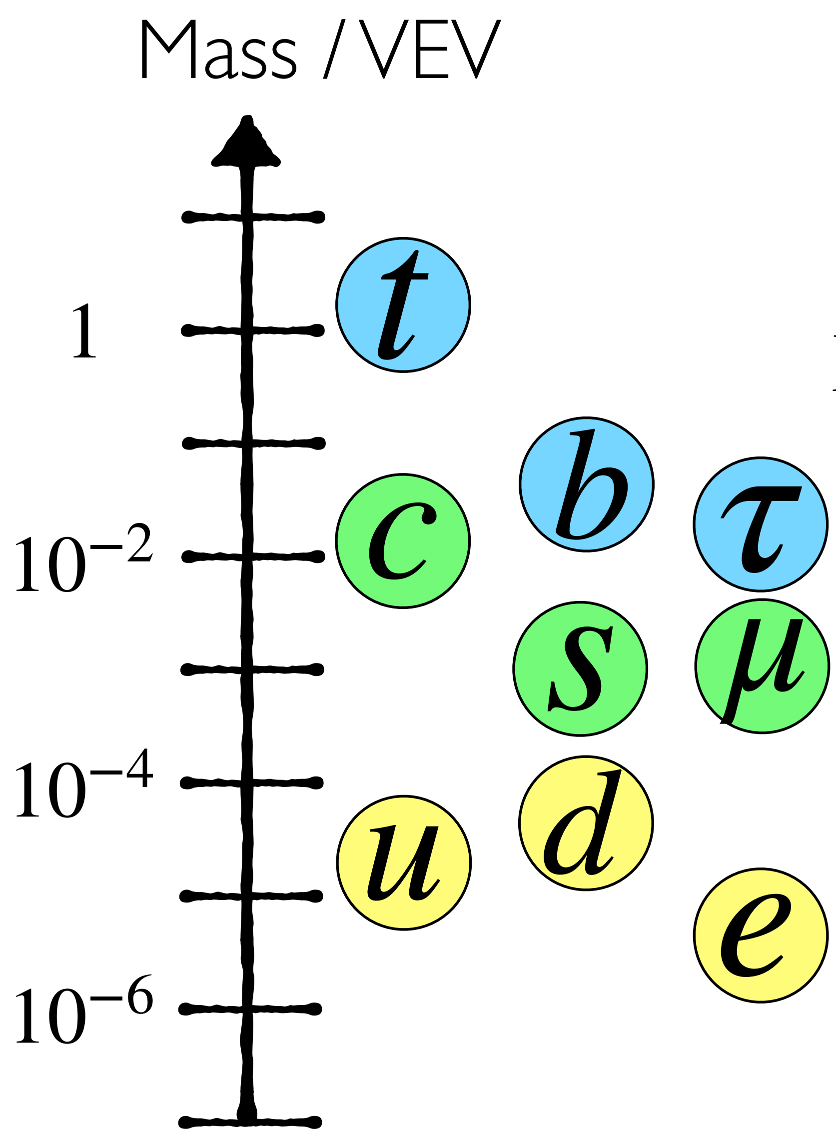
- The breaking spurions

$$Y^u = (3,\bar{3},1,1,1) \qquad Y^d = (3,1,\bar{3},1,1) \qquad Y^e = (1,1,1,3,\bar{3})$$

- The birth of flavor physics

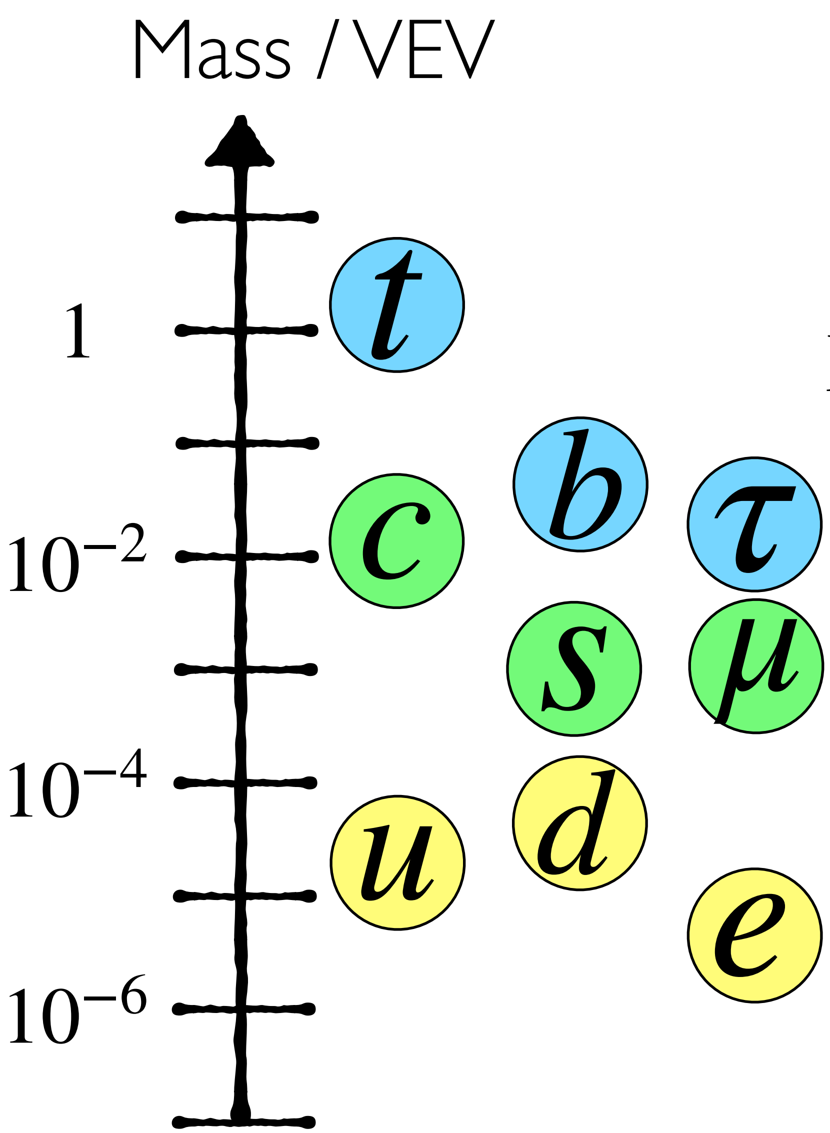
$$G^{\mathrm{SM}}_{\mathrm{global}}(Y^{u,d,e}\neq 0) = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

[Success: No proton decay, no cLFV]



