Indirect constraints on top quark operators from a global SMEFT analysis

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F. Garosi, D. Marzocca, A. Stanzione, ARS, JHEP 12 (2023) 129, 2310.00047

SISSA

Starting point

- BSM exists. Hopefully found in the next scale jump...
- Plausible scenario: new physics mainly couples to the top quark
- Assume that mostly top quark operators are induced at the TeV

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

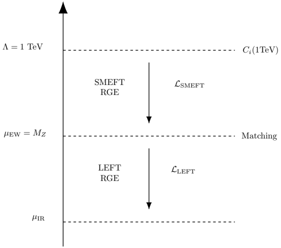
Higgs-Top	
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H)(\bar{q}^3 \gamma^\mu q^3)$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{\mathcal{D}}^a_\mu H)(\bar{q}^3 \gamma^\mu \tau^a q^3)$
$\mathcal{O}_{Hu}$	$(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu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

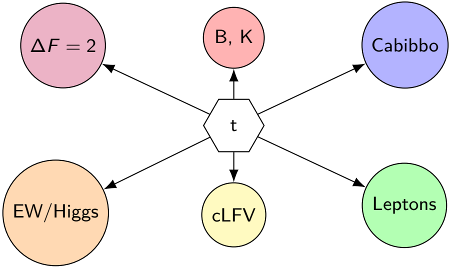
- Otherwise (yet setting $q^i = (u^i_L,\ V_{ij} d^j_L)$) model independent

Overview of low-energy sectors

- Quark flavor rotation induce some low-energy processes even at tree level (suppressed by CKM angles)

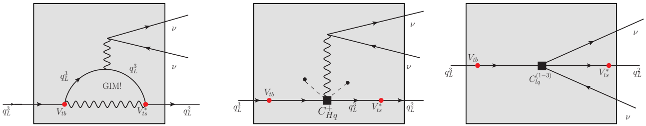
- Radiative corrections induced by tops are leading in some cases. Use **DsixTools** Eur.Phys.J.C 81 (2021) 2



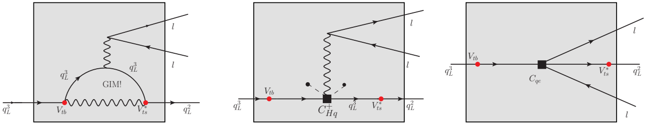


B and K physics. Examples

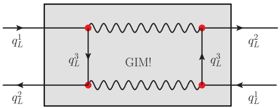
- $R^{\nu}_{K^{(*)}}$, $K \to \pi\nu\bar{\nu}$

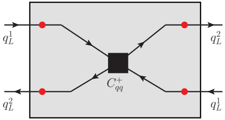


- $B \to K^{(*)}\ell_\alpha\ell_\beta$, $B_{s,d} \to \ell_\alpha\ell_\beta$, $K \to \pi\ell_\alpha\ell_\beta$, $K \to \ell_\alpha\ell_\beta$, $R_{K^{(*)}}$



$\Delta F = 2$. Examples



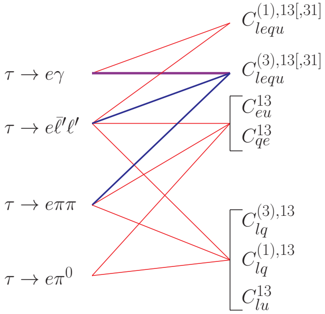


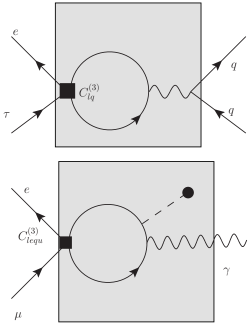
Observable	Experimental value	SM prediction
ϵ_K	$(2.228 \pm 0.011) \times 10^{-3}$	$(2.14 \pm 0.12) \times 10^{-3}$
ΔM_s	$(17.765 \pm 0.006)\,\mathrm{ps}^{-1}$	$(17.35 \pm 0.94)\,\mathrm{ps}^{-1}$
ΔM_d	$(0.5065 \pm 0.0019)\,\mathrm{ps}^{-1}$	$(0.502 \pm 0.031)\,\mathrm{ps}^{-1}$

