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)

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

e.g:

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

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

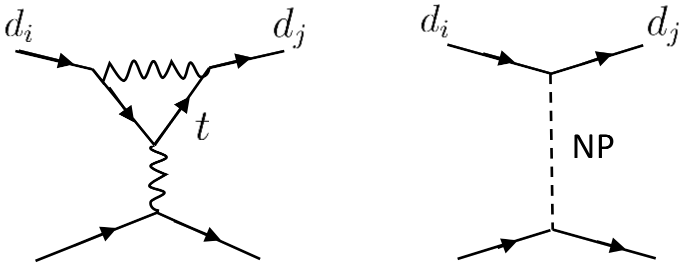
$$\mathcal{O}_{qq}^{(1)} = (\bar{q}^3\gamma^\mu q^3)(\bar{q}^3\gamma_\mu q^3)$$

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

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

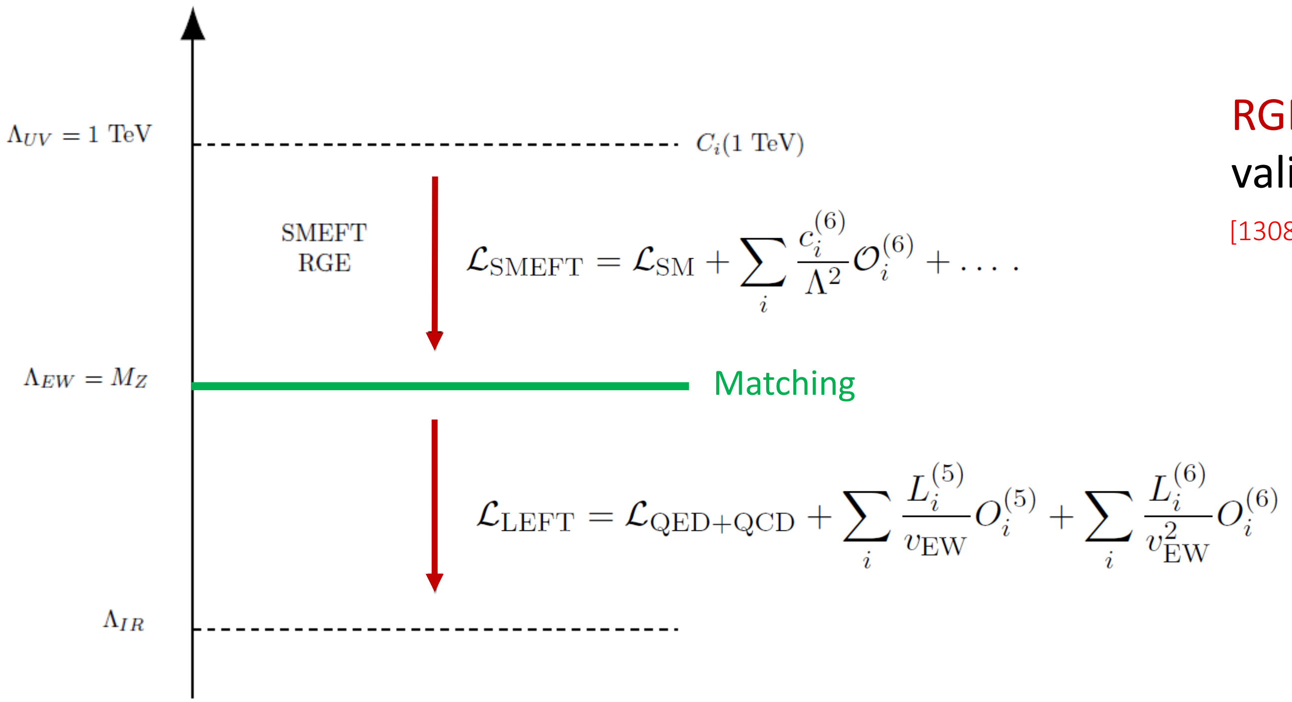
Semi-leptonic	
$\mathcal{O}_{\ell q}^{(1),\alpha\beta}$	$(\bar{\ell}^{a}\gamma_{\mu}\ell^{\beta})(\bar{q}^{3}\gamma^{\mu}q^{3})$
$\mathcal{O}_{\ell q}^{(3),\alpha\beta}$	$(\bar{\ell}^{a}\gamma_{\mu}\tau^{a}\ell^{\beta})(\bar{q}^{3}\gamma^{\mu}\tau^{a}q^{3})$
$\mathcal{O}_{\ell u}^{\alpha\beta}$	$(\bar{\ell}^{\alpha}\gamma^{\mu}\ell^{\beta})(\bar{u}^{3}\gamma_{\m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