Hierarchy

Y^u, Y^d, Y^e



Hierarchy

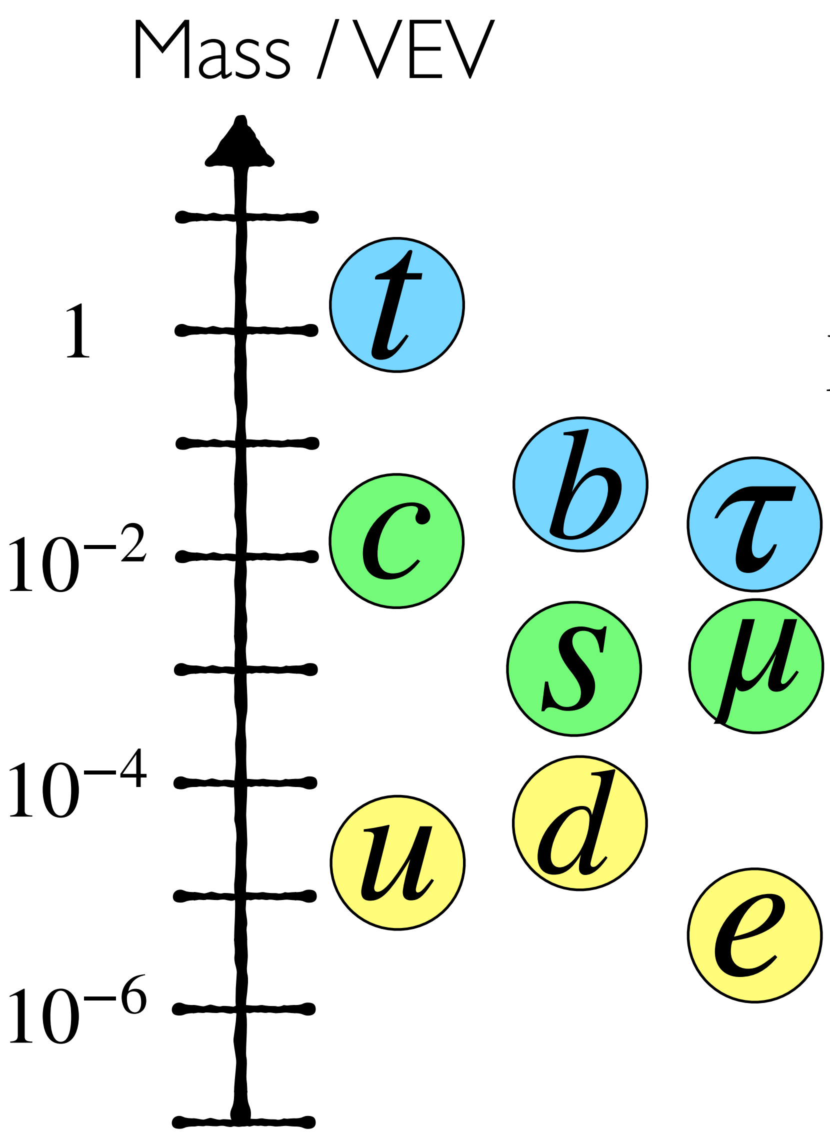
Y^u, Y^d, Y^e

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

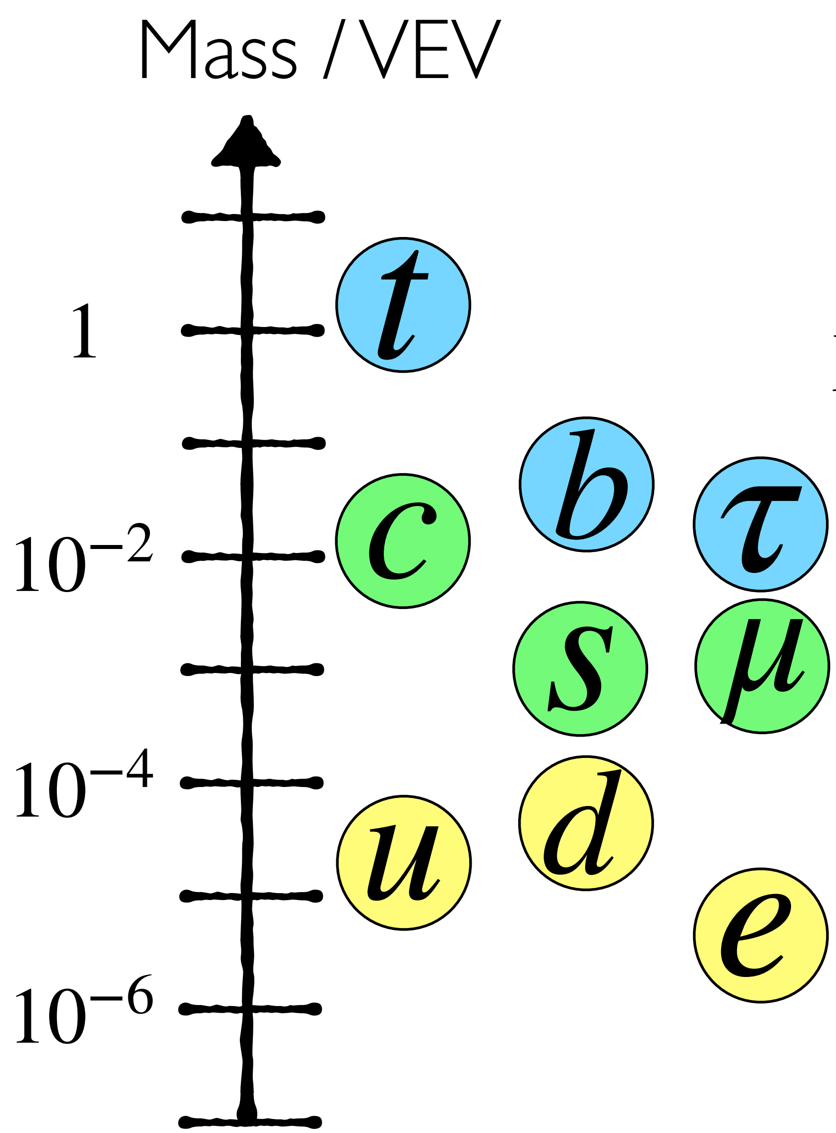
The CKM mixing

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

Alignment

Y^u & Y^d

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



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

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

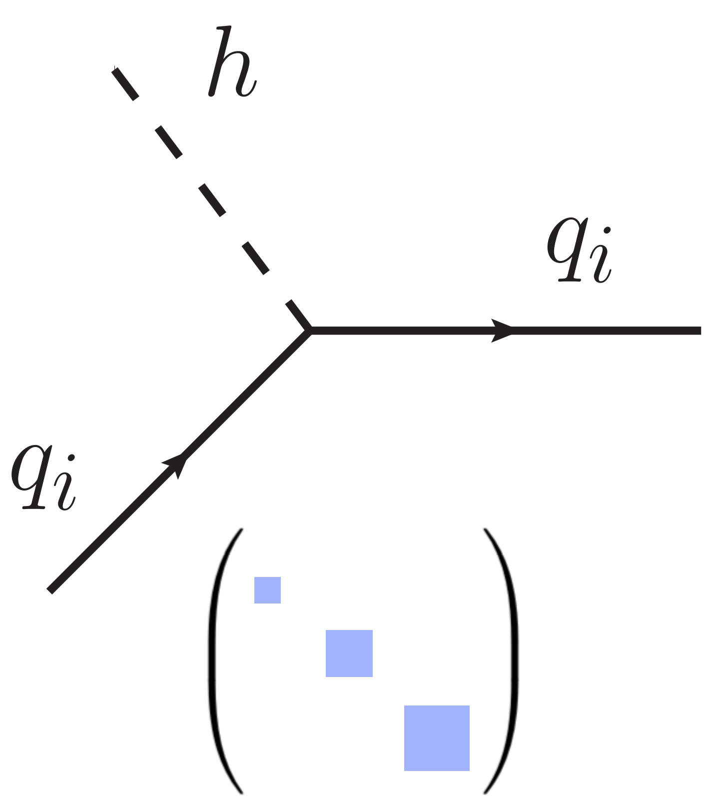
? The SM flavour puzzle

Flavor physics of the Higgs Boson

In the SM

$$H_0 \to v + h$$

$$\mathcal{L}_{\text{Yuk}} = -\frac{h}{v}\left(m_e\,\overline{e_L}\,e_R + m_\mu\,\overline{\mu_L}\,\mu_R + m_\tau\,\overline{\tau_L}\,\tau_R + m_u\,\overline{u_L}\,u_R + m_c\,\overline{c_L}\,c_R + m_t\,\overline{t_L}\,t_R + m_d\,\overline{d_L}\,d_R + m_s\,\overline{s_L}\,s_R + m_b\,\overline{b_L}\,b_R + \text{h.c.}\right)$$



- Diagonal
- Non-universal
- Proportional to the fermion masses
- Real in the mass basis

Flavor physics of the Higgs Boson

- Beyond the SM

    New sources of flavour and (or) EWS breaking would ***change*** these predictions!

Flavor physics of the Higgs Boson

Beyond the SM

New sources of flavour and (or) EWS breaking would *change* these predictions!

- 2HDM example

Add another Higgs doublet H_i where $i = 1{,}2$

$$-\mathscr{L}_{\text{Yuk}} = \bar{f} Y_i^f H_i F$$

$$M^f = Y_1^f v_1 + Y_2^f v_2$$

$$h = h_1 \cos\alpha + h_2 \sin\alpha$$

In general, the Higgs boson can have couplings that are neither proportional to the mass matrix nor diagonal, nor CP conserving.

Flavor physics of the Higgs Boson

