Constraining Top Quark operators

Based on «Indirect constraints on top quark operators from a global SMEFT analysis»

F. Garosi, D. Marzocca, A. Rodriguez-Sanchez, A. Stanzione [2310.00047]

Outline

- ❑ Introduction: EFT framework and procedures
- ❑ Individual and two-parameter fits
- ❑ Example of global analysis and UV interpretation
- ❑ Concluding remarks

EFT framework

We work within the (SM)EFT framework: higher-dim operators built out of the SM fields and allowed by its symmetries (plus B and L conservation)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \dots .$$

e.g:

$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}^3\gamma^\mu q^3)$$

$$\mathcal{O}_{\ell q}^{(1),\alpha\beta} = (\bar{\ell}^\alpha\gamma_\mu\ell^\beta)(\bar{q}^3\gamma^\mu q^3)$$

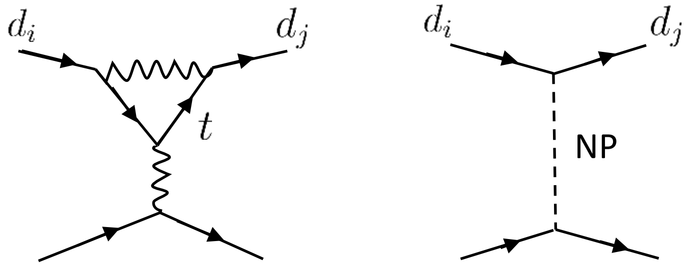
$$\mathcal{O}_{qq}^{(1)} = (\bar{q}^3\gamma^\mu q^3)(\bar{q}^3\gamma_\mu q^3)$$

$$\mathcal{O}_{uW} = (\bar{q}^3\sigma^{\mu\nu}u^3)\tau^a\tilde{H}W^a_{\mu\nu}$$

Top-philic assumption: only top quark operators generated at tree level, i.e. 19 SMEFT operators up to flavour indices (including LFV cases)

B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek [1008.4884]

We work in the up-type quark basis $q^i = (u_L^i,\, V_{ij}d_L^j)$:
FCNC $d_L^i \to d_L^j$ processes allowed at tree level, suppressed by $V_{tj}^* V_{ti}$ factors



SMEFT operators

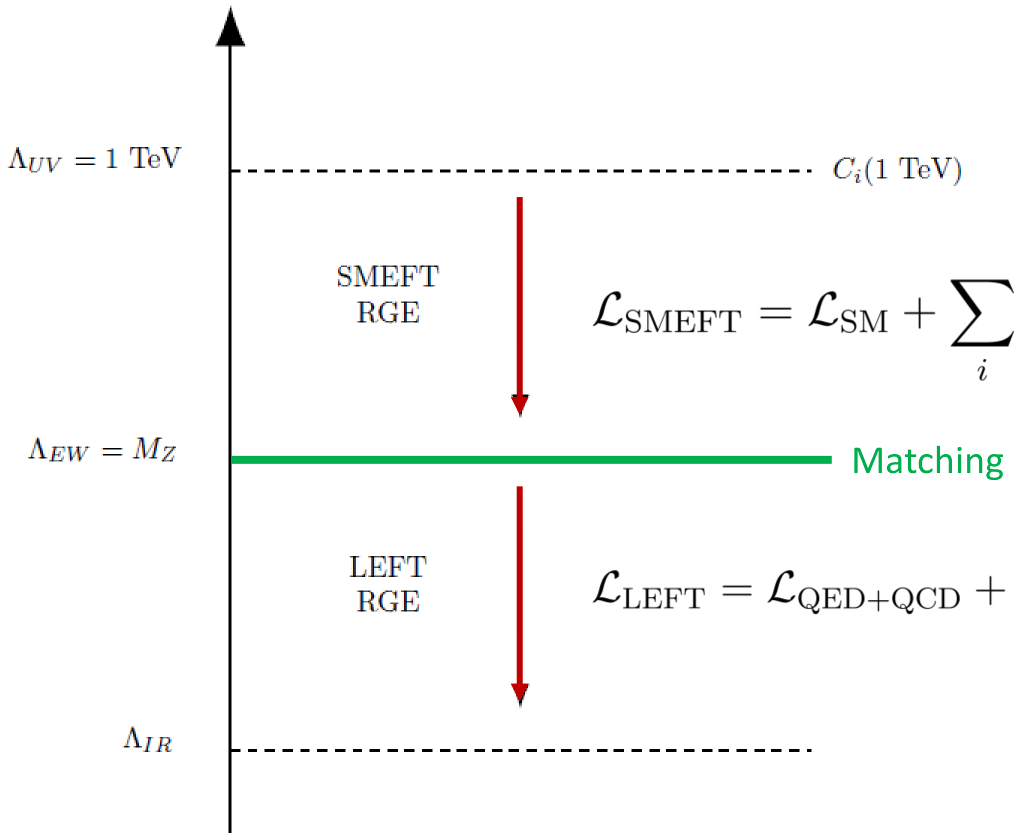
Semi-leptonic	
$\mathcal{O}_{lq}^{(1),\alpha\beta}$	$(\bar{l}^a \gamma_\mu l^\beta)(\bar{q}^3 \gamma^\mu q^3)$
$\mathcal{O}_{lq}^{(3),\alpha\beta}$	$(\bar{l}^a \gamma_\mu \tau^a l^\beta)(\bar{q}^3 \gamma^\mu \tau^a q^3)$
$\mathcal{O}_{lu}^{\alpha\beta}$	$(\bar{l}^\alpha \gamma^\mu l^\beta)(\bar{u}^3 \gamma_\mu u^3)$
$\mathcal{O}_{qe}^{\alpha\beta}$	$(\bar{q}^3 \gamma^\mu q^3)(\bar{e}^\alpha \gamma_\mu e^\beta)$
$\mathcal{O}_{eu}^{\alpha\beta}$	$(\bar{e}^\alpha \gamma^\mu e^\beta)(\bar{u}^3 \gamma_\mu u^3)$
$\mathcal{O}_{lequ}^{(1),\alpha\beta}$	$(\bar{l}^\alpha e^\beta)\epsilon(\bar{q}^3 u^3)$
$\mathcal{O}_{lequ}^{(3),\alpha\beta}$	$(\bar{l}^\alpha \sigma_{\mu\nu} e^\beta)\epsilon(\bar{q}^3 \sigma^{\mu\nu} u^3)$

Dipoles	
$\mathcal{O}_{uG}$	$(\bar{q}^3 \sigma^{\mu\nu} T^A u^3)\tilde{H} G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar{q}^3 \sigma^{\mu\nu} u^3)\tau^a \tilde{H} W^a_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar{q}^3 \sigma^{\mu\nu} u^3)\tilde{H} B_{\mu\nu}$

