UNIVERSITÄT BERN

Higgs and Flavour

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Outline

- Yukawa puzzle
- Flavored Higgs interactions: Dim-4
- Higher-dimensional interactions
- Backup: Higgs physics and Flavor anomalies

Flavor symmetries

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

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

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

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

$$\left(\begin{array}{c} g_S \sim 1,\ g_W \sim 0.6,\ g_Y \sim 0.3,\ \lambda_H \sim 0.2 \\ v_{EW} \ll M_P \text{ - The EW hierarchy problem} \\ \theta \lesssim 10^{-10} \text{ - The strong CP problem} \end{array} \right)$$

Flavor symmetries

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$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Yukawas break $U(3)^5$

Flavor symmetries

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

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

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

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

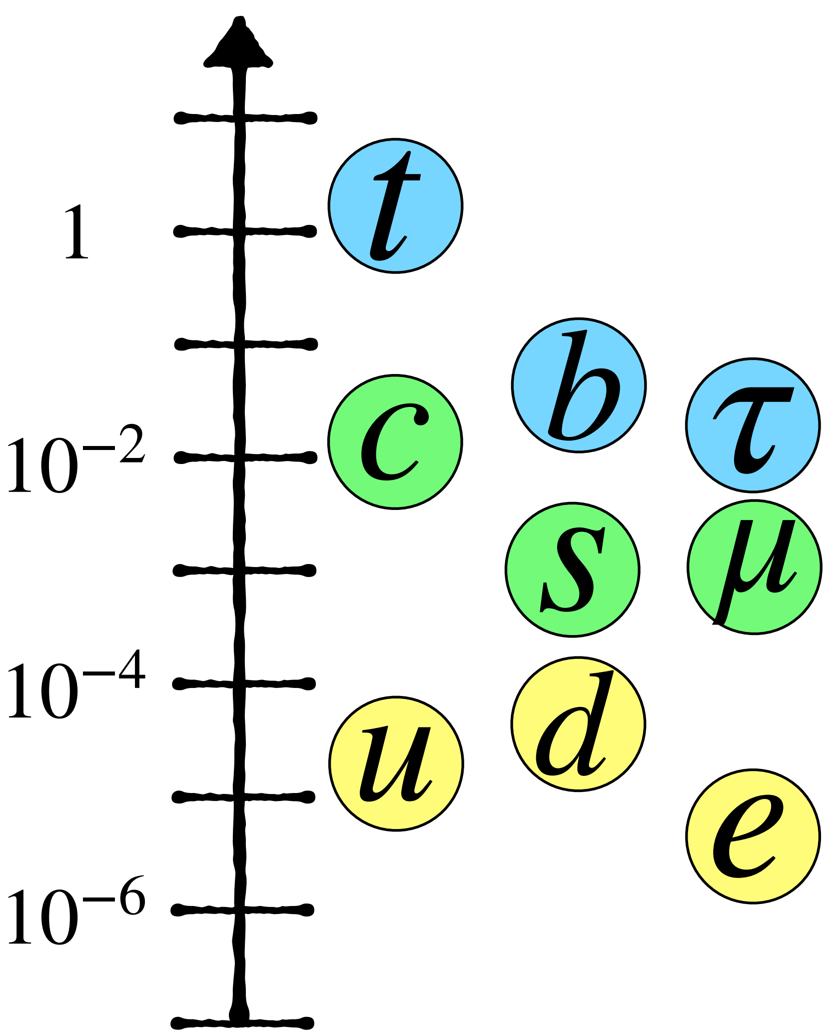
$\mathscr{L}_4^{SM}$: $\boxed{U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau}$

No proton decay nor cLFV

The Yukawa puzzle

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

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



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

The origin of flavor?

Peculiar $Y^{u,d,e} \Longrightarrow$ Approximate accidental symmetries

- CP is an *approximate* accidental symmetry

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

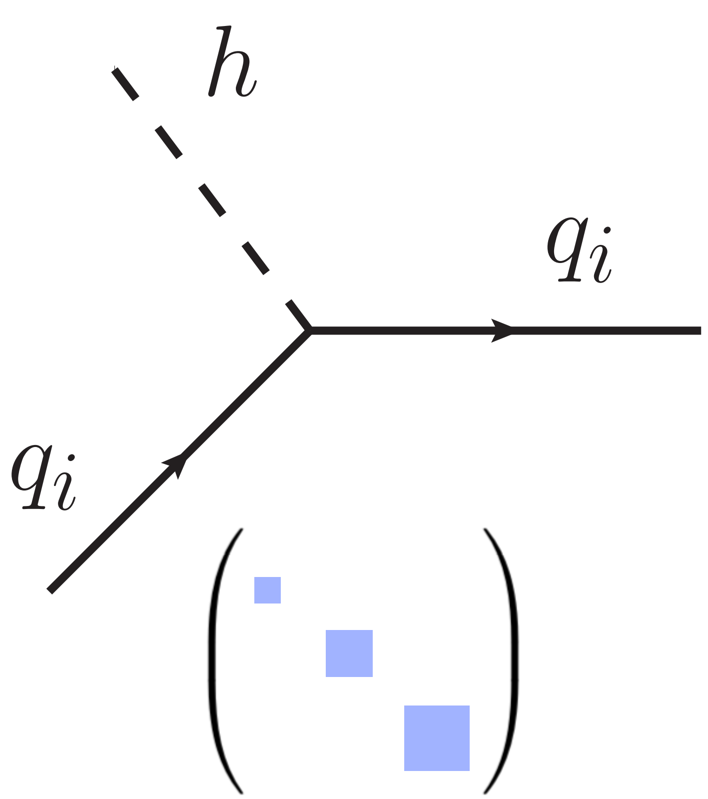
Hierarchy+Alignment

Higgs Boson Interactions

In the SM

$$H_0 \to v + h$$

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



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

Higgs Boson Interactions

- Beyond the SM

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

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

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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.