Beyond the SM

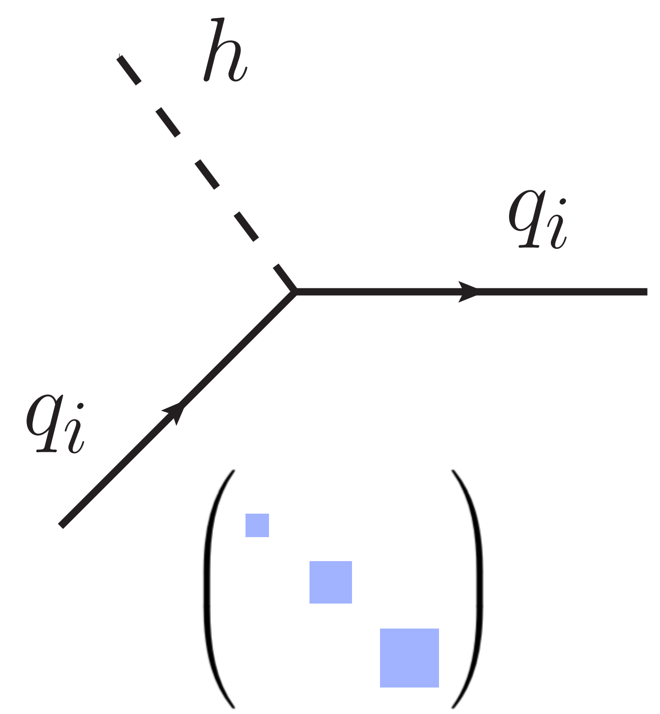
New sources of flavour and (or) EWS breaking would *change* these predictions!

• 2HDM example	• SM EFT example
Add another Higgs doublet H_i where $i = 1,2$	Add a dim-6 SM EFT correction
$-\mathscr{L}_{\text{Yuk}} = \bar{f} Y^f_i H_i F$	$-\mathscr{L}_{\text{Yuk}} = \bar{f} Y^f_1 H F + \frac{1}{\Lambda^2} \bar{f} Y^f_2 H F H^\dagger H$
$M^f = Y^f_1 v_1 + Y^f_2 v_2$ $h = h_1 \cos\alpha + h_2 \sin\alpha$	$M^f \propto Y^f_1 + Y^f_2 \frac{v^2}{\Lambda^2}$ $\quad h: \; Y^f_1 + 3\, Y^f_2 \frac{v^2}{\Lambda^2}$

In general, the Higgs boson can have couplings that are neither proportional to the mass matrix nor diagonal, nor CP conserving.

Flavor physics of the Higgs Boson

Test it!



- Diagonal couplings?
- Off-diagonal couplings?
- CP violation?

Flavor physics of the Higgs Boson

Diagonal couplings

$$\kappa_t = 1.43 \pm 0.23, \qquad \kappa_b = 0.60 \pm 0.18, \qquad \kappa_c \lesssim 6.2,$$
$$\kappa_s < 65, \qquad \kappa_d < 1.4 \cdot 10^3, \qquad \kappa_u < 3.0 \cdot 10^3,$$
$$\kappa_\tau = 0.88 \pm 0.13, \qquad \kappa_\mu = 0.2^{+1.2}_{-0.2}, \qquad \kappa_e \lesssim 630.$$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

Flavor physics of the Higgs Boson

Diagonal couplings

$\kappa_t = 1.43 \pm 0.23,$ $\kappa_b = 0.60 \pm 0.18,$ $\kappa_c \lesssim 6.2,$

$\kappa_s < 65,$ $\kappa_d < 1.4 \cdot 10^3,$ $\kappa_u < 3.0 \cdot 10^3,$

$\kappa_\tau = 0.88 \pm 0.13,$ $\kappa_\mu = 0.2^{+1.2}_{-0.2},$ $\kappa_e \lesssim 630.$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

- Only third family Yukawas are observed.