Four quarks	
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}^3 \gamma^\mu q^3)(\bar{q}^3 \gamma_\mu q^3)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}^3 \gamma^\mu \tau^a q^3)(\bar{q}^3 \gamma_\mu \tau^a q^3)$
$\mathcal{O}_{uu}$	$(\bar{u}^3 \gamma^\mu u^3)(\bar{u}^3 \gamma_\mu u^3)$
$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}^3 \gamma^\mu q^3)(\bar{u}^3 \gamma_\mu u^3)$
$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}^3 \gamma^\mu T^A q^3)(\bar{u}^3 \gamma_\mu T^A u^3)$

Higgs-Top	
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H)(\bar{q}^3 \gamma^\mu q^3)$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{\mathcal{D}}^a_\mu H)(\bar{q}^3 \gamma^\mu \tau^a q^3)$
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H)(\bar{u}^3 \gamma^\mu u^3)$
$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}^3 u^3 \tilde{H})$

Constrain TeV-scale operators from GeV-scale observables



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

$$\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QED+QCD}} + \sum_i \frac{L_i^{(5)}}{v_{\text{EW}}} O_i^{(5)} + \sum_i \frac{L_i^{(6)}}{v_{\text{EW}}^2} O_i^{(6)}$$

RGEs connect different energy scales within the range of validity of the EFT:

[1308.2627] [1310.4838] [1312.2014] [1711.05270]

$$\mu \frac{\partial C_n}{\partial \mu} = \gamma_{nm}(\lambda) C_m$$

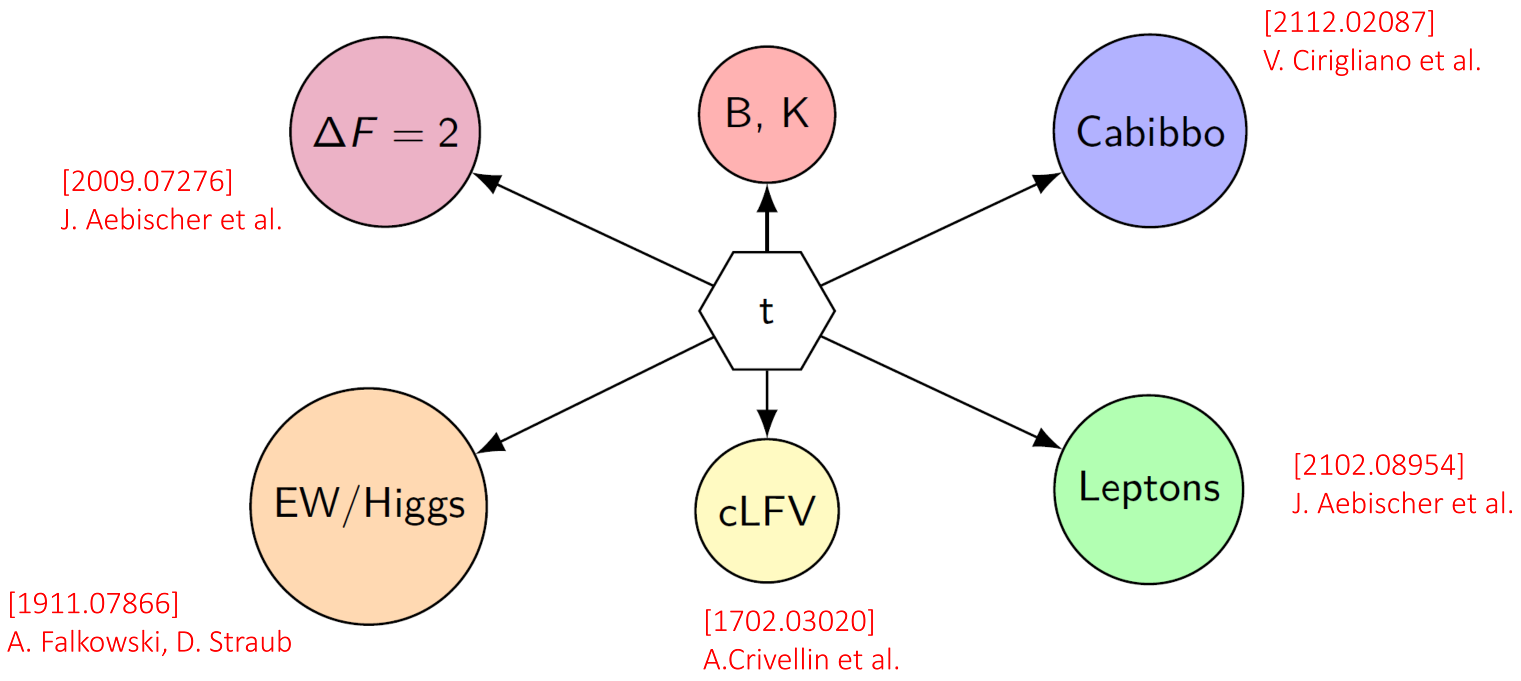
Matching procedures allow to integrate out heavy degrees of freedom, linking EFTs valid above or below the threshold

W. Dekens, P. Stoffer [1908.05295]

Use DSixTools! [2010.16341]

We can write the low energy observables in terms of UV Wilson Coefficients and build a global likelihood:

$$-2\log\mathcal{L}(C_i) \equiv \chi^2(C_i) = \sum_i \frac{(\mathcal{O}_i(C_j) - \mu_i)^2}{\sigma_i^2}$$

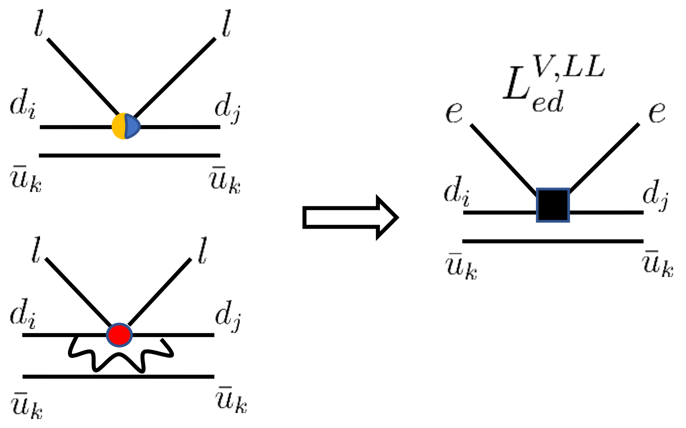


SMEFT-LEFT gym: a few examples

Recall

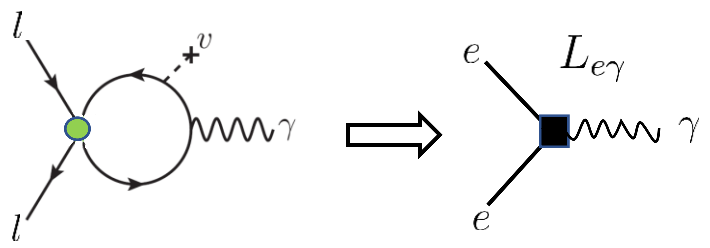
$q^i = (u_L^i, V_{ij} d_L^j)$!