Higgs Boson Interactions

Beyond the SM

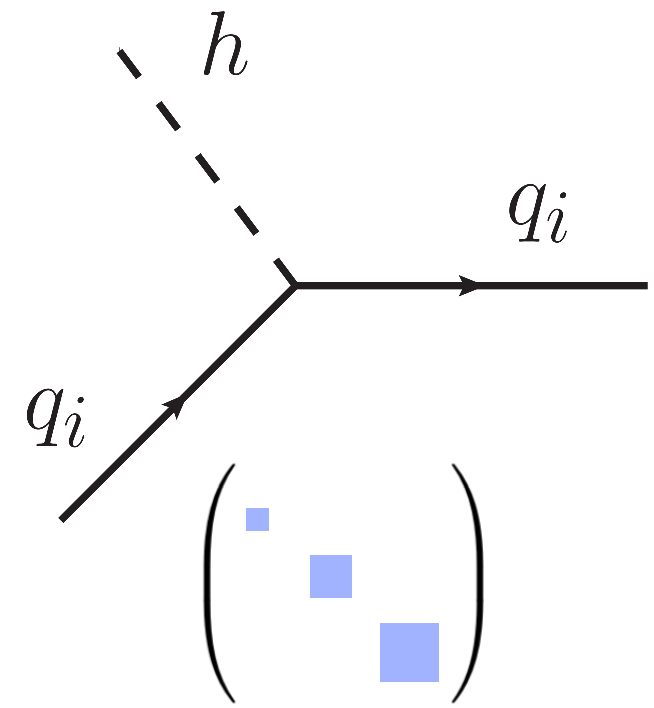
New sources of flavour and (or) EWS breaking would *change* these predictions!

• 2HDM example	• SM EFT example
Add another Higgs doublet H_i where $i = 1,2$	Add a dim-6 SM EFT correction
$-\mathscr{L}_{\rm Yuk} = \bar{f} Y_i^f H_i F$	$-\mathscr{L}_{\rm Yuk} = \bar{f} Y_1^f H F + \frac{1}{\Lambda^2} \bar{f} Y_2^f H F H^\dagger H$
$M^f = Y_1^f v_1 + Y_2^f v_2$ $h = h_1 \cos\alpha + h_2 \sin\alpha$	$M^f \propto Y_1^f + Y_2^f \frac{v^2}{\Lambda^2}$ $h :\ Y_1^f + \mathbf{3}\, Y_2^f \frac{v^2}{\Lambda^2}$

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

Higgs Boson Interactions

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

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- 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 $\mathcal{O}(y_c)$

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  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?

Off-diagonal couplings

Quarks

- Neutral meson mixing provide stringent constraints

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

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1610.07922, Section IV.6.2.c,
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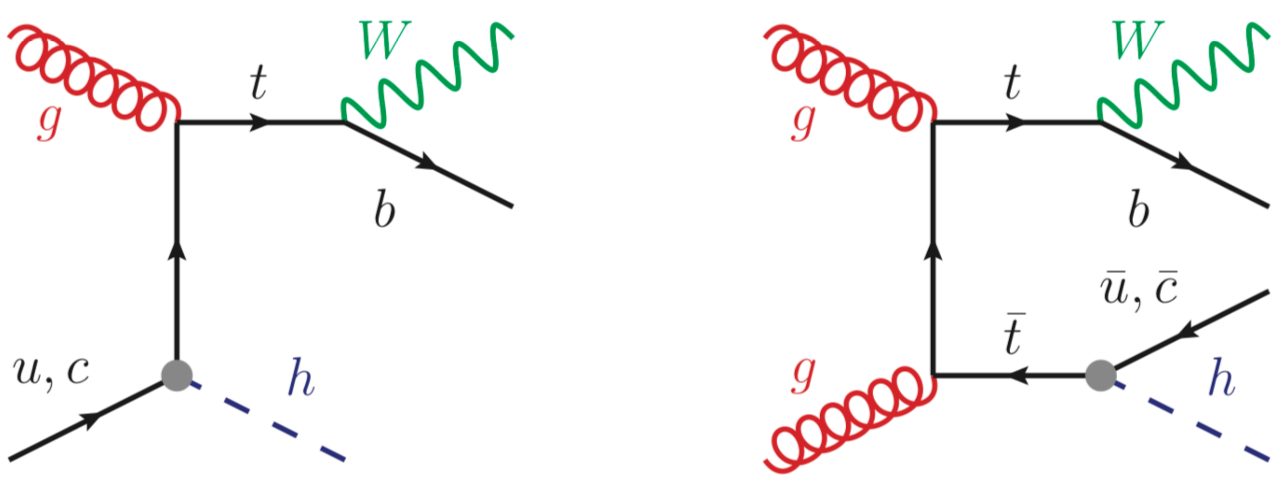
- Top decays and tH production