Flavor physics of the Higgs Boson

Diagonal couplings

$\kappa_t = 1.43 \pm 0.23,$	$\kappa_b = 0.60 \pm 0.18,$	$\kappa_c \lesssim 6.2,$
$\kappa_s < 65,$	$\kappa_d < 1.4 \cdot 10^3,$	$\kappa_u < 3.0 \cdot 10^3,$
$\kappa_\tau = 0.88 \pm 0.13,$	$\kappa_\mu = 0.2^{+1.2}_{-0.2},$	$\kappa_e \lesssim 630.$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

- Only third family Yukawas are observed.
- Light Yukawa is a pressing issue! Q: Is the same mechanism at work?

Flavor physics of the Higgs Boson

Diagonal couplings

$\kappa_t = 1.43 \pm 0.23,$	$\kappa_b = 0.60 \pm 0.18,$	$\kappa_c \lesssim 6.2,$
$\kappa_s < 65,$	$\kappa_d < 1.4 \cdot 10^3,$	$\kappa_u < 3.0 \cdot 10^3,$
$\kappa_\tau = 0.88 \pm 0.13,$	$\kappa_\mu = 0.2^{+1.2}_{-0.2},$	$\kappa_e \lesssim 630.$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

- Only third family Yukawas are observed.
- Light Yukawa is a pressing issue! Q: Is the same mechanism at work?

- Charm Yukawa
  - Exclusive Higgs decays to mesons: 1407.6695, 1406.1722, 1505.03870
  - Vh associated production: 1503.00290,1505.06689,1505.06689
  - Higgs differential distributions: 1606.09253, 1606.09621

HL-LHC sensitivity $\mathcal{O}(y_c)$

Flavor physics of the Higgs Boson

Diagonal couplings

$\kappa_t = 1.43 \pm 0.23,$	$\kappa_b = 0.60 \pm 0.18,$	$\kappa_c \lesssim 6.2,$
$\kappa_s < 65,$	$\kappa_d < 1.4 \cdot 10^3,$	$\kappa_u < 3.0 \cdot 10^3,$
$\kappa_\tau = 0.88 \pm 0.13,$	$\kappa_\mu = 0.2^{+1.2}_{-0.2},$	$\kappa_e \lesssim 630.$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

- Only third family Yukawas are observed.
- Light Yukawa is a pressing issue! Q: Is the same mechanism at work?

- Charm Yukawa
  - Exclusive Higgs decays to mesons: 1407.6695, 1406.1722, 1505.03870
  - Vh associated production: 1503.00290,1505.06689;1505.06689
  - Higgs differential distributions: 1606.09253, 1606.09621

  HL-LHC sensitivity $\mathcal{O}(y_c)$

- Muon Yukawa

  1.2 ± 0.6, ATLAS 2007.07830.

  1.2 ± 0.4, CMS CMS-PAS-HIG-19-006.

  The observation at the end of Run 3?

Flavor physics of the Higgs Boson

Off-diagonal couplings

Quarks

- Neutral meson mixing provide stringent constraints

$K - \bar{K}$	$\mathrm{Br}(h \to s\bar{d} + d\bar{s}) < 4.2 \times 10^{-7}$
$D - \bar{D}$	$\mathrm{Br}(h \to c\bar{u} + u\bar{c}) < 3.7 \times 10^{-6}$
$B - \bar{B}$	$\mathrm{Br}(h \to b\bar{d} + d\bar{b}) < 1.7 \times 10^{-5}$
$B_s - \bar{B}_s$	$\mathrm{Br}(h \to b\bar{s} + s\bar{b}) < 1.3 \times 10^{-3}$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

Flavor physics of the Higgs Boson

Off-diagonal couplings

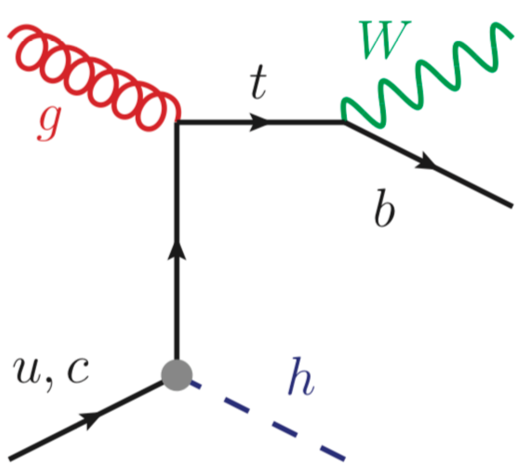
Quarks

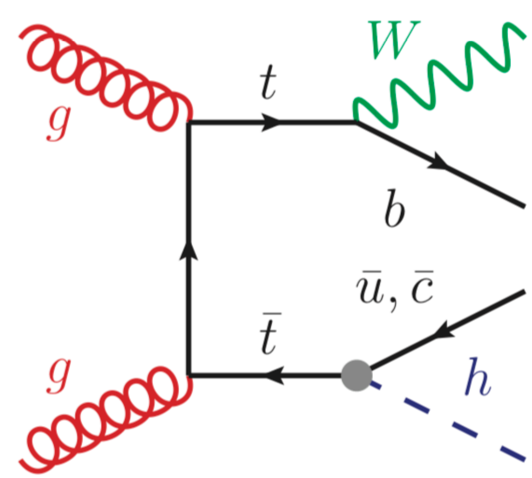
- Neutral meson mixing provide stringent constraints

$K-\bar{K}$	$\mathrm{Br}(h \to s\bar{d} + d\bar{s}) < 4.2 \times 10^{-7}$
$D-\bar{D}$	$\mathrm{Br}(h \to c\bar{u} + u\bar{c}) < 3.7 \times 10^{-6}$
$B-\bar{B}$	$\mathrm{Br}(h \to b\bar{d} + d\bar{b}) < 1.7 \times 10^{-5}$
$B_s-\bar{B}_s$	$\mathrm{Br}(h \to b\bar{s} + s\bar{b}) < 1.3 \times 10^{-3}$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

- Top decays and tH production





1404.1278

$$Br(t \to ch) < 0.11\,\%$$

ATLAS, 1812.11568

$$Br(t \to ch) < 0.47\,\%$$

CMS, 1712.02399

Flavor physics of the Higgs Boson

Off-diagonal couplings

Leptons

$\mu \to e\gamma$ implies stringent constraints on $h \to \mu e$

Flavor physics of the Higgs Boson

Off-diagonal couplings

Leptons

$\mu \to e\gamma$ implies stringent constraints on $h \to \mu e$

- For $h \to \tau\mu$ and $h \to \tau e$ the best constraints are from Higgs decays