- $C_{\ell q}^{(1)} (\bar{\ell} \gamma_\mu \ell)(\bar{q}^3 \gamma^\mu q^3)$
- $C_{\ell q}^{(3)} (\bar{\ell} \gamma_\mu \tau^\alpha \ell)(\bar{q}^3 \gamma^\mu \tau^\alpha q^3)$
- $C_{\ell u} (\bar{\ell} \gamma_\mu \ell)(\bar{u}^3 \gamma^\mu u^3)$



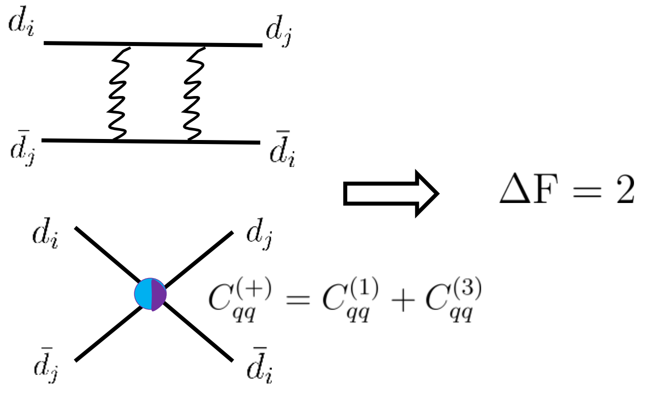
Contribution to FCNC processes (e.g. semileptonic B/K decays)

- $C_{\ell equ}^{(3)} (\bar{\ell} \sigma_{\mu\nu} e) \epsilon (\bar{q}^3 \sigma^{\mu\nu} u^3)$



Contribution to the magnetic dipole moment Δa_ℓ

- $C_{qq}^{(1)} (\bar{q}^3 \gamma_\mu q^3)(\bar{q}^3 \gamma^\mu q^3)$
- $C_{qq}^{(3)} (\bar{q}^3 \gamma_\mu \tau^\alpha q^3)(\bar{q}^3 \gamma^\mu \tau^\alpha q^3)$

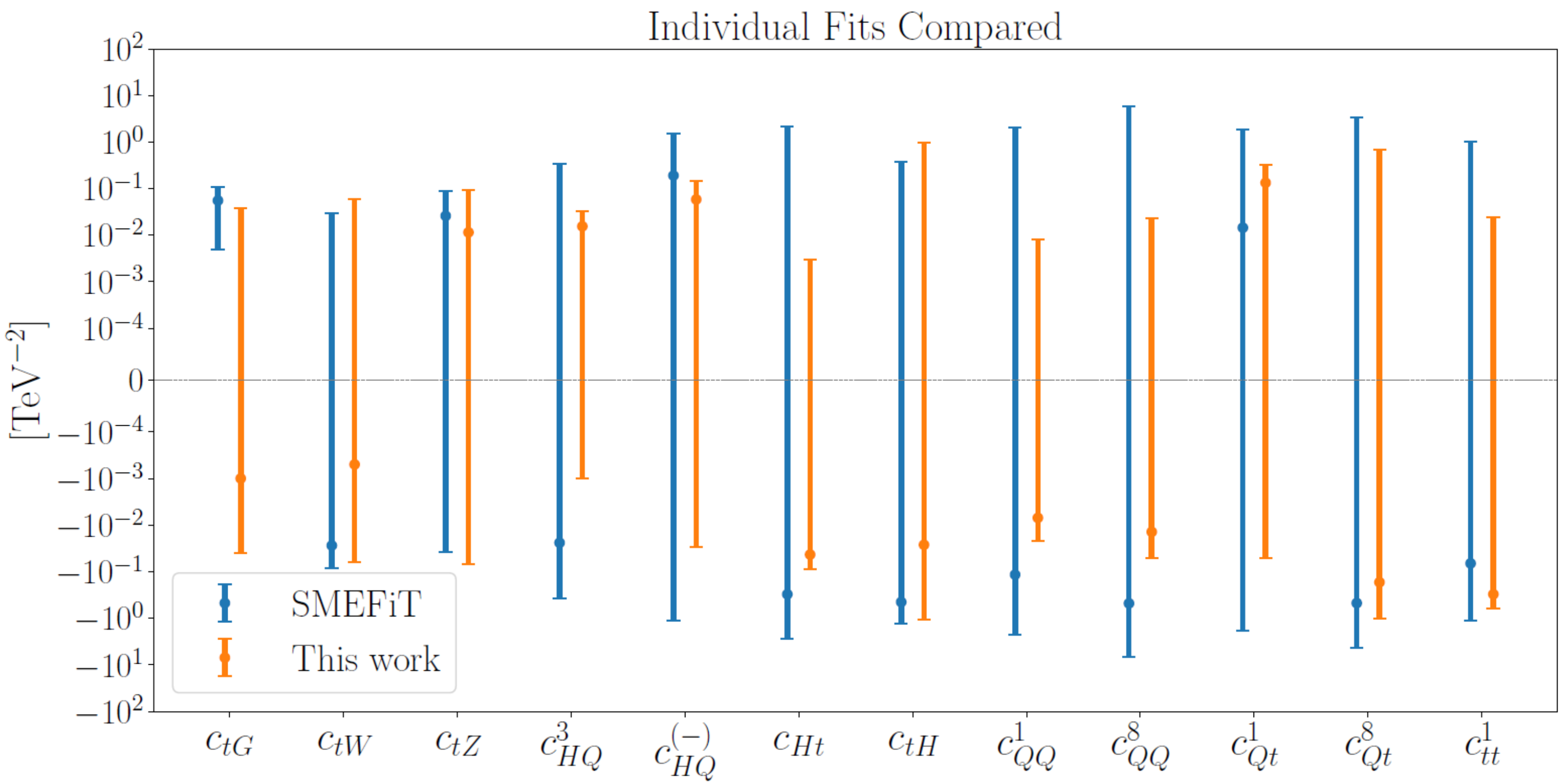


Contribution to meson oscillations

One-parameter fits

Comparison with LHC direct bounds provided by CMS and ATLAS measurements (SMEFiT package)

T. Giani, G. Magni, and J. Roj [2302.06660]



SMEFiT basis employed, e.g.:

$$c_{QQ}^{(8)} = 8C_{qq}^{(3)}$$

$$c_{QQ}^{(1)} = 2C_{qq}^{(1)} - \frac{2}{3}C_{qq}^{(3)}$$

Indirect constraints are competitive or stronger in most cases!

One parameter fits are also studied for semileptonic operators, including LFV cases. More discussions in [2310.00047].