1404.1278

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

ATLAS, 1812.11568

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

CMS, 1712.02399

Off-diagonal couplings

Leptons

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

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

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

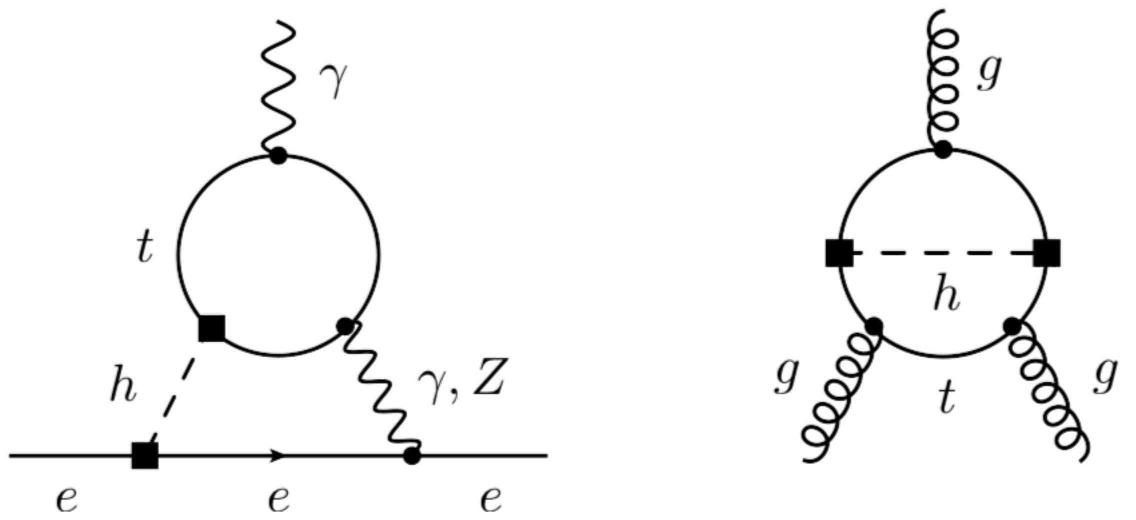
$$Br(h \to \tau e) < 0.47\,\%$$

ATLAS 1907.06131

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

CP violation

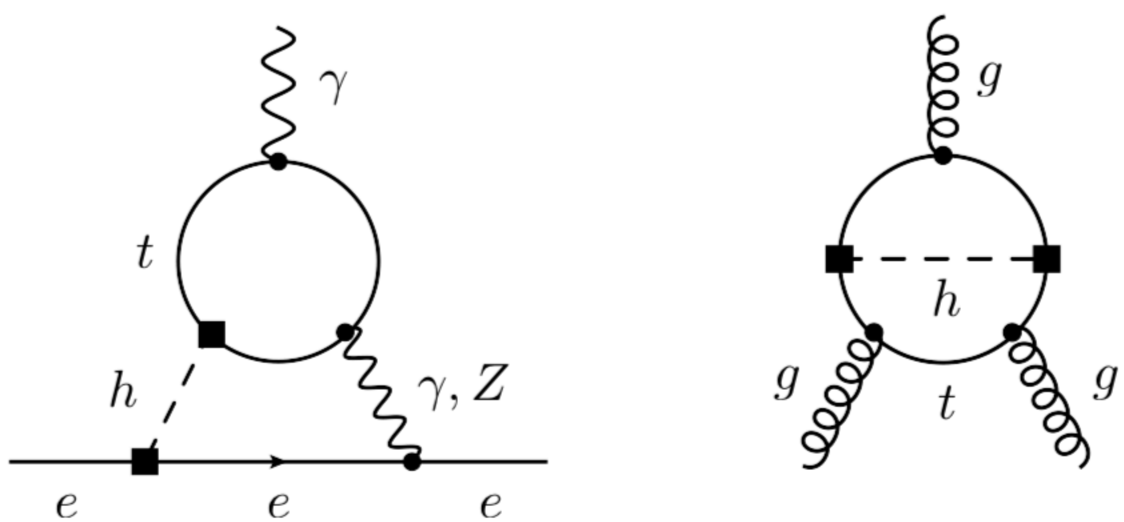
- EDMs



1310.1385, 1503.04830, 1510.00725

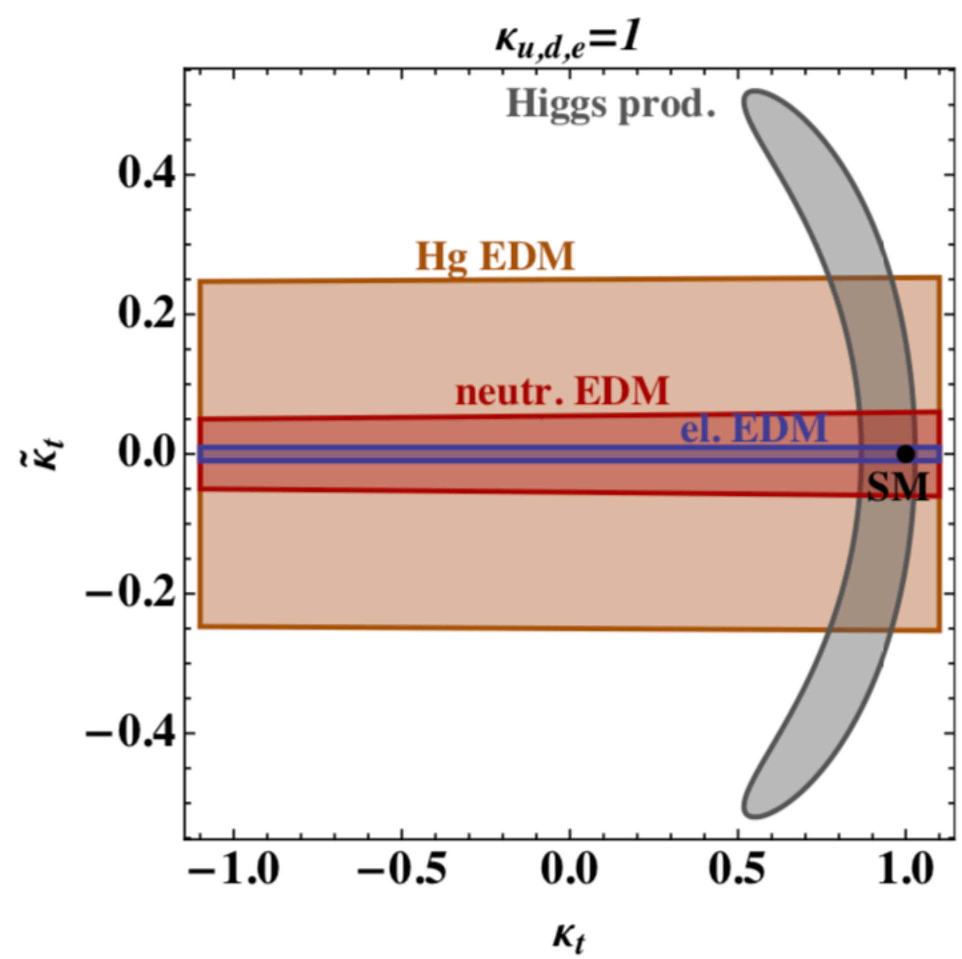
CP violation

- EDMs



1310.1385, 1503.04830, 1510.00725

- EDMs versus LHC interplay

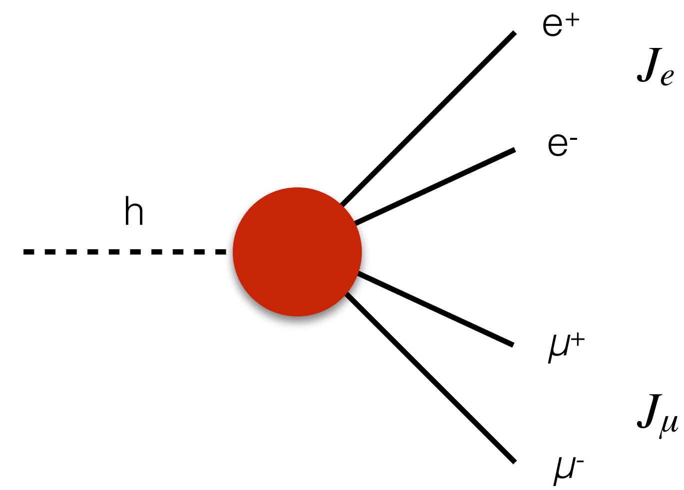


1310.1385

Higher-dimensional interactions

Example: h→2e2μ

Decomposition of the ***(helicity-conserving)*** *amplitude:*

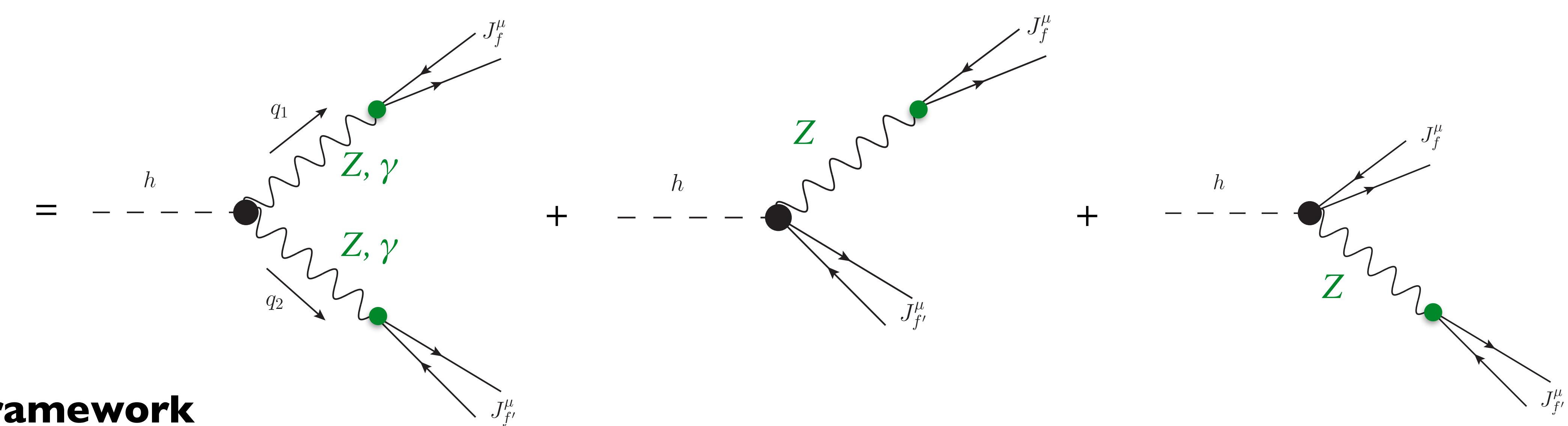


$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$

$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\ g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

Momentum expansion of the form factors around the physical poles:

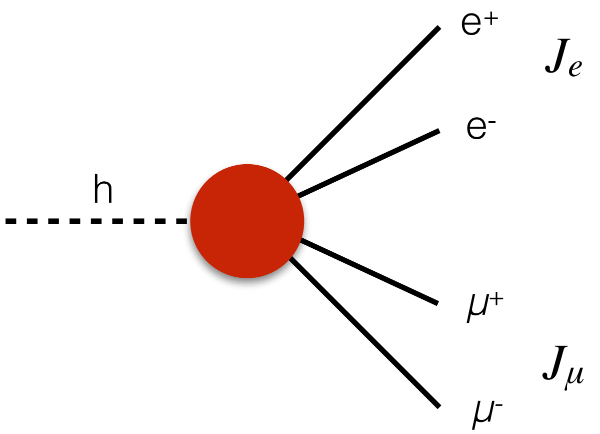
- Smooth kinematical distortions from the SM (heavy NP)



Higgs PO framework