$$Br(h \to \tau\mu) < 0.25\,\%$$
$$Br(h \to \tau e) < 0.61\,\%$$

CMS 1712.07173

$$Br(h \to \tau\mu) < 0.28\,\%$$
$$Br(h \to \tau e) < 0.47\,\%$$

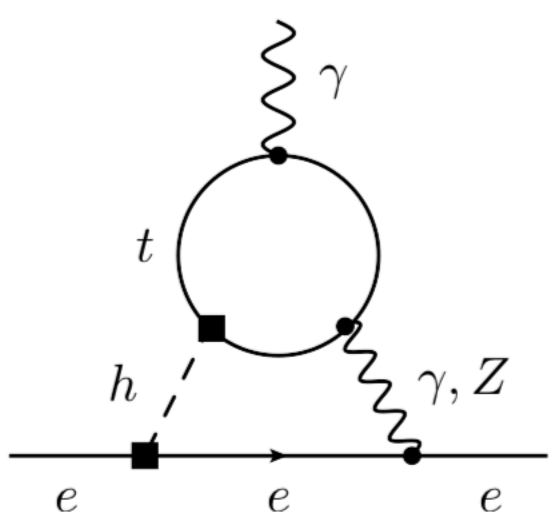
ATLAS 1907.06131

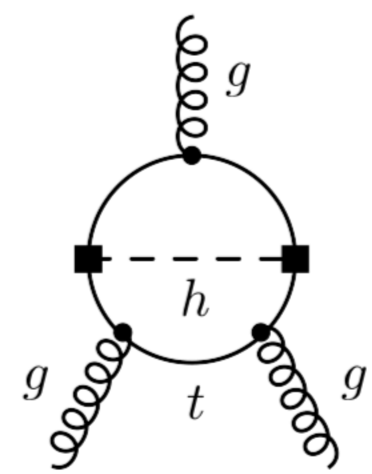
[For New Physics Models Facing Lepton Flavor Violating Higgs Decays at the Percent Level see 1502.07784]