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

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

Constrain TeV-scale operators from GeV-scale observables



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

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

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

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

W. Dekens, P. Stoffer [1908.05295]

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

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

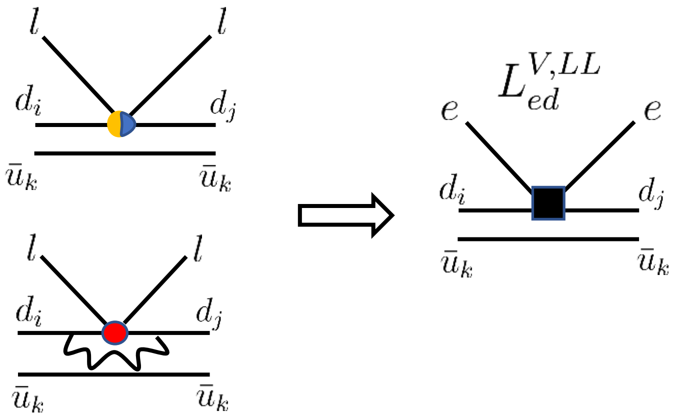
- B and K physics
- Higgs measurements
- Z and W decays
- Cabibbo angle
- g-2
- Lepton decays
- LFU tests
- LFV decay channels

SMEFT-LEFT gym: a few examples

Recall

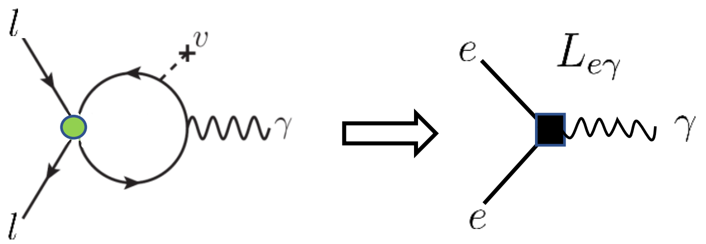
$q^i = (u_L^i,\, V_{ij} d_L^j)$!

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



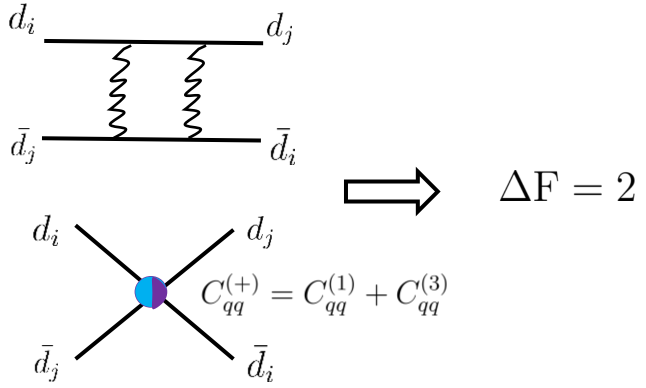
Contribution to FCNC processes (e.g. semileptonic B/K decays)