1412.6038, 1504.04018, 1512.06135, …

Higher-dimensional interactions

Example: **h→2e2μ**



$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$

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Momentum expansion

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$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} + \right.$$

$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\ g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} +$$

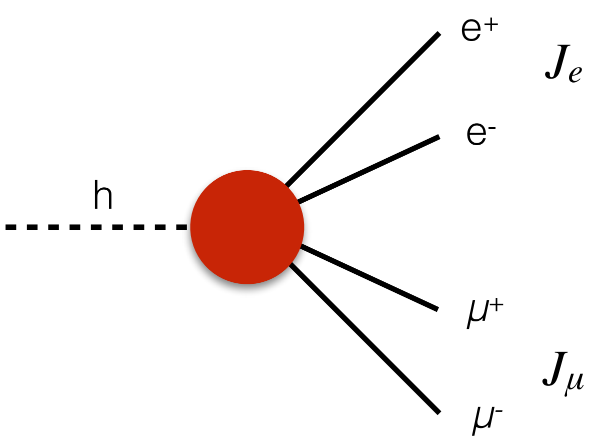
$$\left. + \left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

In the SM: $\kappa_X \to 1,\ \epsilon_X \to 0$

$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

Higher-dimensional interactions

Example: h→2e2μ



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Momentum expansion

Flavor

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$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\ g^{\alpha\beta} - {q_2}^\alpha {q_1}^\beta}{m_Z^2} +$$
$$\left. + \left(\epsilon_{ZZ}^{\text{CP}}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{\text{CP}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{\text{CP}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

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Higher-dimensional interactions