Use JHEP 12 (2020) 187

Charged Lepton Flavor-Violating decay modes

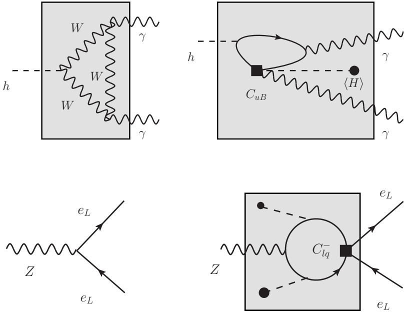
- $\mu \to e$. A few modes, extremely stringent
- $\tau \to \ell$. Many modes. Not so precise
- Top-philic + LFV? $\to \bar{\ell}\ell'\bar{t}t$





EW/Higgs

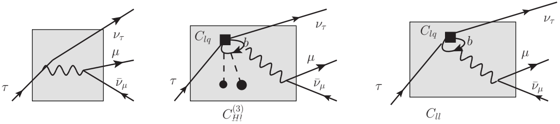
Include EWPOs, such as Z pole observable and $H \to \gamma\gamma$



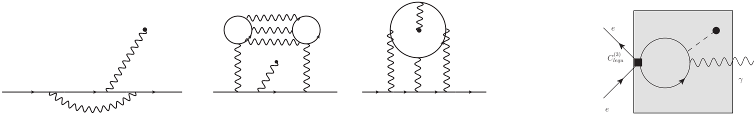
Global likelihood from Falkowski et al. JHEP 04 (2020) 066

Leptons

- Lepton Flavor Universality



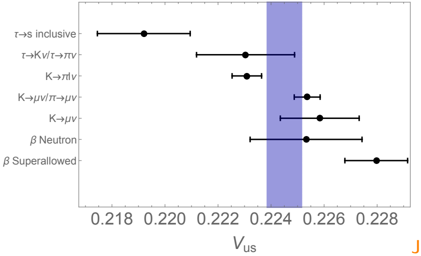
- Magnetic moments



Observable	Experimental value HFLAV	
	$\ell = e$	$\ell = \mu$
$g_\tau / g_\ell - 1$	$(2.7 \pm 1.4) \times 10^{-3}$	$(0.9 \pm 1.4) \times 10^{-3}$
Δa_ℓ	$(2.8 \pm 7.4) \times 10^{-13}$	$(20.0 \pm 8.4) \times 10^{-10}$

Cabibbo angle

- $\pi \to \ell\nu$, $K \to \ell\nu$, $K \to \pi\ell\nu$, $\tau \to \nu H$, $\mathcal{N} \to \mathcal{N}' e\nu$, $n \to pe\nu$
- Related by unitarity $|V_{ud}|^2 + |V_{us}|^2 = 1$ V_{ub} has a negligible effect.



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- Most interesting effect: modify apparent V_{ud}^{β} (muon vertex)

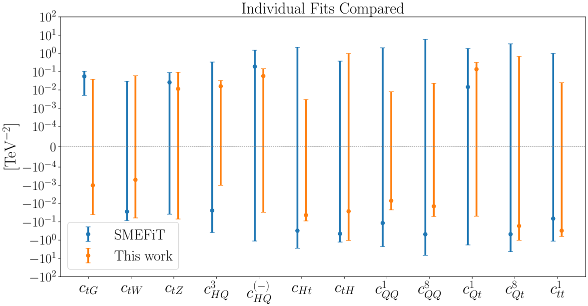
One parameter fits

- Useful to compare experimental reach, scale tested
- If Wilson is induced in a model, where to look at first?

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}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$
$C_{Hq}^{(+)}$	$(18.7 \pm 8.8) \times 10^{-3}$	$B_s \to \mu\mu$
$C_{Hq}^{(-)}$	$(5.8 \pm 4.5) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
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}	$(-0.1 \pm 3.1) \times 10^{-2}$	$c_{\gamma\gamma}$