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



Contribution to the magnetic dipole moment Δa_ℓ

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

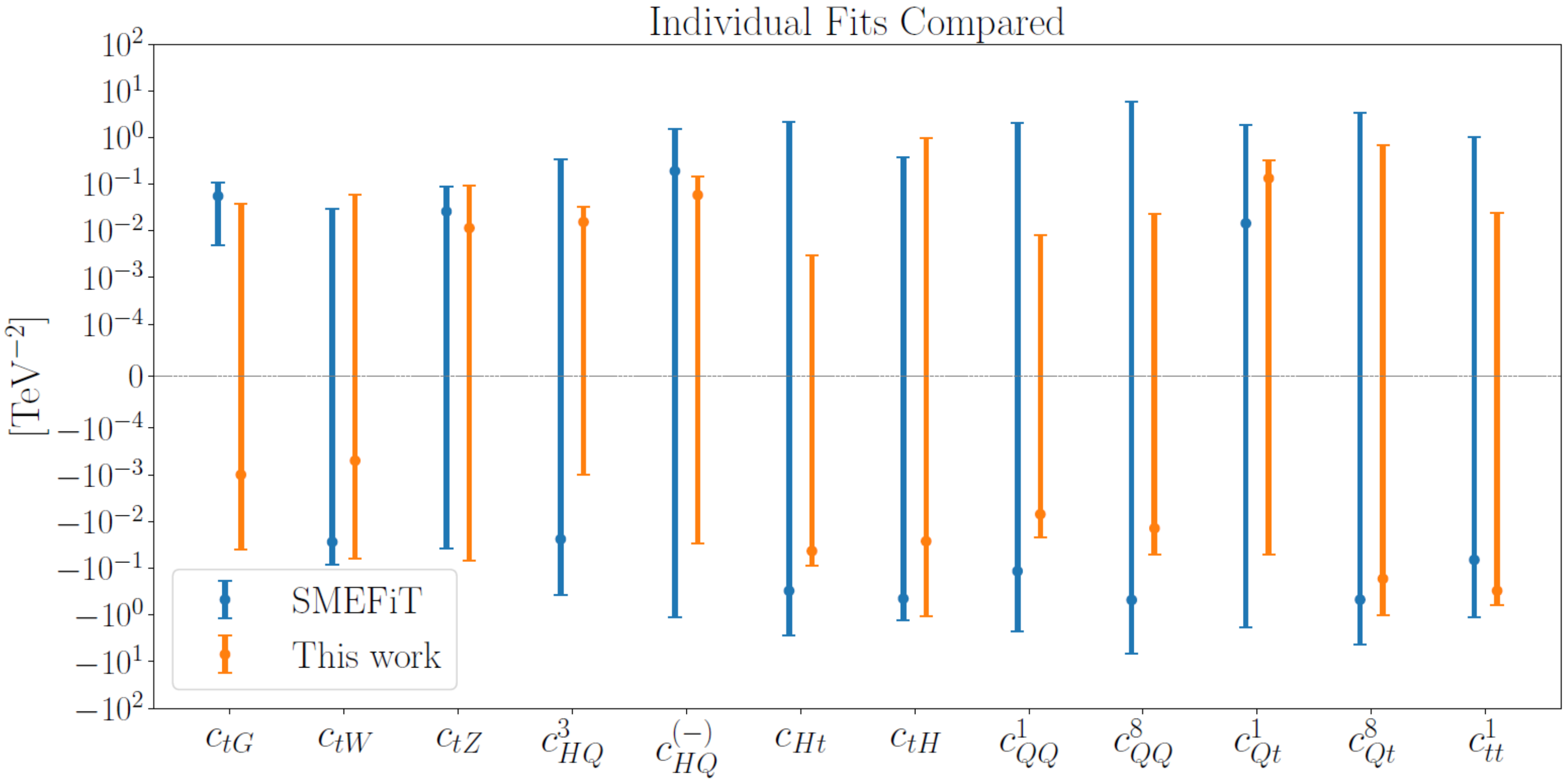


Contribution to meson oscillations

One-parameter fits

One-parameter fits: we vary one WC at a time while fixing the other parameters to zero.

We can compare our results to the LHC direct bounds provided by CMS and ATLAS measurements, obtained through the SMEFiT fitting framework. WCs are expressed in the basis of T. Giani, G. Magni, and J. Roj [2302.06660] (instead of Warsaw basis) just for this plot.