Flavor physics of the Higgs Boson

CP violation

- EDMs



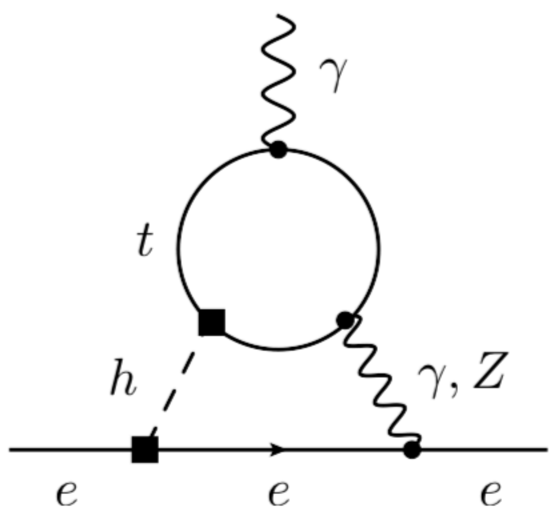


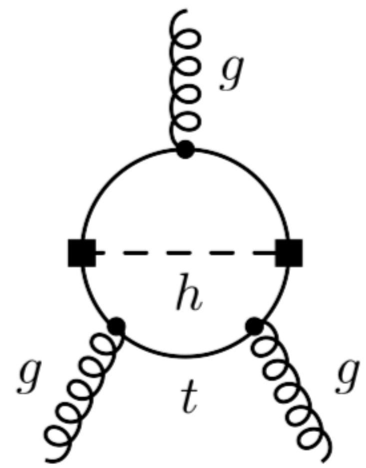
1310.1385, 1503.04830, 1510.00725

Flavor physics of the Higgs Boson

CP violation

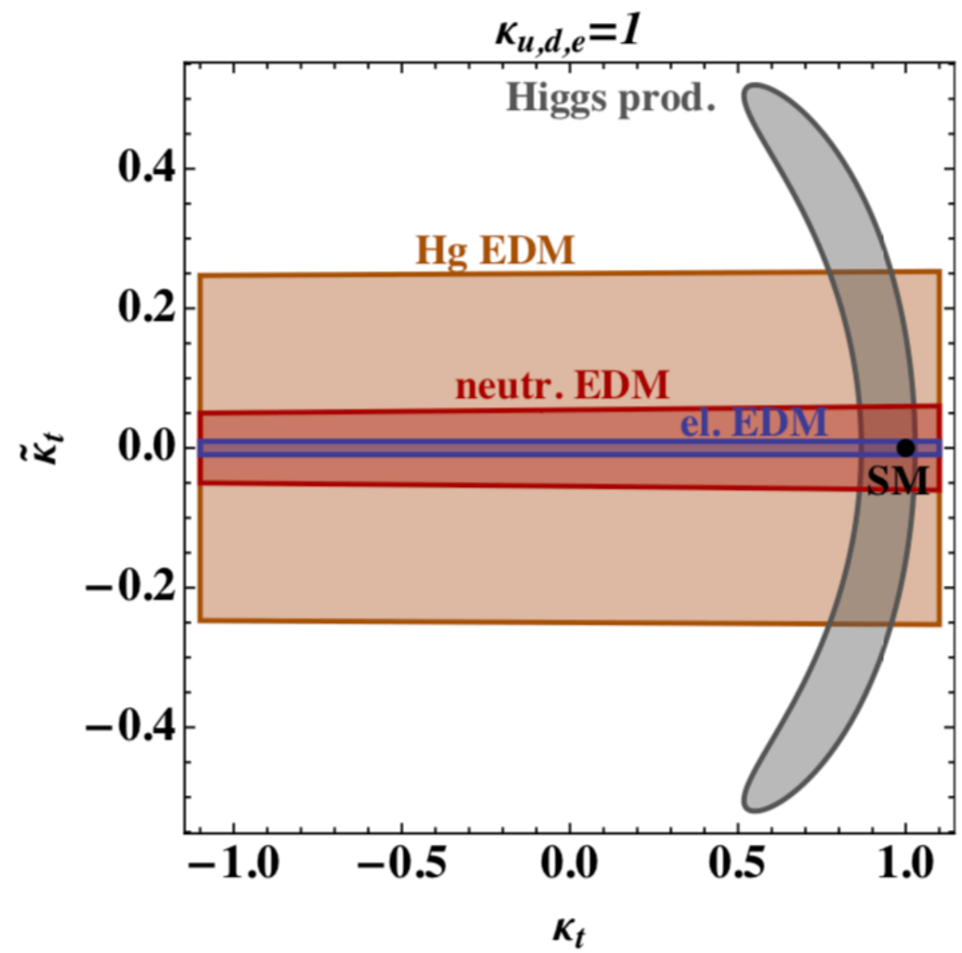
- EDMs





1310.1385, 1503.04830, 1510.00725

- EDMs versus LHC interplay

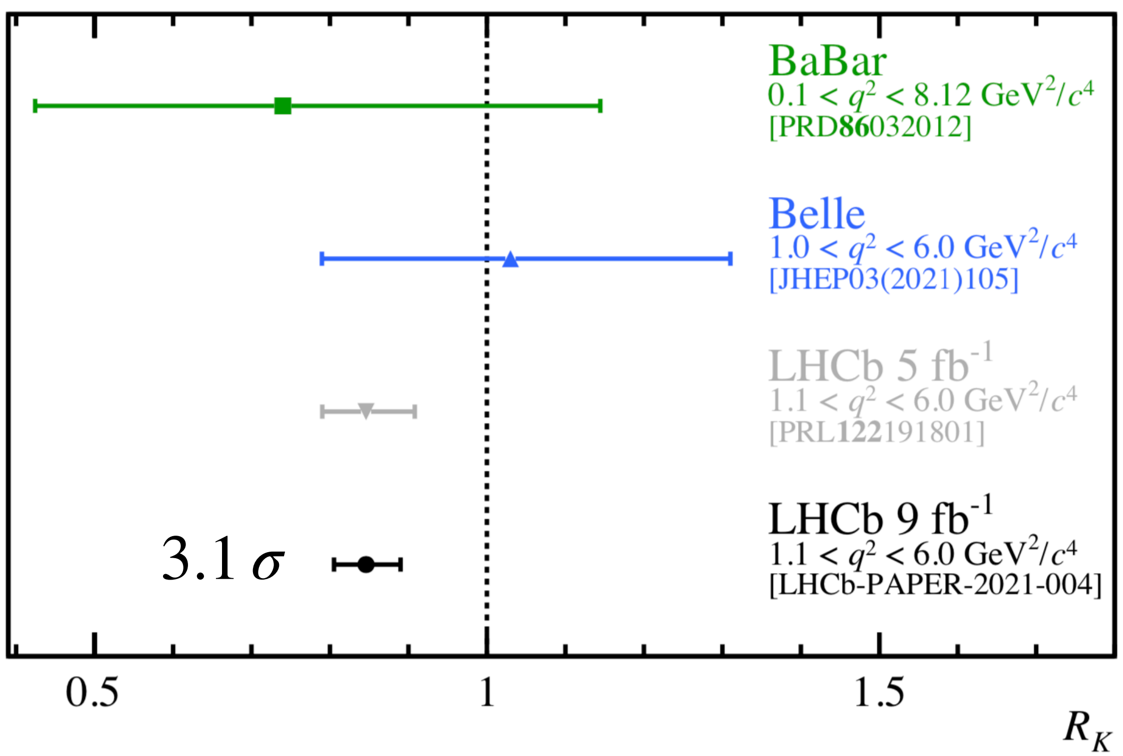


1310.1385

Part II

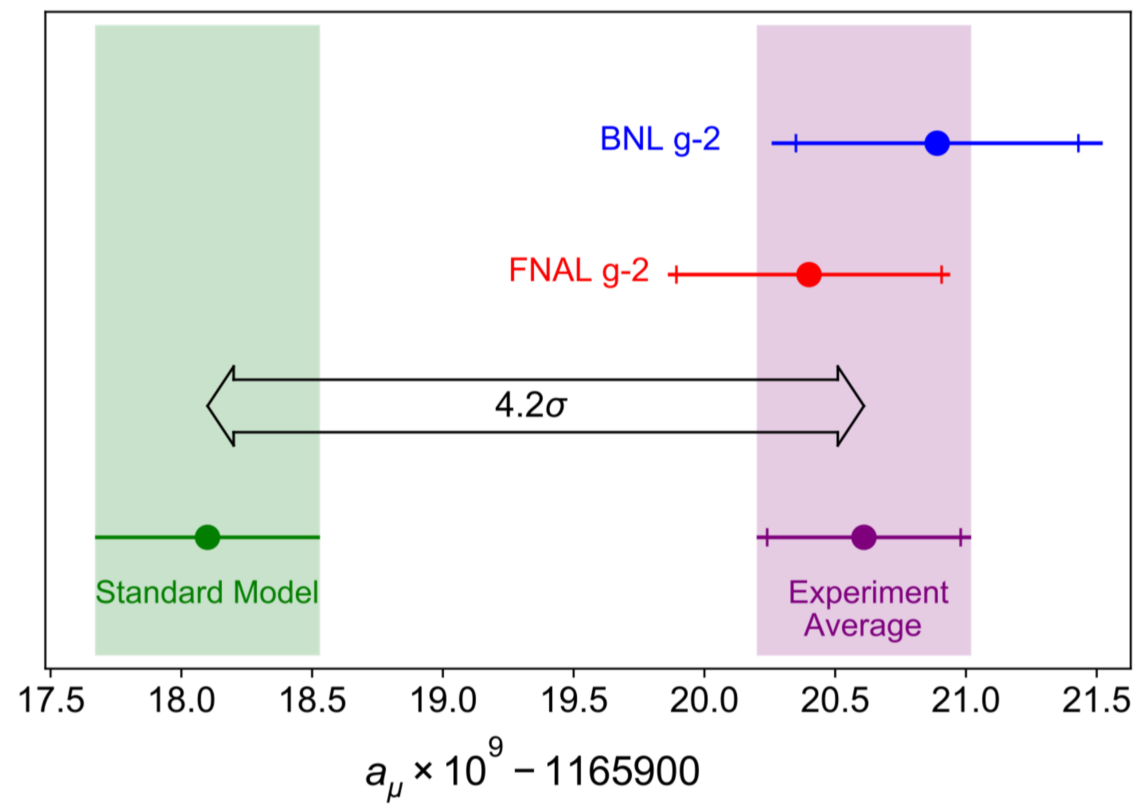
Hot topic in flavour physics: **Muon Anomalies**

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



LHCb, CERN, 2103.11769

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



The Muon g-2, Fermilab, 2104.03281

A **model** of Muon Anomalies

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

AG, Stangl, Thomsen, 2103.13991

A **model** of Muon Anomalies

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

A **model** of Muon Anomalies

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

Muoquark

A **model** of Muon Anomalies

- $SM \times U(1)_{B-3L_\mu}$ 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
S_3	$\bar{\mathbf{3}}$	**3**	$1/3$	$8/3$