One-parameter fits: a closer look 1

Wilson	Global fit [TeV^{-2}]	Dominant
$C_{qq}^{(+)}$	$(-1.9 \pm 2.3) \times 10^{-3}$	ΔM_s
$C_{qq}^{(-)}$	$(-2.0 \pm 1.0) \times 10^{-1}$	$B_s \to \mu\mu$
$C_{qu}^{(1)}$	$(1.3 \pm 1.0) \times 10^{-1}$	ΔM_s
$C_{qu}^{(8)}$	$(-1.7 \pm 4.4) \times 10^{-1}$	ΔM_s
C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$

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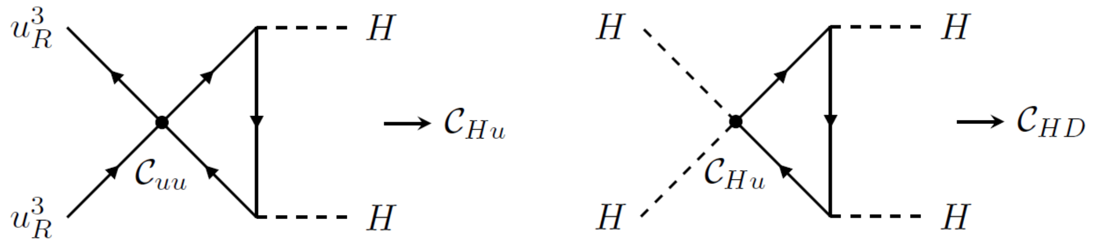
Indirect bounds from the EW sector, e.g. Z pole observables, can be competitive or stronger than direct limits.

See L. Allwicher, C. Cornella, B. A. Stefanek, G. Isidori [2311.00020]

What is the mechanism?



$$\mathcal{O}_{Hu}^{ij} = (H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H)(\bar{u}_i \gamma^\mu u_j) \qquad \mathcal{O}_{HD} = (H^\dagger \mathcal{D}_\mu H)^* (H^\dagger \mathcal{D}^\mu H)$$

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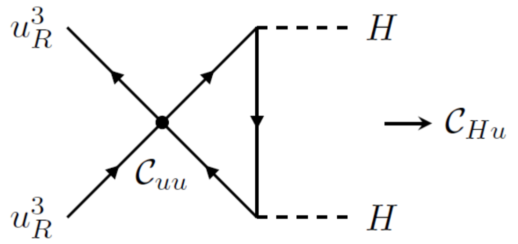
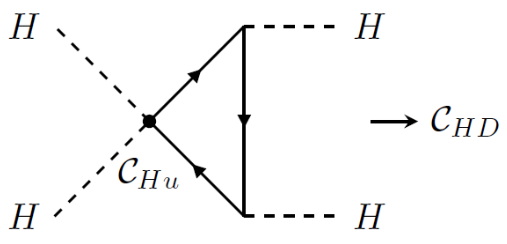




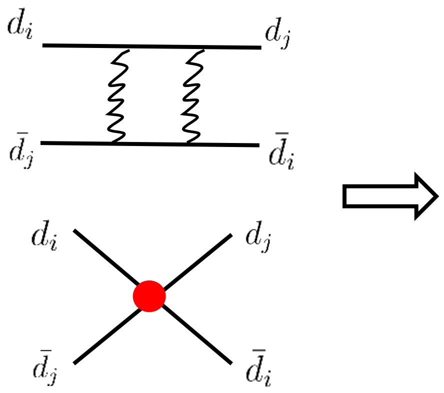
$$\mathcal{O}_{Hu}^{ij} = (H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H)(\bar{u}_i \gamma^\mu u_j) \qquad \mathcal{O}_{HD} = (H^\dagger \mathcal{D}_\mu H)^* (H^\dagger \mathcal{D}^\mu H)$$

Higher loops effects included in the LL resummation !

One-parameter fits: a closer look 2

Wilson	Global fit $[\mathrm{TeV}^{-2}]$	Dominant
$C_{qq}^{(+)}$	$(-1.9 \pm 2.3) \times 10^{-3}$	ΔM_s
$C_{qq}^{(-)}$	$(-2.0 \pm 1.0) \times 10^{-1}$	$B_s \to \mu\mu$
$C_{qu}^{(1)}$	$(1.3 \pm 1.0) \times 10^{-1}$	ΔM_s
$C_{qu}^{(8)}$	$(-1.7 \pm 4.4) \times 10^{-1}$	ΔM_s
C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$

Meson oscillations provide strong constraints on 4-quark operators, both via tree level or radiative effects