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

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

Indirect constraints are competitive or stronger in most cases

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

One-parameter fits: a closer look

Wilson	Global fit $[\text{TeV}^{-2}]$	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}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$

One-parameter fits: a closer look 1

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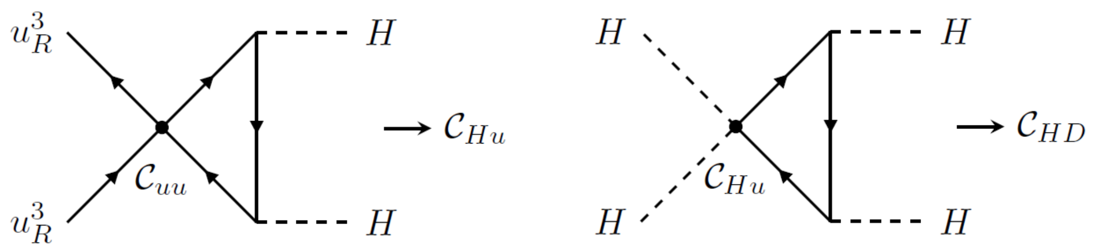
Indirect bounds from the EW sector, e.g. Z pole observables, can be competitive or stronger than direct collider searches.

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

What is the mechanism?



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

As an example, this result stresses the relevance of radiative corrections and the importance of including higher loops effects in the LL resummation.

One-parameter fits: a closer look 1

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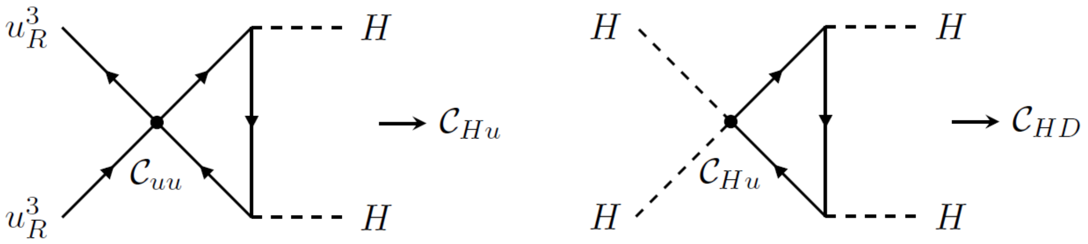

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One-parameter fits: a closer look 2

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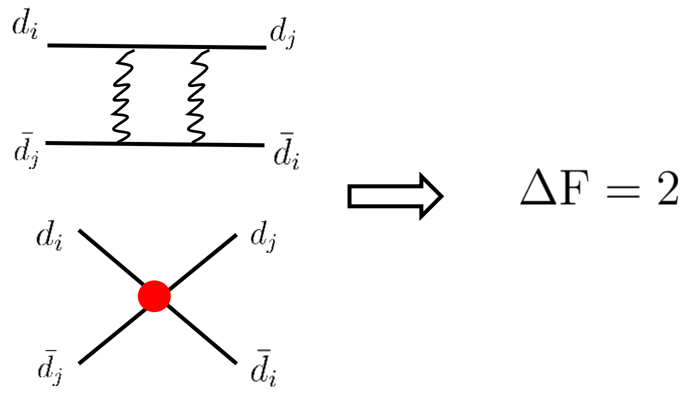
$C_{qu}^{(1)}$	$(1.3 \pm 1.0) \times 10^{-1}$	ΔM_s
$C_{qu}^{(8)}$	$(-1.7 \pm 4.4) \times 10^{-1}$	ΔM_s
C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$