$h \to WW^*$, $h \to ZZ^*$, $h \to Z\gamma$, $h \to \gamma\gamma$

Neutral currents

$h \to e^+e^-\mu^+\mu^-$

$h \to \mu^+\mu^-\mu^+\mu^-$

$h \to e^+e^-e^+e^-$

$h \to \gamma e^+e^-$

$h \to \gamma\mu^+\mu^-$

$h \to \gamma\gamma$ 11

Charged currents

$h \to e^+\mu^-\nu\nu$

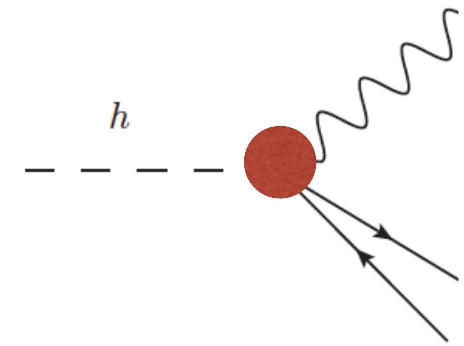
$h \to e^-\mu^+\nu\nu$ 7

N. & C. interference

$h \to e^+e^-\nu\nu$

$h \to \mu^-\mu^+\nu\nu$ 2

Compared to only 4 parameters in the present "kappa-framework"



- "Flavourful contact terms"
- Also in production $q_i q_j \to hV$
  1512.06135

Symmetry limits:

Flavour universality

$$\epsilon_{Ze_L} = \epsilon_{Z\mu_L} \,, \quad \epsilon_{Ze_R} = \epsilon_{Z\mu_R} \,, \quad \epsilon_{Z\nu_e} = \epsilon_{Z\nu_\mu} \,, \quad \epsilon_{We_L} = \epsilon_{W\mu_L} \,.$$

Custodial symmetry

$$\begin{aligned}
\epsilon_{WW} &= c_w^2 \epsilon_{ZZ} + 2 c_w s_w \epsilon_{Z\gamma} + s_w^2 \epsilon_{\gamma\gamma} \,, \\
\epsilon_{WW}^{CP} &= c_w^2 \epsilon_{ZZ}^{CP} + 2 c_w s_w \epsilon_{Z\gamma}^{CP} + s_w^2 \epsilon_{\gamma\gamma}^{CP} \,, \\
\kappa_{WW} - \kappa_{ZZ} &= -\frac{2}{g} \left(\sqrt{2} \epsilon_{We_L^i} + 2 c_w \epsilon_{Ze_L^i} \right) \,, \\
\epsilon_{We_L^i} &= \frac{c_w}{\sqrt{2}} \left(\epsilon_{Z\nu_L^i} - \epsilon_{Ze_L^i} \right) \,,
\end{aligned}$$

CP conservation

$$\epsilon_{ZZ}^{CP} = \epsilon_{Z\gamma}^{CP} = \epsilon_{\gamma\gamma}^{CP} = \epsilon_{WW}^{CP} = \mathrm{Im}\,\epsilon_{We_L} = \mathrm{Im}\,\epsilon_{W\mu_L} = 0$$

1412.6038

Higher-dimensional interactions

Linear effective field theory: *SMEFT*

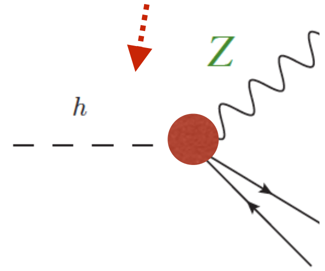
- Higgs boson is a part of $SU(2)_L$ doublet field **H**
- Leading effects expected at dimension six

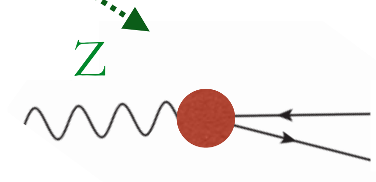
$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \ldots$$

[arXiv:1504.04018]
[arXiv:1508.00581]

"Contact term" Higgs **PO** constrained from non-Higgs processes (e.g. EWP data)

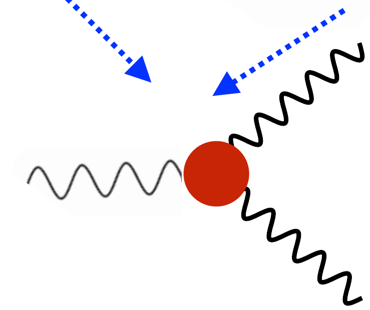
$$\epsilon_{Zf} = \frac{2m_Z}{v}\left(\delta g^{Zf} - (c_\theta^2 T_f^3 + s_\theta^2 Y_f)\mathbf{1}_3 \delta g_{1,z} + t_\theta^2 Y_f \mathbf{1}_3 \delta\kappa_\gamma\right)$$