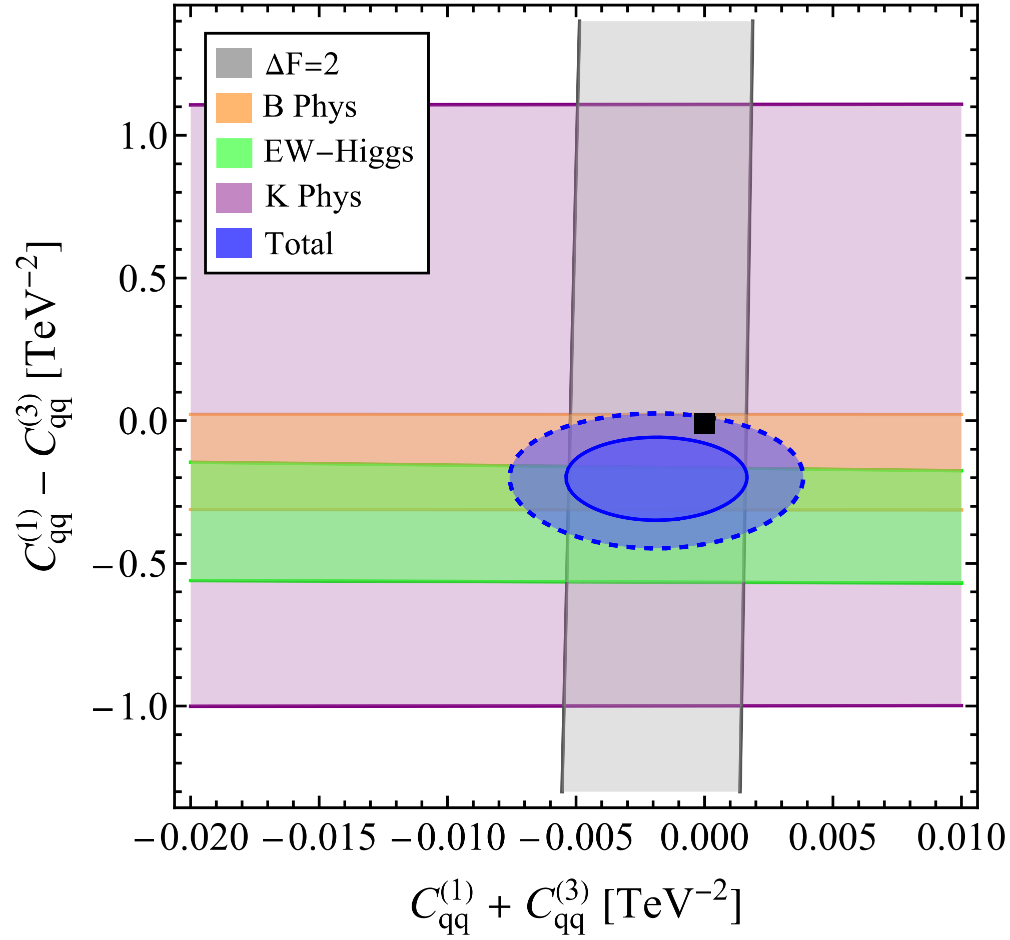
$\Delta \mathrm{F} = 2$

$$c_{QQ}^{(8)} = 8C_{qq}^{(3)}$$
$$c_{QQ}^{(1)} = 2C_{qq}^{(1)} - \frac{2}{3}C_{qq}^{(3)}$$

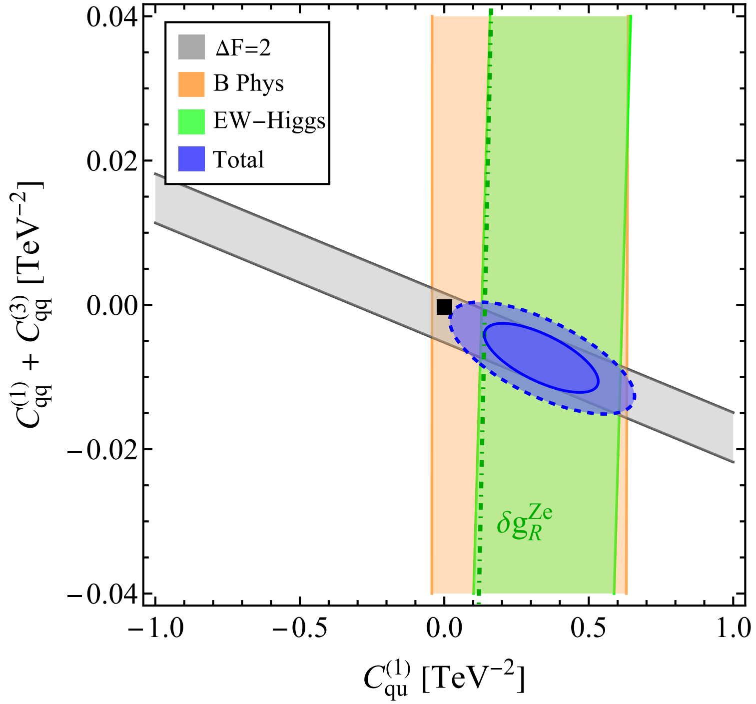
Both strongly constrained as they are not aligned with low energy observables.
One-parameter fits do not highlight flat directions.

Two-parameters fits

We vary two WCs at a time and study the allowed regions in the plane



EW observables and B Physics sector (e.g. $B_s \to \mu\mu$) provide the best bounds on the orthogonal combination, unconstrained by $\Delta\mathrm{F} = 2$



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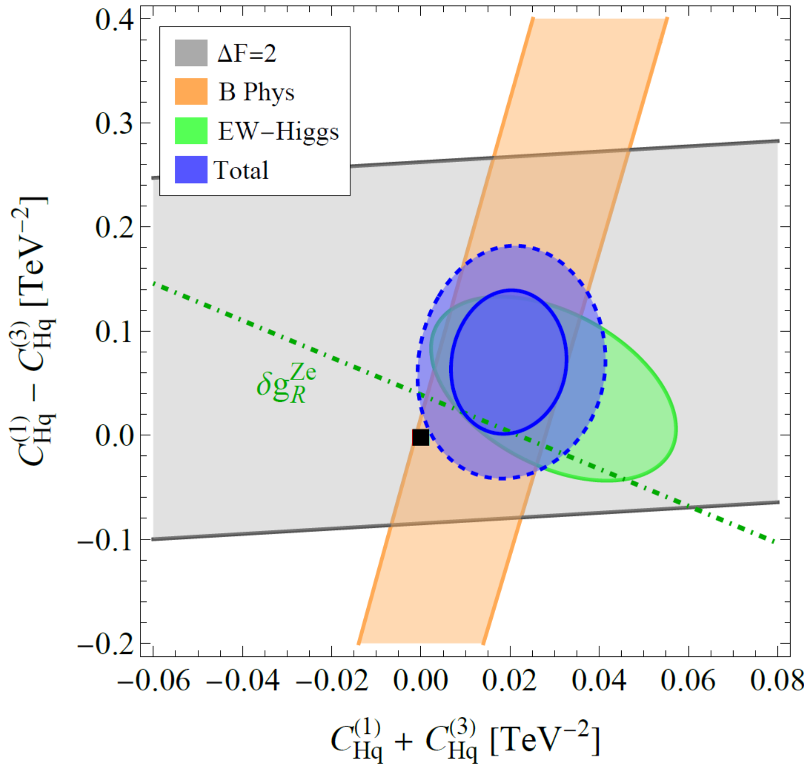
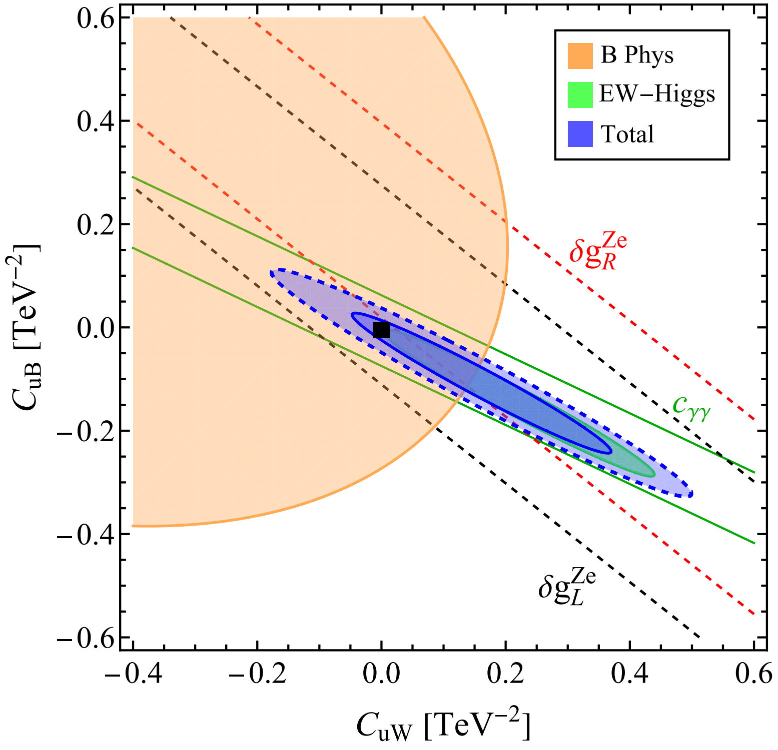
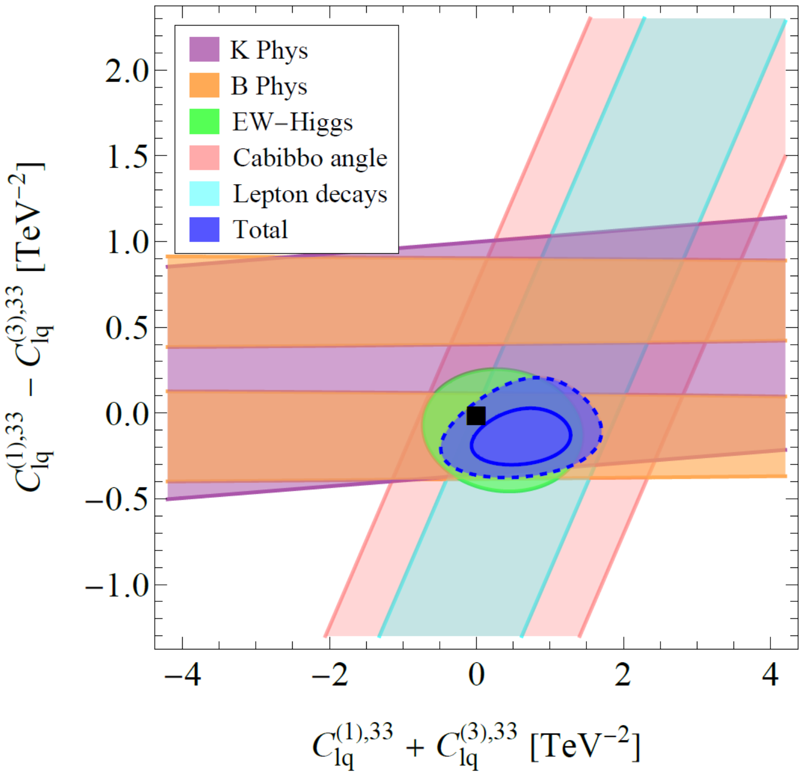