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



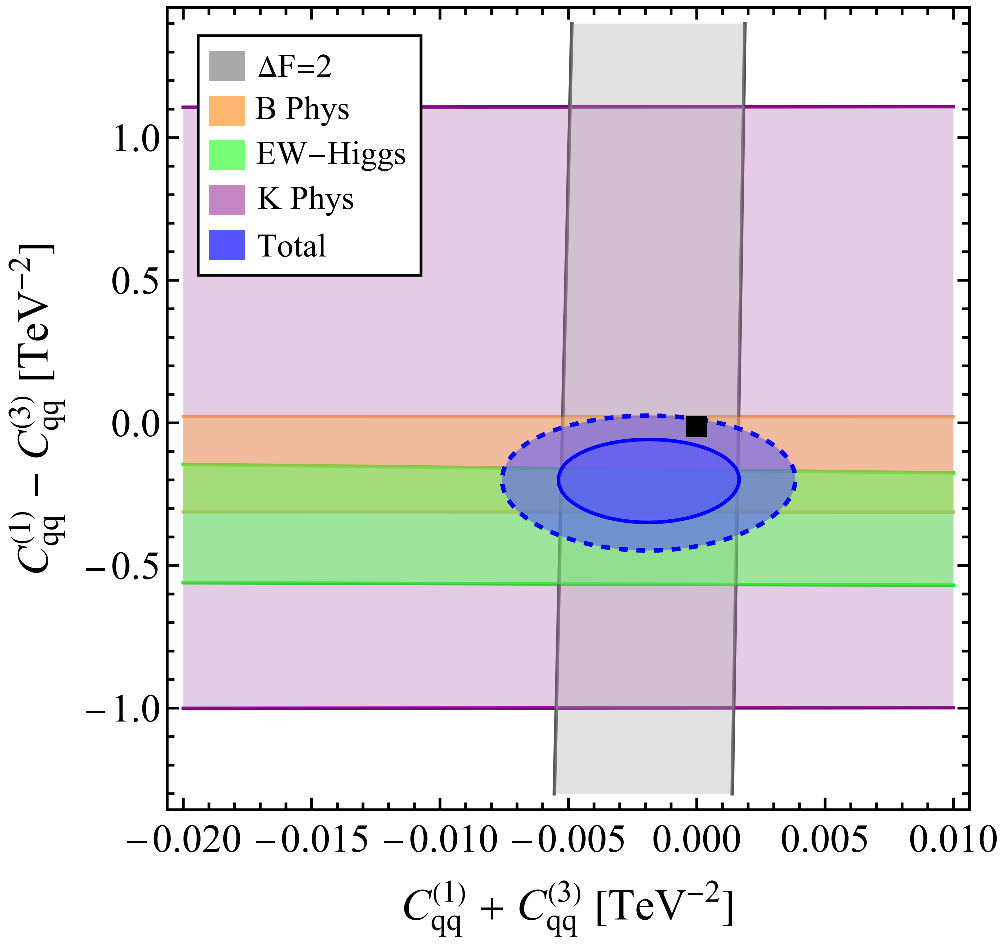
$$c_{QQ}^{(8)} = 8C_{qq}^{(3)}$$

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

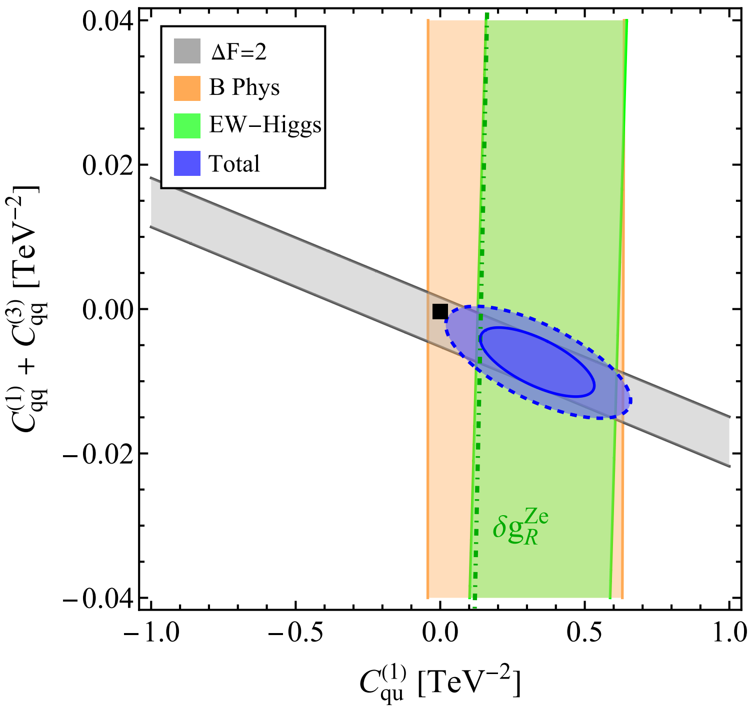
Both are severely constrained as they are not aligned with low energy observables. In general, one-parameter fits do not highlight the flat directions left by flavour physics sectors.