One parameter fits: comparison with direct bounds

- Use SMEFiT JHEP 11 (2021) 089



- Indirect bounds typically stronger or at least complementary

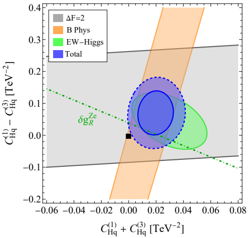
One parameter fits

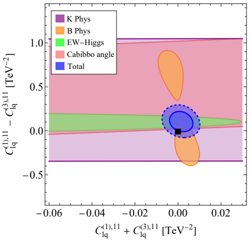
Wilson	Global fit [TeV^{-2}]	Dominant
$C_{lq}^{(+),11}$	$(2.4 \pm 3.5) \times 10^{-3}$	R_K
$C_{lq}^{(+),22}$	$(-4.0 \pm 3.4) \times 10^{-3}$	R_K
$C_{lq}^{(+),33}$	$(7.2 \pm 4.4) \times 10^{-1}$	g_τ / g_i
$C_{lq}^{(-),11}$	$(10.9 \pm 7.6) \times 10^{-2}$	$R^{\nu}_{K(*)}$
$C_{lq}^{(-),22}$	$(-6.0 \pm 7.0) \times 10^{-2}$	$R^{\nu}_{K(*)}$
$C_{lq}^{(-),33}$	$(-1.8 \pm 1.0) \times 10^{-1}$	$R^{\nu}_{K(*)}$
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}	$(2.2 \pm 2.4) \times 10^{-1}$	$\delta g^{Ze}_{R,33}$

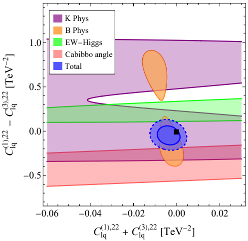
Wilson	Global fit [TeV^{-2}]	Dominant
C_{eu}^{11}	$(5.0 \pm 8.1) \times 10^{-2}$	$\Delta g^{Ze}_{R}{}_{11}$
C_{eu}^{22}	$(4.8 \pm 2.1) \times 10^{-1}$	$\Delta g^{Ze}_{R}{}_{22}$
C_{eu}^{33}	$(-2.3 \pm 2.5) \times 10^{-1}$	$\Delta g^{Ze}_{R}{}_{33}$
$C_{lequ}^{(1),11}$	$(0.4 \pm 1.0) \times 10^{-2}$	$(g-2)_e$
$C_{lequ}^{(1),22}$	$(1.8 \pm 1.6) \times 10^{-2}$	C_{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}

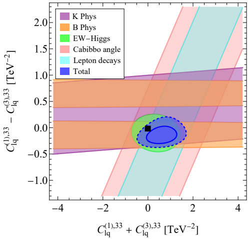
Two parameter fits

Some insight on the interplay between coefficients/sectors





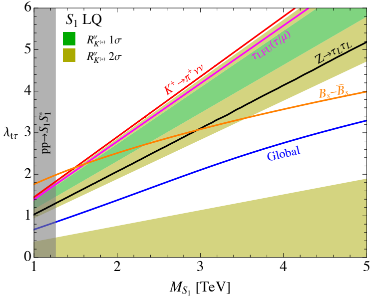




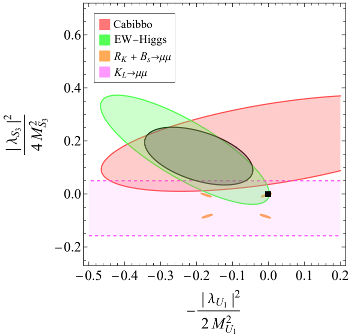
Applications to UV models

- $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{+1/3}$

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



- Top-philic LQ for the Cabibbo tension



- Killed by B/K physics (unless top-philic condition is imposed in down-quark basis)

Conclusions

- Phenomenological study of top-philic scenarios
- Strong interplay between different sectors
- Low-energy physics important to understand how heavy new physics might be
- Let us hope we find new physics both in low-energy and high-energy searches!

Thanks!

BACK-UP SLIDES

B and K physics

	Tree level matching	RG and 1-loop matching
$R^{\nu}_{K^{(*)}}$ $K \to \pi\nu\bar{\nu}$	$C^{(1,3)}_{Hq},\ C^{(1,3),\alpha\beta}_{lq}$	$C_{Hu},\ C^{(1,3)}_{qq},\ C^{\alpha\beta}_{lu},\ C^{\alpha\beta}_{qe}$ $C^{(1,8)}_{qu},\ C_{uu},\ C_{uW}$
$B \to K^{(*)}\ell_\alpha\ell_\beta$ $B_{s,d} \to \ell_\alpha\ell_\beta$ $K \to \pi\ell_\alpha\ell_\beta$ $K \to \ell_\alpha\ell_\beta$	$C^{(1,3)}_{Hq},\ C^{(1,3),\alpha\beta}_{lq},\ C^{\alpha\beta}_{qe}$	$C^{(1,3)}_{qq},\ C^{\alpha\beta}_{lu},\ C^{\alpha\beta}_{eu}$
$R_{K^{(*)}}$	$C^{(1,3),\ell\ell}_{lq},\ C^{\ell\ell}_{qe}$	$C^{\ell\ell}_{lu}$
$B \to X_s\gamma$		$C^{(1,3)}_{Hq},\ C_{uB},\ C_{uW},\ C_{uG}$