Relevant directions for future sensitivity improvements, correlations between coefficient and flat directions can be read

Global analysis and UV implications

We perform a Gaussian global fit considering all the operators except for the semi-leptonic ones

$$\vec{C} = (C_{qq}^{(+)}, C_{qq}^{(-)}, C_{uu}, C_{qu}^{(1)}, C_{qu}^{(8)}, C_{Hq}^{(+)}, C_{Hq}^{(-)}, C_{Hu}, C_{uH}, C_{uG}, C_{uW}, C_{uB}) \ .$$

$$\chi^2 = \chi^2_{\text{best-fit}} + (C_i - \mu_{C_i})(\sigma^2)^{-1}_{ij}(C_j - \mu_{C_j}) = \chi^2_{\text{best-fit}} + \frac{(K_i - \mu_{K_i})^2}{\sigma^2_{K_i}} .$$

Some approximate flat directions:

$$K_{11} \approx -0.86 C_{qq}^{(-)} + 0.26 C_{uu} - 0.41 C_{qu}^{(1)} - 0.10 C_{Hu} + \ldots \ ,$$
$$K_{12} \approx +0.23 C_{qq}^{(-)} + 0.95 C_{uu} + 0.16 C_{qu}^{(1)} - 0.12 C_{Hu} + \ldots \ .$$

Coefficient	Gaussian fit [TeV^{-2}]	Coefficient	Gaussian fit [TeV^{-2}]
K_1	0.0019 ± 0.0023	K_7	0.56 ± 0.79
K_2	0.0169 ± 0.0083	K_8	0.80 ± 0.88
K_3	-0.001 ± 0.015	K_9	-0.8 ± 1.3
K_4	-0.017 ± 0.021	K_{10}	-1.1 ± 1.7
K_5	0.044 ± 0.029	K_{11}	20.5 ± 12
K_6	-0.26 ± 0.38	K_{12}	-14 ± 15

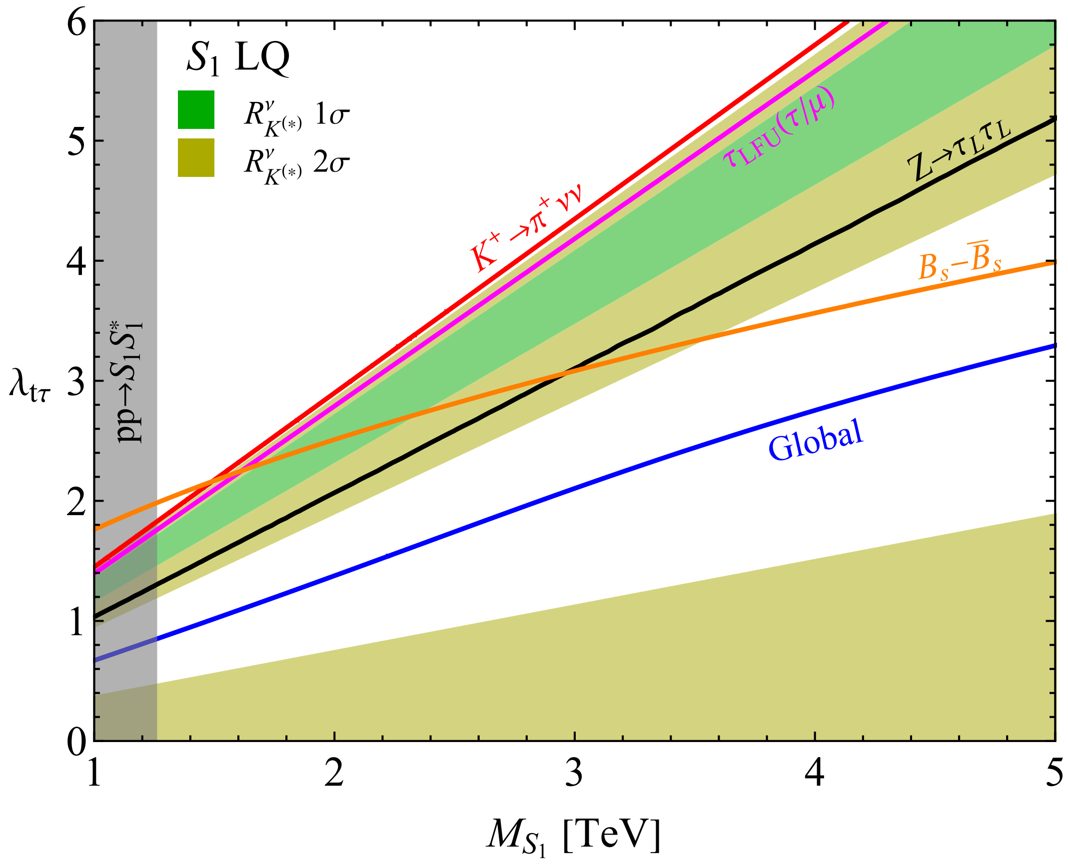
Global analysis and UV implications

Consider one scalar leptoquark $S_1 \sim (\bar{3}, 1)_{+1/3}$ coupled only to the third generation fermions

$$\mathcal{L} \supset \lambda_{t\tau} \bar{q}_3^c i\sigma_2 l_3 S_1 + h.c$$

When integrated out, SMEFT operators are generated:

$$C_{lq}^{(1),33} = -C_{lq}^{(3),33} = \frac{|\lambda_{t,\tau}|^2}{4M_{S_1}^2} \qquad C_{qq}^{(1)} = C_{qq}^{(3)} = -\frac{|\lambda_{t\tau}|^4}{256\pi^2 M_{S_1}^2}$$