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 $\Delta \mathrm{F} = 2$



Two-parameters fits

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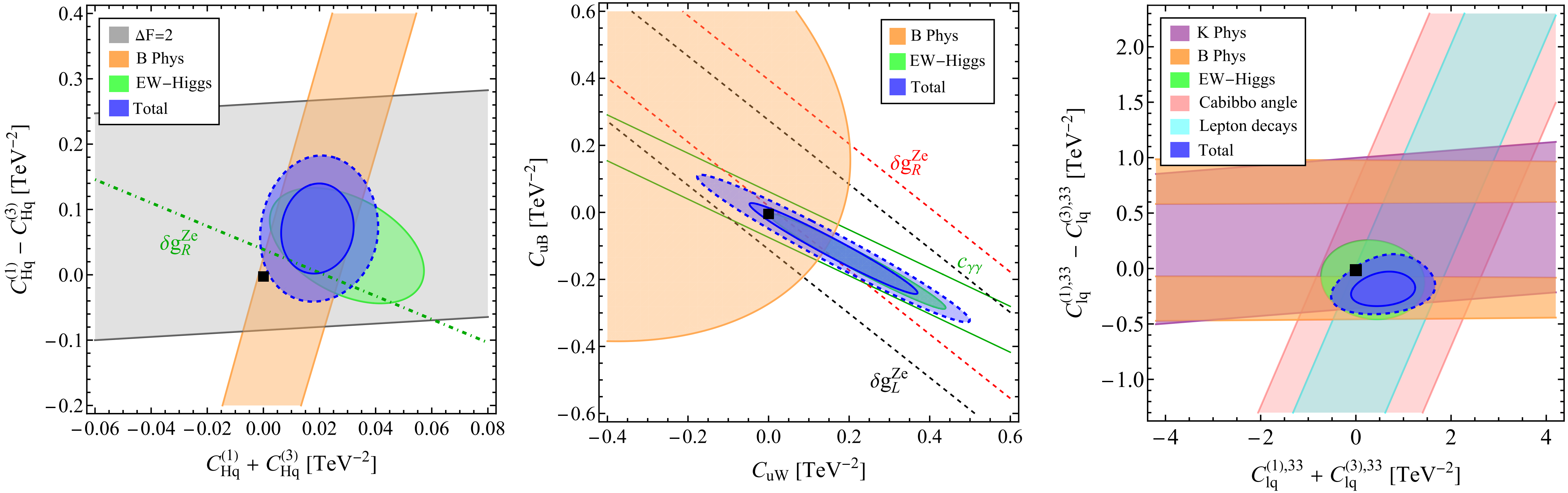


Relevant directions for future sensitivity improvements, correlations between coefficient and flat directions can be easily read from the plots.