B and K physics

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*}^{ν}	< 3.21 Belle-II

$R_K[1.1, 6]$	0.949 ± 0.047 LHCb
$R_{K*}[1.1, 6]$	1.027 ± 0.077 LHCb
$\mathcal{B}(B \to K e \mu)$	$< 4.5 \times 10^{-8}$ Belle
$\mathcal{B}(B \to K e \tau)$	$< 3.6 \times 10^{-5}$ BaBar
$\mathcal{B}(B \to K \mu \tau)$	$< 4.5 \times 10^{-5}$ LHCb

Observable	Experimental value
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	$(1.14^{+0.4}_{-0.33}) \times 10^{-10}$ 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
$\mathcal{B}(B_s \to ee)$	$< 11.2 \times 10^{-9}$ 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

EW/Higgs

$$
\begin{array}{rcl}
\delta g_L^{Z\ell} & \longleftarrow & C_{uB},\; C_{uW}, C_{Hu},\; C_{Hq}^{(1,3)},\; C_{lq}^{(1,3),\ell\ell},\; C_{lu}^{\ell\ell},\; \ldots \\
\delta g_L^{W\ell} & \longleftarrow & C_{uB},\; C_{uW},\; C_{Hu},\; C_{Hq}^{(1,3)},\; C_{lq}^{(3),\ell\ell},\; \ldots \\
\delta g_R^{Z\ell} & \longleftarrow & C_{uB},\; C_{uW},\; C_{Hu},\; C_{Hq}^{(1,3)},\; C_{eu}^{\ell\ell},\; C_{qe}^{\ell\ell},\; \ldots \\
\delta g_L^{Zb} & \longleftarrow & C_{Hq}^{(1,3)},\; C_{Hu},\; C_{qq}^{(1,3)},\; \ldots \\
\delta g_R^{Zb} & \longleftarrow & C_{Hq}^{(1)},\; C_{Hu},\; C_{qq}^{(1,3)},\; C_{uB},\; C_{uW},\; \ldots \\
c_{\gamma\gamma} & \longleftarrow & C_{uB},\; C_{uW},\; C_{uG} \\
c_{gg} & \longleftarrow & C_{uG} \\
[C_{eH}]_{\alpha\alpha} & \longleftarrow & C_{lequ}^{(1),\alpha\alpha} \\
[C_{uH}]_{33} & \longleftarrow & C_{uH},\; C_{uG},\; C_{Hq}^{(1,3)},\; C_{qu}^{(1,8)},\; \ldots
\end{array}
$$

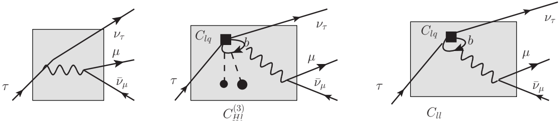
Charged Lepton Flavor-Violating decay modes

- Use JHEP 05 (2017) 117 and JHEP 03 (2021) 256 and use DsixTools to run to 1 TeV

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 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

Leptons

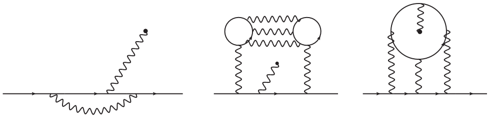


Tests of LFU comparing with $\mu \to e$

$$\frac{g_\tau}{g_e} - 1 = 0.0038\,(C_{lq}^{(3),33} - C_{lq}^{(3),11})$$
$$\frac{g_\tau}{g_\mu} - 1 = 0.0038\,(C_{lq}^{(3),33} - C_{lq}^{(3),22})$$