Concluding remarks

- We derived indirect constraints on top quark operators and found a very rich phenomenology and strong interplay between the different sectors
- Indirect constraints can be competitive or stronger than the direct ones
- Radiative corrections can widen the impact of low energy data even via higher loops effects (encoded in the LL resummation in our example)
- Be careful about the basis choice when extracting numerical results
- Future sensitivity improvements (e.g. LHCb and Belle II upgrades) will increase the strength of indirect bounds from low energy measurements

Thanks for the attention!

Backup slides

SMEFiT results (TeV^{-2})

Class	Coefficients	Warsaw basis	95% CL Individual	95% CL Marginalised
Dipoles	c_{tG}	C_{uG}	[0.01,0.11]	[0.01,0.23]
	c_{tW}	C_{uW}	[-0.085,0.030]	[-0.28,0.13]
	c_{tZ}	$-s_\theta C_{uB} + c_\theta C_{uW}$	[-0.038,0.090]	[-0.50,0.14]
Higgs-Top	c_{HQ}^{3}	$C_{Hq}^{(3)}$	[-0.39,0.34]	[-0.42,0.31]
	$c_{HQ}^{(-)}$	$C_{Hq}^{(1)} - C_{Hq}^{(3)}$	[-1.1,1.5]	[-2.7,2.7]
	c_{Ht}	C_{Hu}	[-2.8,2.2]	[-15,4]
	c_{tH}	C_{uH}	[-1.3,0.4]	[-0.5,2.9]
4 quarks	c_{QQ}^{1}	$2C_{qq}^{(1)} - \frac{2}{3}C_{qq}^{(3)}$	[-2.3,2.0]	[-3.7,4.4]
	c_{QQ}^{8}	$8C_{qq}^{(3)}$	[-6.8,5.9]	[-13,10]
	c_{Qt}^{1}	$C_{qu}^{(1)}$	[-1.8,1.9]	[-1.5,1.4]
	c_{Qt}^{8}	$C_{qu}^{(8)}$	[-4.3,3.3]	[-3.4,2.5]
	c_{tt}^{1}	C_{uu}	[-1.1,1.0]	[-0.88,0.81]

Individual fits (TeV^{-2})

Wilson	Global fit [TeV^{-2}]	Dominant
$C_{qq}^{(+)}$	$(-1.9 \pm 2.3) \times 10^{-3}$	ΔM_s
$C_{qq}^{(-)}$	$(-2.0 \pm 1.0) \times 10^{-1}$	$B_s \to \mu\mu$
$C_{qu}^{(1)}$	$(1.3 \pm 1.0) \times 10^{-1}$	ΔM_s
$C_{qu}^{(8)}$	$(-1.7 \pm 4.4) \times 10^{-1}$	ΔM_s
C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g^{Ze}_{L,11}$
$C_{Hq}^{(+)}$	$(18.7 \pm 8.8) \times 10^{-3}$	$B_s \to \mu\mu$
$C_{Hq}^{(-)}$	$(5.8 \pm 4.5) \times 10^{-2}$	$\delta g^{Ze}_{L,11}$
C_{Hu}	$(-4.3 \pm 2.3) \times 10^{-2}$	$\delta g^{Ze}_{L,11}$
C_{uB}	$(-0.6 \pm 2.0) \times 10^{-2}$	$c_{\gamma\gamma}$
C_{uG}	$(-0.1 \pm 2.0) \times 10^{-2}$	c_{gg}
C_{uH}	$(-0.3 \pm 5.2) \times 10^{-1}$	$C_{uH,33}$
C_{uW}	$(-0.1 \pm 3.1) \times 10^{-2}$	$c_{\gamma\gamma}$

Wilson	Global fit [TeV^{-2}]	Dominant
$C_{lq}^{(+),11}$	$(2.4 \pm 3.5) \times 10^{-3}$	R_K
$C_{lq}^{(+),22}$	$(-4.0 \pm 3.4) \times 10^{-3}$	R_K
$C_{lq}^{(+),33}$	$(7.2 \pm 4.4) \times 10^{-1}$	g_τ / g_i
$C_{lq}^{(-),11}$	$(10.9 \pm 7.6) \times 10^{-2}$	$R^\nu_{K^{(*)}}$
$C_{lq}^{(-),22}$	$(-6.0 \pm 7.0) \times 10^{-2}$	$R^\nu_{K^{(*)}}$
$C_{lq}^{(-),33}$	$(-1.8 \pm 1.0) \times 10^{-1}$	$R^\nu_{K^{(*)}}$
C_{lu}^{11}	$(-1.7 \pm 7.0) \times 10^{-2}$	$\delta g^{Ze}_{L,11}$
C_{lu}^{22}	$(-4.3 \pm 1.8) \times 10^{-1}$	$\delta g^{Ze}_{L,22}$, R_K
C_{lu}^{33}	$(0.5 \pm 2.4) \times 10^{-1}$	$\Delta g^{Ze}_{L,33}$
C_{qe}^{11}	$(-0.7 \pm 3.9) \times 10^{-2}$	R_{K^*}
C_{qe}^{22}	$(12.1 \pm 9.2) \times 10^{-3}$	$B_s \to \mu\mu$
C_{qe}^{33}	$(2.2 \pm 2.4) \times 10^{-1}$	$\delta g^{Ze}_{R,33}$