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

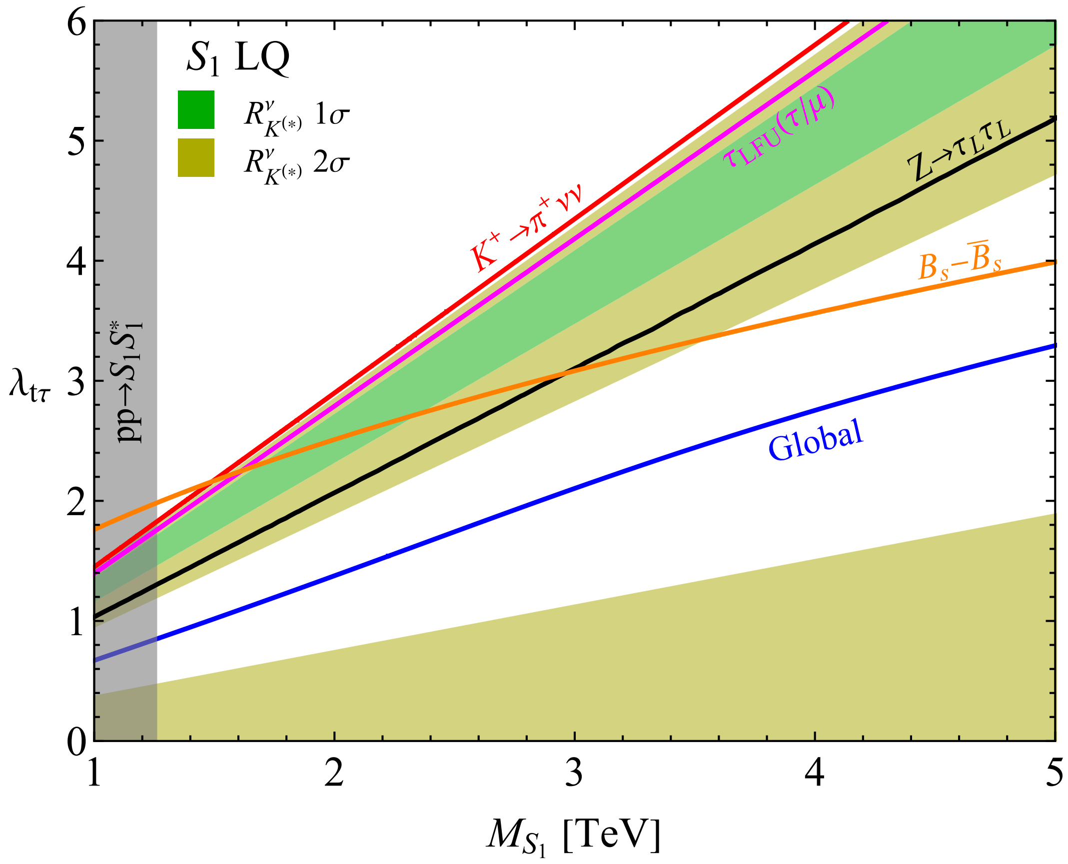
Global analysis and UV implications

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

- The analysis of low energy observables do provide useful insights on Top Quark interactions at the New Physics scale

- Meson oscillations establish by far the strongest constraint along some direction of the parameter space, e.g. $C_{qq}^{(1)+(3)}$

- Loop level matching and RG evolution can widen the effects of low energy bounds via operator mixing, extending sizable effects on a wider set of WCs. (e.g. EW-Higgs observables and 4 quark or semileptonic operators)

- 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

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^3_{HQ}	$C^{(3)}_{Hq}$	[-0.39,0.34]	[-0.42,0.31]
	$c^{(-)}_{HQ}$	$C^{(1)}_{Hq} - C^{(3)}_{Hq}$	[-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^1_{QQ}	$2C^{(1)}_{qq} - \frac{2}{3}C^{(3)}_{qq}$	[-2.3,2.0]	[-3.7,4.4]
	c^8_{QQ}	$8C^{(3)}_{qq}$	[-6.8,5.9]	[-13,10]
	c^1_{Qt}	$C^{(1)}_{qu}$	[-1.8,1.9]	[-1.5,1.4]
	c^8_{Qt}	$C^{(8)}_{qu}$	[-4.3,3.3]	[-3.4,2.5]
	c^1_{tt}	C_{uu}	[-1.1,1.0]	[-0.88,0.81]

Individual fits (TeV^{-2})

Wilson	Global fit	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}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$
$C_{Hq}^{(+)}$	$(18.2 \pm 8.9) \times 10^{-3}$	$B_s \to \mu\mu$
$C_{Hq}^{(-)}$	$(5.9 \pm 4.5) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{Hu}	$(-4.3 \pm 2.3) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
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}	$(0.0 \pm 3.1) \times 10^{-2}$	$c_{\gamma\gamma}$