$\delta g^{Z\ell} \lesssim 10^{-3}$

LEP I *[Efrati, Falkowski, Soreq]*



$\delta g_{1,z}$, $\delta\kappa_\gamma \lesssim 10^{-2}$

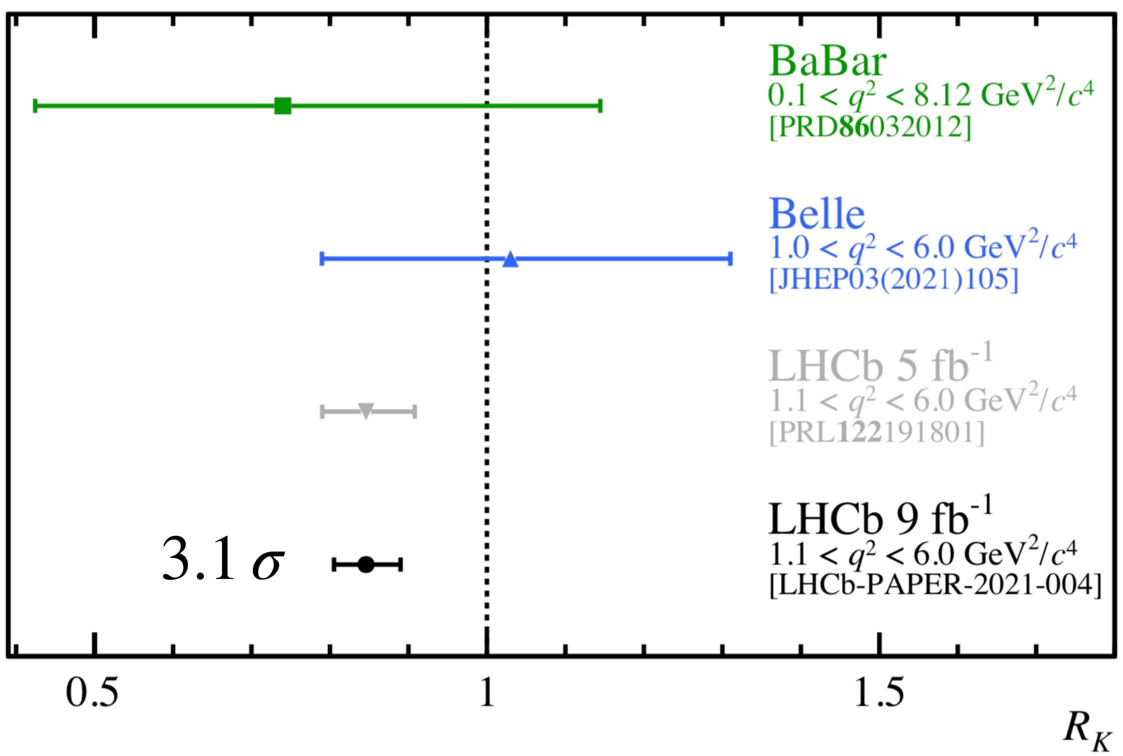
LEP II *[Falkowski, Riva]*

Backup

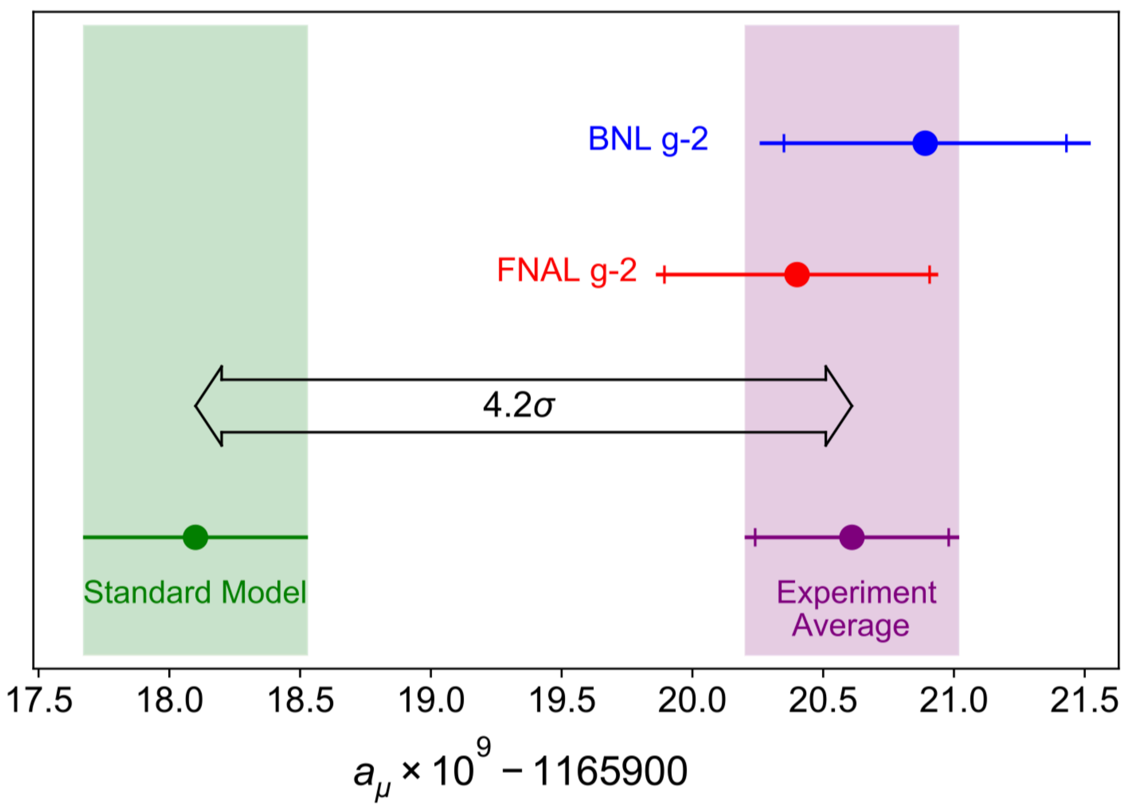
Hot topic in flavour physics: **Muon Anomalies**

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

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



LHCb, CERN, 2103.11769



The Muon g-2, Fermilab, 2104.03281

A **model** of Muon Anomalies

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

AG, Stangl, Thomsen, 2103.13991

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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

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

AG, Stangl, Thomsen, 2103.13991

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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

SM

Muon force

* Minimal type-I seesaw for the neutrino masses

Muoquark

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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**	$1/3$	$8/3$