Wilson	Global fit [TeV^{-2}]	Dominant
C_{eu}^{11}	$(5.0 \pm 8.1) \times 10^{-2}$	$\Delta g^{Ze}_R{}_{11}$
C_{eu}^{22}	$(4.8 \pm 2.1) \times 10^{-1}$	$\Delta g^{Ze}_R{}_{22}$
C_{eu}^{33}	$(-2.3 \pm 2.5) \times 10^{-1}$	$\Delta g^{Ze}_R{}_{33}$
$C_{lequ}^{(1),11}$	$(0.4 \pm 1.0) \times 10^{-2}$	$(g-2)_e$
$C_{lequ}^{(1),22}$	$(1.8 \pm 1.6) \times 10^{-2}$	$C_{eH\,22}$
$C_{lequ}^{(1),33}$	$(8.0 \pm 9.1) \times 10^{-2}$	$C_{eH\,33}$
$C_{lequ}^{(3),11}$	$(-0.6 \pm 1.5) \times 10^{-5}$	$(g-2)_e$
$C_{lequ}^{(3),22}$	$(-19.3 \pm 8.1) \times 10^{-5}$	$(g-2)_\mu$
$C_{lequ}^{(3),33}$	$(-7.0 \pm 7.8) \times 10^{-1}$	$C_{eH\,33}$

B-phys and K-phys observables

Observable	Experimental value
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.14^{+0.4}_{-0.33}) \times 10^{-10}$ NA62
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$	$< 3.6 \times 10^{-9}$ KOTO
$\mathcal{B}(K_S \to \mu^+\mu^-)$	$< 2.5 \times 10^{-10}$ LHCb
$\mathcal{B}(K_L \to \mu^+\mu^-)_{SD}$	$< 2.5 \times 10^{-9}$ Isidori:2003
$\mathcal{B}(K_L \to \mu^\pm e^\mp)$	$< 5.6 \times 10^{-12}$ BNL
$\mathcal{B}(K_L \to \pi^0\mu^+\mu^-)$	$< 4.5 \times 10^{-10}$ KTEV
$\mathcal{B}(K_L \to \pi^0 e^+ e^-)$	$< 3.3 \times 10^{-10}$ KTeV
$\mathcal{B}(K_L \to \pi^0 e^+ \mu^-)$	$< 9.1 \times 10^{-11}$ KTeV
$\mathcal{B}(K^+ \to \pi^+ e^+ \mu^-)$	$< 7.9 \times 10^{-11}$ NA62

Observable	Experimental value
$B \to X_s\gamma$	$(3.49 \pm 0.19) \times 10^{-4}$ PDG
R_K^ν	2.93 ± 0.90 Belle-II
$R_{K^*}^\nu$	< 3.21 Belle-II
$R_K[1.1, 6]$	0.949 ± 0.047 LHCb
$R_{K^*}[1.1, 6]$	1.027 ± 0.077 LHCb
$\mathcal{B}(B \to Ke\mu)$	$< 4.5 \times 10^{-8}$ Belle
$\mathcal{B}(B \to Ke\tau)$	$< 3.6 \times 10^{-5}$ BaBar
$\mathcal{B}(B \to K\mu\tau)$	$< 4.5 \times 10^{-5}$ LHCb

Observable	Experimental value
$\mathcal{B}(B_s \to ee)$	$< 11.2 \times 10^{-9}$ LHCb
$\mathcal{B}(B_s \to \mu\mu)$	$(3.01 \pm 0.35) \times 10^{-9}$ LHCb
$\mathcal{B}(B_s \to \tau\tau)$	$< 6.8 \times 10^{-3}$ LHCb
$\mathcal{B}(B_s \to e\mu)$	$< 6.3 \times 10^{-9}$ LHCb
$\mathcal{B}(B_s \to \mu\tau)$	$< 4.2 \times 10^{-5}$ LHCb
$\mathcal{B}(B_d \to ee)$	$< 3.0 \times 10^{-9}$ LHCb
$\mathcal{B}(B_d \to \mu\mu)$	$< 2.6 \times 10^{-10}$ LHCb
$\mathcal{B}(B_d \to \tau\tau)$	$< 2.1 \times 10^{-3}$ LHCb
$\mathcal{B}(B_d \to e\mu)$	$< 1.3 \times 10^{-9}$ LHCb
$\mathcal{B}(B_d \to \mu\tau)$	$< 1.4 \times 10^{-5}$ LHCb

Observable	Experimental value	SM prediction
ϵ_K	$(2.228 \pm 0.011) \times 10^{-3}$	$(2.14 \pm 0.12) \times 10^{-3}$
ΔM_s	$(17.765 \pm 0.006)\ \mathrm{ps}^{-1}$	$(17.35 \pm 0.94)\ \mathrm{ps}^{-1}$
ΔM_d	$(0.5065 \pm 0.0019)\ \mathrm{ps}^{-1}$	$(0.502 \pm 0.031)\ \mathrm{ps}^{-1}$

Lepton observables

Observable	Experimental limit
$\mathcal{B}(\tau \to e\pi^+\pi^-)$	2.7×10^{-8} Belle
$\mathcal{B}(\tau \to eK^+K^-)$	4.1×10^{-8} Belle
$\mathcal{B}(\tau \to \mu\gamma)$	5.0×10^{-8} Belle
$\mathcal{B}(\tau \to 3\mu)$	2.5×10^{-8} Belle
$\mathcal{B}(\tau \to \mu\, \bar{e}e)$	2.1×10^{-8} Belle
$\mathcal{B}(\tau \to \mu\pi^0)$	1.3×10^{-7} Belle
$\mathcal{B}(\tau \to \mu\eta)$	7.7×10^{-8} Belle
$\mathcal{B}(\tau \to \mu\eta')$	1.5×10^{-7} Belle
$\mathcal{B}(\tau \to \mu\pi^+\pi^-)$	2.5×10^{-8} Belle
$\mathcal{B}(\tau \to \mu K^+K^-)$	5.2×10^{-8} Belle

Observable	Experimental limit
$\mathcal{B}(\mu \to e\gamma)$	5.0×10^{-13} MEG
$\mathcal{B}(\mu \to 3e)$	1.2×10^{-12} SINDRUM
$\mathcal{B}(\mu\, \mathrm{Au} \to e\, \mathrm{Au})$	8.3×10^{-13} SINDRUM
$\mathcal{B}(\tau \to e\gamma)$	3.9×10^{-8} BaBar
$\mathcal{B}(\tau \to 3e)$	3.2×10^{-8} Belle
$\mathcal{B}(\tau \to e\, \bar{\mu}\mu)$	3.2×10^{-8} Belle
$\mathcal{B}(\tau \to e\pi^0)$	9.5×10^{-8} Belle
$\mathcal{B}(\tau \to e\eta)$	1.1×10^{-7} Belle
$\mathcal{B}(\tau \to e\eta')$	1.9×10^{-7} Belle

Observable	Experimental value	
	$\ell = e$	$\ell = \mu$
Δa_ℓ	$(2.8 \pm 7.4) \times 10^{-13}$	$(20.0 \pm 8.4) \times 10^{-10}$

Observable	Experimental value	
	$\ell = e$	$\ell = \mu$
$g_\tau / g_\ell - 1$	$(2.7 \pm 1.4) \times 10^{-3}$	$(0.9 \pm 1.4) \times 10^{-3}$