Wilson	Global fit	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
$C_{lq}^{(-),11}$	$(10.1 \pm 7.7) \times 10^{-2}$	$R^{\nu}_{K^{(*)}}$
$C_{lq}^{(-),22}$	$(-7.4 \pm 7.0) \times 10^{-2}$	$R^{\nu}_{K^{(*)}}$
$C_{lq}^{(-),33}$	$(-22.1 \pm 9.6) \times 10^{-2}$	$R^{\nu}_{K^{(*)}}$
C_{lu}^{11}	$(-1.7 \pm 7.0) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{lu}^{22}	$(-4.3 \pm 1.8) \times 10^{-1}$	$\delta g_{L,22}^{Ze}$, R_K
C_{lu}^{33}	$(0.5 \pm 2.4) \times 10^{-1}$	$\Delta g_{L,33}^{Ze}$
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}	$(2.2 \pm 2.4) \times 10^{-1}$	$\delta g_{R,33}^{Ze}$

Wilson	Global fit	Dominant
C_{eu}^{11}	$(5.0 \pm 8.1) \times 10^{-2}$	$\Delta g_R^{Ze}{}_{11}$
C_{eu}^{22}	$(4.6 \pm 2.2) \times 10^{-1}$	$\Delta g_R^{Ze}{}_{22}$
C_{eu}^{33}	$(-2.3 \pm 2.5) \times 10^{-1}$	$\Delta g_R^{Ze}{}_{33}$
$C_{lequ}^{(1),11}$	$(0.4 \pm 1.0) \times 10^{-2}$	$(g-2)_e$
$C_{lequ}^{(1),22}$	$(1.8 \pm 1.6) \times 10^{-2}$	C_{eH22}
$C_{lequ}^{(1),33}$	$(8.0 \pm 9.1) \times 10^{-2}$	C_{eH33}
$C_{lequ}^{(3),11}$	$(-0.6 \pm 1.5) \times 10^{-5}$	$(g-2)_e$
$C_{lequ}^{(3),22}$	$(-19.3 \pm 8.1) \times 10^{-5}$	$(g-2)_\mu$
$C_{lequ}^{(3),33}$	$(-7.0 \pm 7.8) \times 10^{-1}$	C_{eH33}

LFV coefficients

Wilson	$\mu \to e$ Limit	$\mu \to e$ Dominant	$\tau \to \mu$ Limit	$\tau \to \mu$ Dominant	$\tau \to e$ Limit	$\tau \to e$ Dominant
$C_{lequ}^{(3)}$	3.9×10^{-9}	$\mu \to e\gamma$	5.0×10^{-5}	$\tau \to \mu\gamma$	4.4×10^{-5}	$\tau \to e\gamma$
$C_{lequ}^{(1)}$	3.6×10^{-5}	$\mu \to 3e, e\gamma$	2.7×10^{-2}	$\tau \to \mu\gamma$	2.4×10^{-2}	$\tau \to e\gamma$
$C_{lq}^{(3)}$	6.7×10^{-5}	$\mu\text{Au} \to e\text{Au}$	6.8×10^{-2}	$\tau \to \mu\pi\pi$	7.0×10^{-2}	$\tau \to e\pi\pi$
$C_{lq}^{(1)}$	4.0×10^{-5}	$\mu\text{Au} \to e\text{Au}$	9.8×10^{-2}	$\tau \to \mu\pi\pi$	1.0×10^{-1}	$\tau \to e\pi\pi$
C_{lu}	4.0×10^{-5}	$\mu\text{Au} \to e\text{Au}$	1.0×10^{-1}	$\tau \to \mu\pi\pi$	1.1×10^{-1}	$\tau \to e\pi\pi$
C_{eu}	3.6×10^{-5}	$\mu\text{Au} \to e\text{Au}$	1.9×10^{-1}	$\tau \to \mu ee$	2.1×10^{-1}	$\tau \to 3e$
C_{qe}	3.6×10^{-5}	$\mu\text{Au} \to e\text{Au}$	2.2×10^{-1}	$\tau \to \mu ee$	2.1×10^{-1}	$\tau \to 3e$

Upper limits (68%) for the different LFV Wilson Coefficients (TeV^{-2})