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

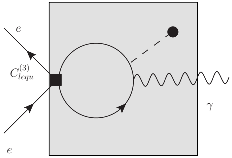
Leptons: magnetic moments



$$\alpha^{-1}(a_e) = 137.035999166(15)$$ PhysRevLett.130.071801

$$\alpha^{-1}(\mathrm{Cs}) = 137.035999046(27)$$ Science 360, 191

$$\alpha^{-1}(\mathrm{Rb}) = 137.035999206(11)$$ Nature 588



Use JHEP 07 (2021) 107

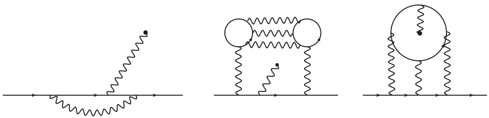
Rydberg frequency codata

$$\frac{\alpha^2 m_e c^2}{2h} = 3.2898419602508(64)\,\mathrm{Hz}$$

h/m_e?

$$(m_e/m_C)\,(m_C/m_{\mathrm{Cs}})\,\frac{m_{\mathrm{Cs}}}{\mathrm{h}}$$

Leptons: magnetic moments



Similar for the muon

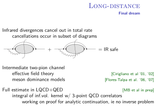
$$\Delta a_e = -4.8 \times 10^{-8}\, C_{lequ}^{(3),11} + 7.1 \times 10^{-11}\, C_{lequ}^{(1),11},$$
$$\Delta a_\mu = -1.0 \times 10^{-5}\, C_{lequ}^{(3),22} + 1.5 \times 10^{-8}\, C_{lequ}^{(1),22}\,.$$

Considering SM tensions...

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

Cabibbo angle

- $\pi \to \ell\nu$ $K \to \ell\nu$ $\tau \to K\nu, \pi\nu$
  - No phase space. Goldstone parity: (ϵ_{L-R}, ϵ_P)
  - $f_{\pi,K}$ from the lattice. Ratios better known (dependence on lattice scale)
  - Other uncertainties: radiative corrections, experimental
- $K \to \pi\ell\nu$
  - Probing ϵ^s_{L+R}, ϵ^s_T, ϵ^s_S
  - Energy-dependent form factors, but smooth
  - Uncertainties: $f_+(0)$, experiment, Radiative corrections
- $\tau \to \pi\pi\nu$. Resonance jungle. But same form factor as $e^+e^- \to$ hadrons Phys.Rev.Lett. 122 (2019) 22, 221801 Main uncertainty: radiative corrections. Some progress...Bruno et al.



Izubuchi, TAU23

Cabibbo angle

- $\tau \to \text{inclusive}$. Total decay width. OPE prediction for V_{us} independently confirmed by lattice, ETMC. Experiments could improve BR precision (potential V_{us} closer to K, enough to test realistic BSM?)

- $n \to pe\nu$, $\mathcal{N} \to \mathcal{N}' e\nu$. $p \ll M_n \sim M_p$. Non-relativistic EFT

$$\mathcal{L}^{(0)} = -(\psi_p^\dagger \psi_n)\Big[C_V^+ \bar{e}_L \gamma^0 \nu_L + C_S^+ \bar{e}_R \nu_L\Big] + (\psi_p^\dagger \sigma^k \psi_n)\Big[C_A^+ \bar{e}_L \gamma^k \nu_L + C_T^+ \bar{e}_R \gamma^0 \gamma^k \nu_L\Big],$$

$$\begin{aligned}
\mathcal{L}^{(1)} = \frac{1}{2m_N}\Big\{ & iC_P^+ (\psi_p^\dagger \sigma^k \psi_n) \nabla_k \left(\bar{e}_R \nu_L\right) - C_M^+ \epsilon^{ijk} (\psi_p^\dagger \sigma^j \psi_n) \nabla_i \left(\bar{e}_L \gamma^k \nu_L\right) \\
& - iC_E^+ (\psi_p^\dagger \sigma^k \psi_n) \nabla_k \left(\bar{e}_L \gamma^0 \nu_L\right) - iC_{E'}^+ (\psi_p^\dagger \sigma^k \psi_n) \partial_t \left(\bar{e}_L \gamma^k \nu_L\right) \\
& - iC_{T1}^+ (\psi_p^\dagger \psi_n) \nabla_k \left(\bar{e}_R \gamma^0 \gamma^k \nu_L\right) + iC_{T2}^+ (\psi_p^\dagger \psi_n)(\bar{e}_R \overleftrightarrow{\partial_t} \nu_L) + 2iC_{T3}^+ (\psi_p^\dagger \sigma^k \psi_n)(\bar{e}_R \overleftrightarrow{\nabla}_k \nu_L) \\
& - iC_{FV}^+ (\psi_p^\dagger \overleftrightarrow{\nabla}_k \psi_n)(\bar{e}_L \gamma^k \nu_L) + iC_{FA}^+ (\psi_p^\dagger \sigma^k \overleftrightarrow{\nabla}_k \psi_n)(\bar{e}_L \gamma^0 \nu_L) + C_{FT}^+ \epsilon^{ijk} (\psi_p^\dagger \sigma^i \overleftrightarrow{\nabla}_j \psi_n)(\bar{e}_R \gamma^0 \gamma^k \nu_L) \Big\},
\end{aligned}$$