SM

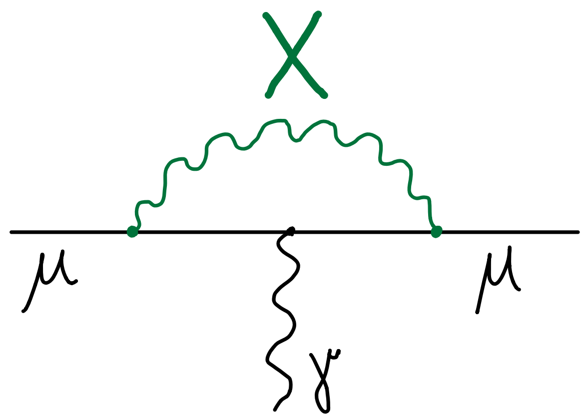
Muon force

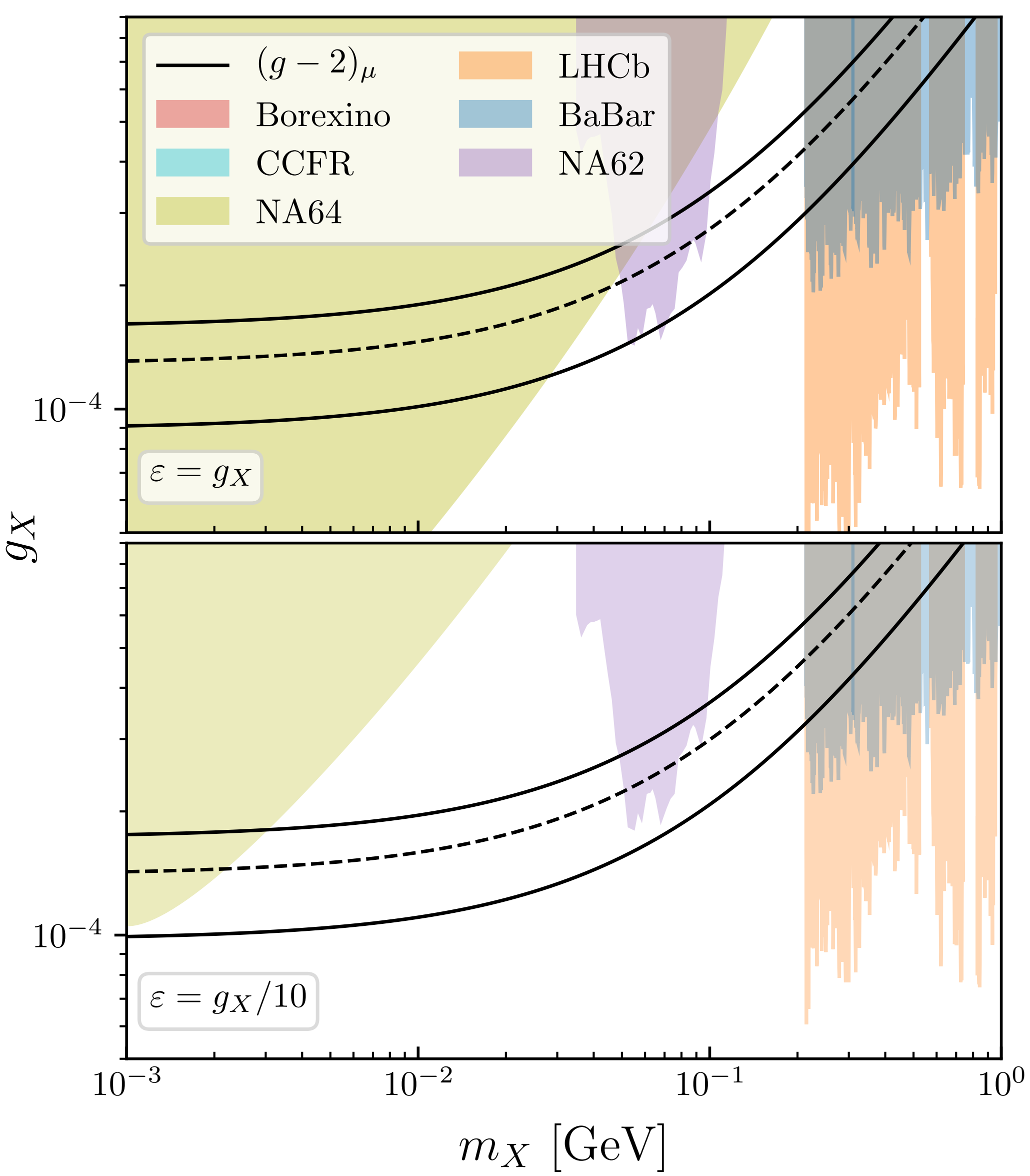
Muoquark

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

A **model** of Muon Anomalies

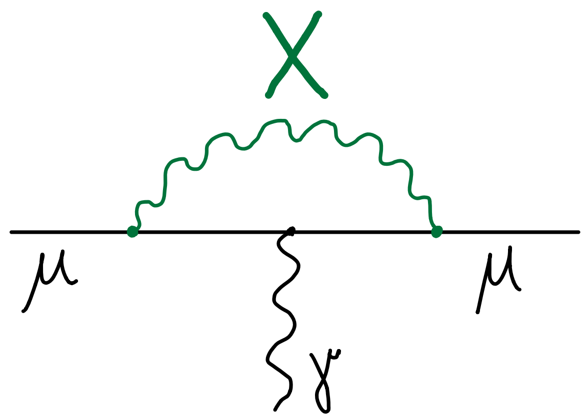
Muon force

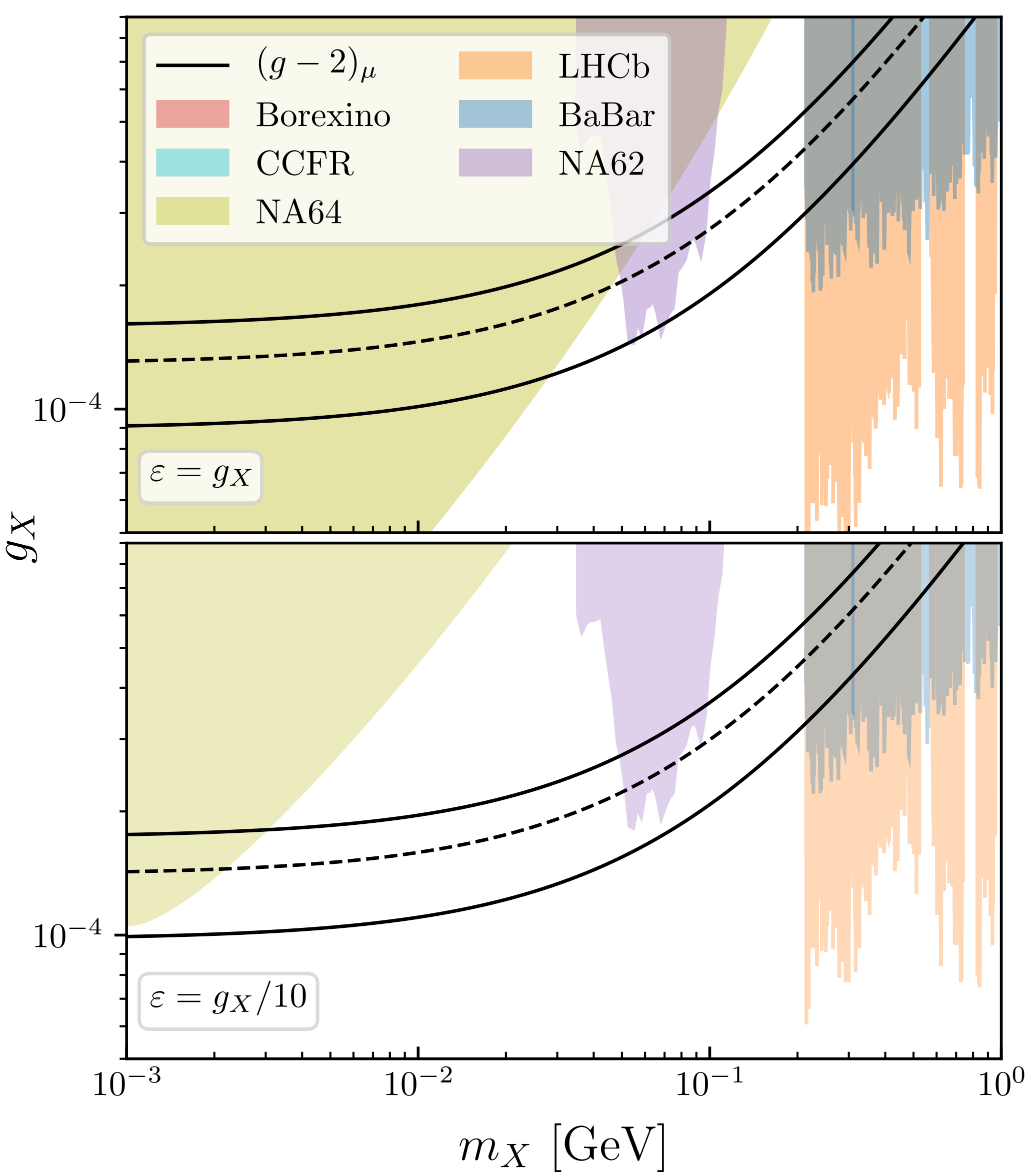




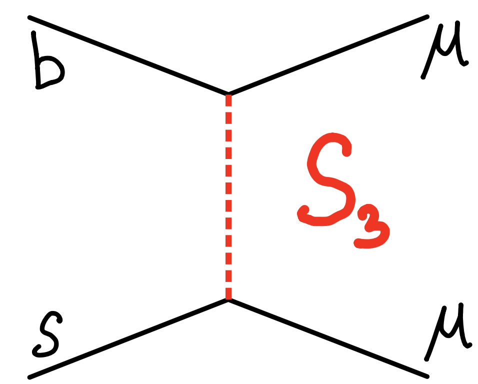
A **model** of Muon Anomalies

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

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