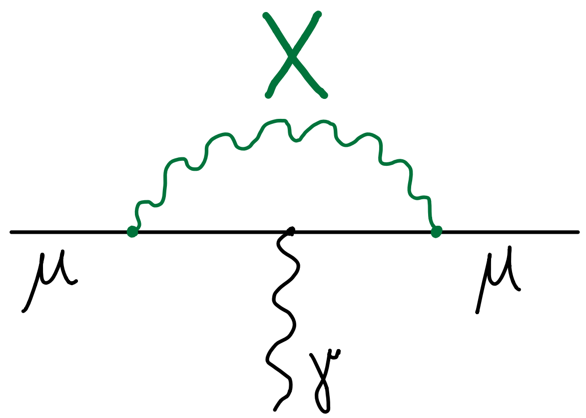
Muon force

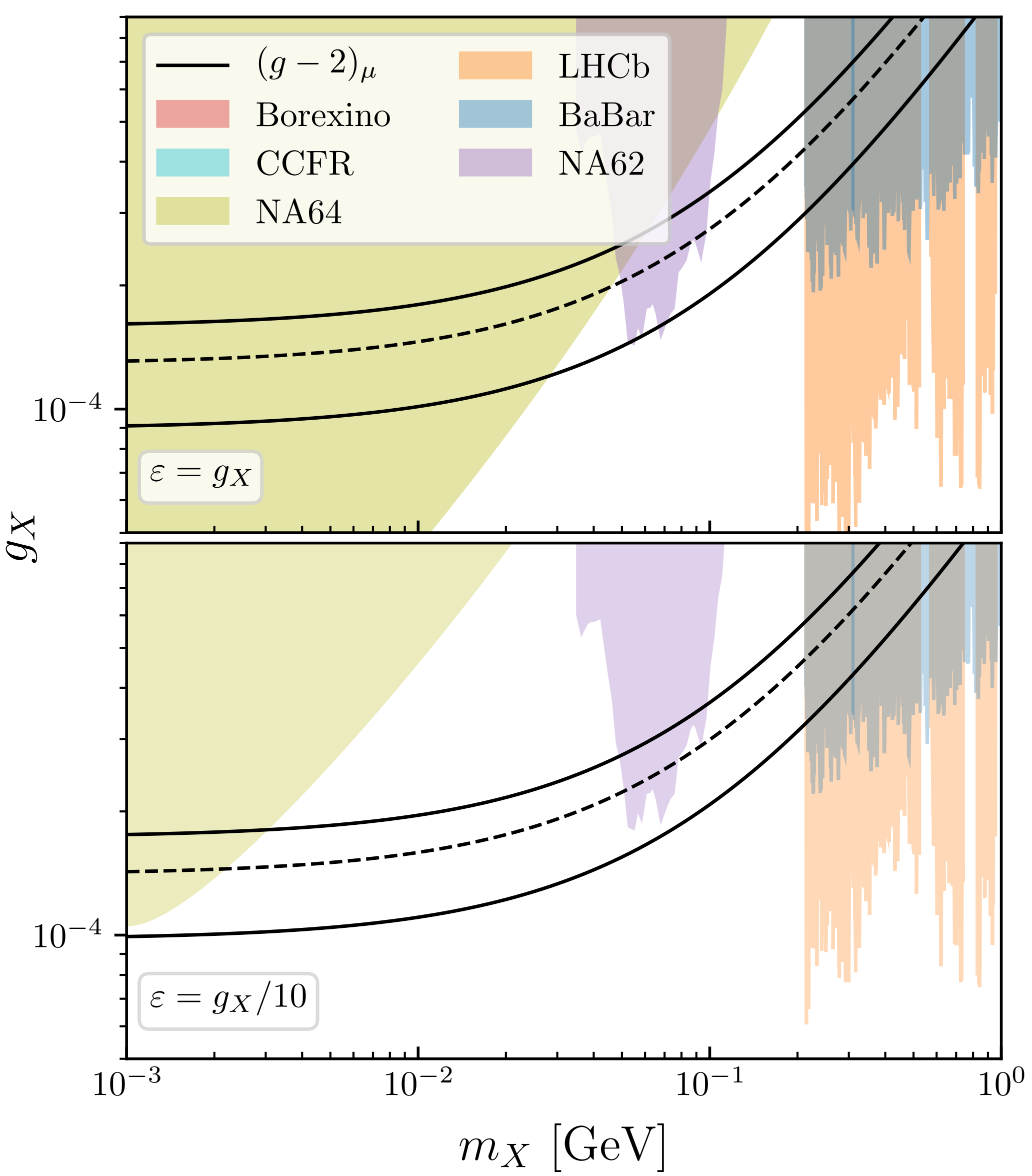
Muoquark

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

A **model** of Muon Anomalies

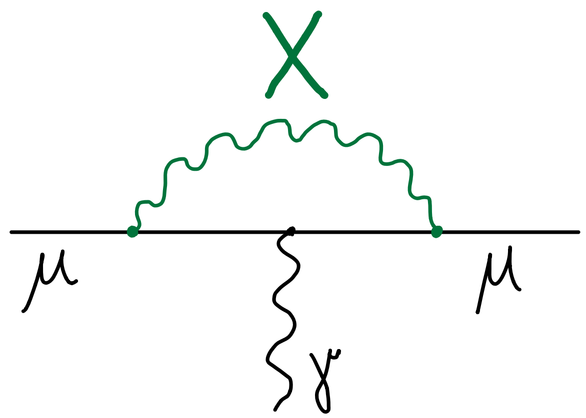
Muon force

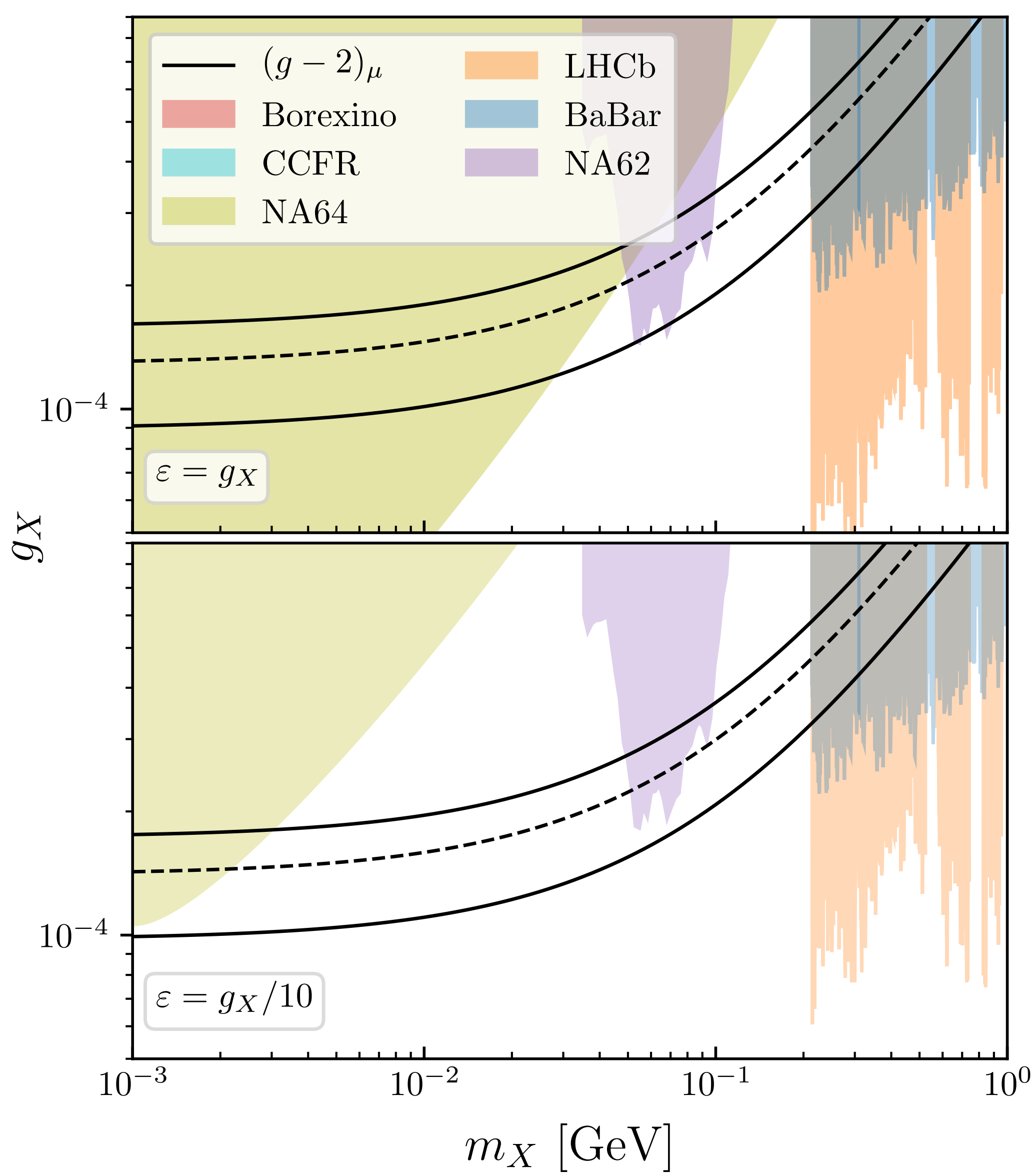




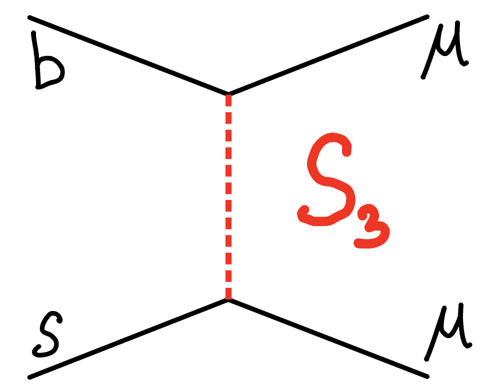
A **model** of Muon Anomalies

Muon force





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

    $$QQS_3^\dagger \quad QQS_3^\dagger\phi$$

Implications for **Higgs physics: Muoquarks**

- The Higgs portal

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

- At one-loop

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

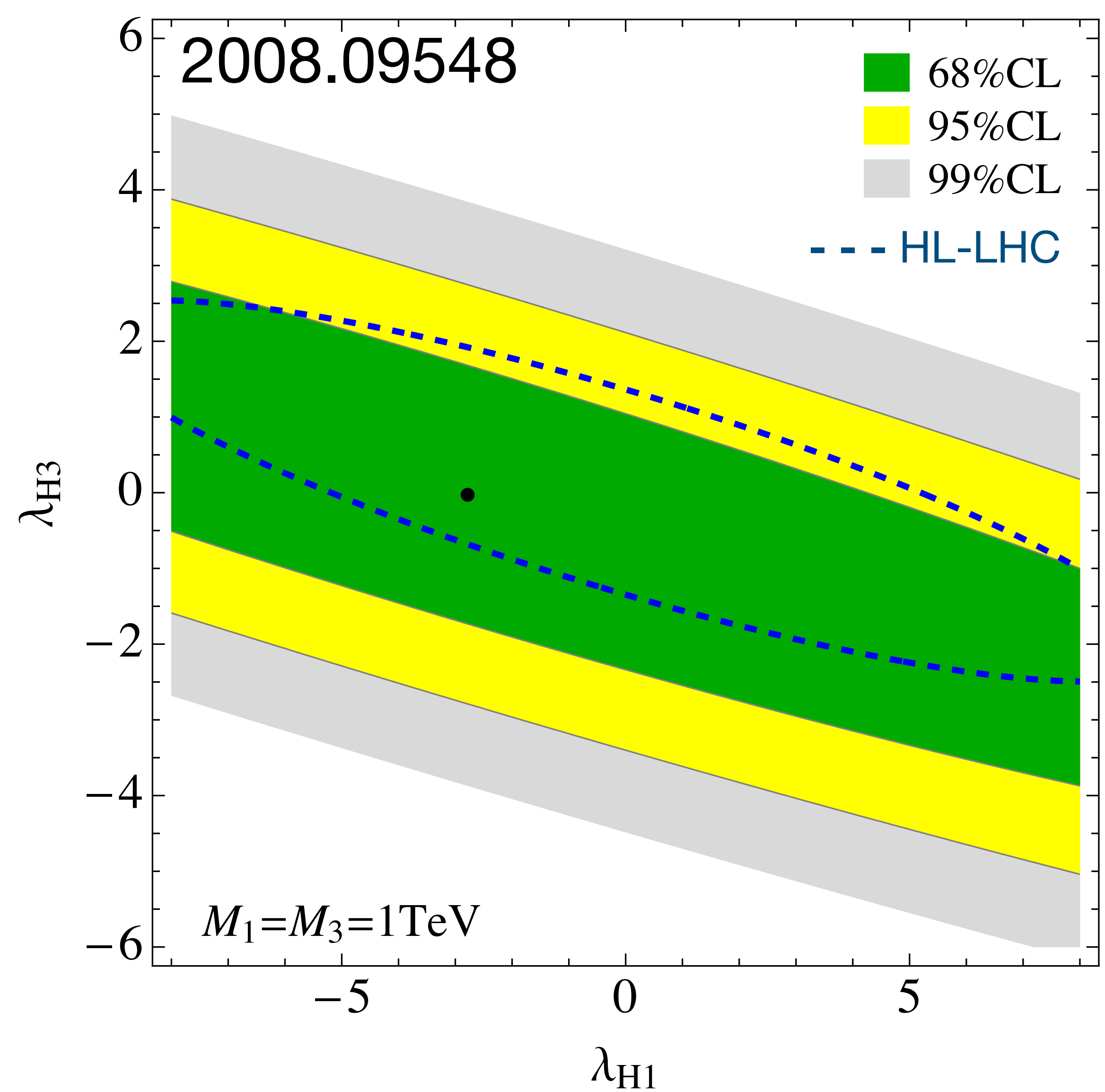
Implications for **Higgs physics: Muoquarks**

- The Higgs portal

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

- At one-loop

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



- Rather weak constraints for a TeV-scale LQ

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**

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

- 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.

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

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

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

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

Conclusions

- Flavor physics of the Higgs Boson is a rich subject
    - *Diagonal couplings*
    - *Off-diagonal couplings*
    - *CP violation*
- Flavor anomalies: *Model specific predictions for Higgs physics*