JHEP 02 (2024) 091

What about CPV? See for example Eur.Phys.J.C 82 (2022) 12, 1134

Cabibbo angle

$$\mathcal{L}_{\rm eff} \approx -\frac{G_\mu V_{uD}}{\sqrt{2}}\Big[\left(1+\epsilon_L^{D\ell}\right)\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{u}\gamma^\mu(1-\gamma_5)D+\epsilon_R^{D\ell}\,\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{u}\gamma^\mu(1+\gamma_5)D$$

$$+\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{u}\left[\epsilon_S^{D\ell}-\epsilon_P^{D\ell}\gamma_5\right]D+\frac{1}{4}\hat{\epsilon}_T^{D\ell}\,\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)D\Big]+\mathrm{h.c.}$$

$$\begin{pmatrix} \hat{V}_{us}\equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\ \epsilon_L^{dse}\equiv\epsilon_L^{de}+\frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\ \epsilon_R^{d} \\ \epsilon_S^{de} \\ \epsilon_P^{de} \\ \hat{\epsilon}_T^{de} \\ \epsilon_L^{s\mu/e} \\ \epsilon_R^{s} \\ \epsilon_P^{se} \\ \epsilon_L^{d\mu/e}-\epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\ \epsilon_S^{s\mu} \\ \epsilon_P^{s\mu} \\ \hat{\epsilon}_T^{s\mu} \\ \epsilon_L^{d\tau/e} \\ \epsilon_P^{d\tau} \\ \hat{\epsilon}_T^{d\tau} \\ \epsilon_L^{s\tau/e}-\epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\ \epsilon_L^{s\tau/e}+0.08(1)\epsilon_S^{s\tau}-0.38\epsilon_P^{s\tau}+0.40(13)\hat{\epsilon}_T^{s\tau} \end{pmatrix} = \begin{pmatrix} 0.22306(56) \\ 2.2(8.6) \\ -3.3(8.2) \\ 3.0(9.9) \\ 1.3(3.4) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.2(5.0) \\ -0.3(2.0) \\ -0.5(1.8) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.1(1.9) \\ 9.2(8.6) \\ 1.9(4.5) \\ 0.0(1.0) \\ -0.7(5.2) \end{pmatrix} \times 10\wedge \begin{pmatrix} 0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2 \end{pmatrix},$$

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- Simplified scenario: LFU and forget about contact terms, $\epsilon_{P,T,S}=0$
- $\theta_{12}^{Kl3}<\theta_{12}^{Kl2}<\theta_{12}^{\beta}$
- ϵ_R^s needed for first (opposite interference with SM). Possible explanation: VLQ doublet. E.g. Phys.Rev.D 108 (2023) 3, 035022

$$\epsilon_R^s\sim C_{Hud}^{12}\sim\frac{h_u^* h_s}{M_Q^2}$$

- But beware of $K\to\pi\pi$! e.g.2311.00021

One parameter fits

SMEFiT, JHEP 11 (2021) 089

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}	$-\mathrm{s}_\theta\ C_{uB} + \mathrm{c}_\theta\ C_{uW}$	[-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]