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

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

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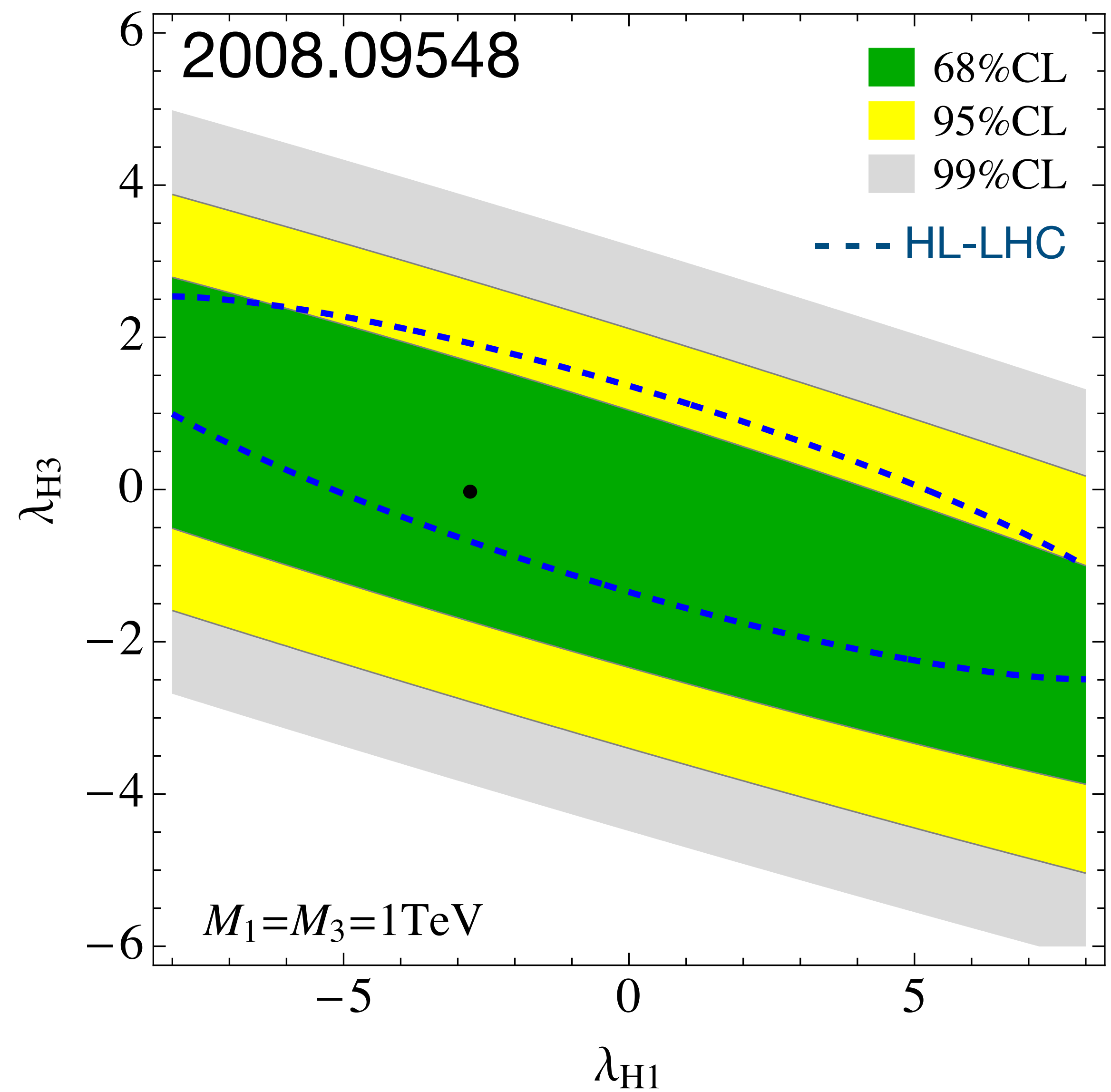

- Rather weak constraints for a TeV-scale LQ

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

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

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- 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.