One parameter fits

Wilson	$\mu \to e$		$\tau \to \mu$		$\tau \to e$	
	Limit	Dominant	Limit	Dominant	Limit	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}	$\mu\mathrm{Au} \to e\mathrm{Au}$	7.1×10^{-2}	$\tau \to \mu\pi\pi$	7.4×10^{-2}	$\tau \to e\pi\pi$
$C_{lq}^{(1)}$	4.0×10^{-5}	$\mu\mathrm{Au} \to e\mathrm{Au}$	1.1×10^{-1}	$\tau \to \mu\pi\pi$	1.1×10^{-1}	$\tau \to e\pi\pi$
C_{lu}	4.0×10^{-5}	$\mu\mathrm{Au} \to e\mathrm{Au}$	1.0×10^{-1}	$\tau \to \mu\pi\pi$	1.1×10^{-1}	$\tau \to e\pi\pi$
C_{eu}	3.6×10^{-5}	$\mu\mathrm{Au} \to e\mathrm{Au}$	1.0×10^{-1}	$\tau \to \mu\pi\pi$	1.1×10^{-1}	$\tau \to e\pi\pi$
C_{qe}	3.6×10^{-5}	$\mu\mathrm{Au} \to e\mathrm{Au}$	1.0×10^{-1}	$\tau \to \mu\pi\pi$	1.0×10^{-1}	$\tau \to e\pi\pi$

Gaussian fits

Limited attempt to overcome previous limitations

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

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

Coefficient	Gaussian fit $[\mathrm{TeV}^{-2}]$	Coefficient	Gaussian fit $[\mathrm{TeV}^{-2}]$
K_1	0.0019 ± 0.0023	K_7	0.54 ± 0.79
K_2	0.0179 ± 0.0083	K_8	0.74 ± 0.88
K_3	-0.002 ± 0.015	K_9	-0.8 ± 1.3
K_4	-0.016 ± 0.021	K_{10}	-0.7 ± 1.8
K_5	0.044 ± 0.029	K_{11}	12 ± 13
K_6	-0.30 ± 0.38	K_{12}	-11 ± 16

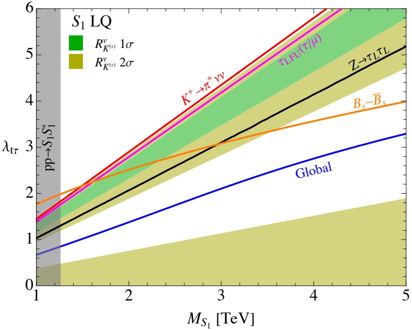
$$U_{KC} = \begin{pmatrix}
-1.00 & 0.000 & 0.000 & -0.016 & -0.004 & -0.004 & 0.021 & -0.001 & 0.000 & 0.000 & 0.000 & 0.000 \\
-0.005 & -0.089 & -0.015 & 0.058 & 0.000 & 0.984 & -0.004 & -0.117 & 0.000 & -0.009 & 0.044 & 0.063 \\
0.004 & 0.011 & -0.039 & 0.018 & -0.001 & -0.1 & 0.145 & -0.28 & 0.015 & -0.494 & 0.447 & 0.667 \\
-0.007 & -0.013 & 0.09 & -0.053 & -0.003 & 0.081 & -0.316 & 0.64 & 0.024 & -0.673 & -0.126 & -0.059 \\
0.005 & 0.007 & -0.074 & 0.042 & -0.002 & -0.025 & 0.259 & -0.525 & 0.025 & -0.548 & -0.213 & -0.55 \\
-0.004 & -0.041 & 0.025 & 0.067 & 0.006 & -0.004 & -0.128 & 0.084 & 0.006 & 0.022 & 0.853 & -0.492 \\
-0.006 & -0.137 & 0.078 & 0.196 & 0.96 & -0.017 & 0.09 & 0.047 & -0.065 & -0.007 & -0.017 & 0.008 \\
0.002 & -0.349 & -0.006 & 0.646 & -0.248 & -0.029 & 0.545 & 0.318 & 0.014 & 0.001 & -0.012 & 0.006 \\
0.005 & 0.007 & 0.028 & -0.138 & 0.077 & 0.017 & 0.145 & 0.06 & 0.973 & 0.037 & 0.017 & -0.003 \\
0.023 & 0.221 & 0.074 & -0.569 & 0.053 & 0.092 & 0.684 & 0.292 & -0.212 & -0.002 & 0.095 & -0.057 \\
0.006 & -0.798 & 0.451 & -0.364 & -0.071 & -0.059 & -0.038 & -0.122 & -0.039 & 0.000 & -0.012 & 0.007 \\
-0.004 & 0.404 & 0.876 & 0.235 & -0.058 & 0.025 & 0.017 & -0.093 & 0.013 & 0.000 & -0.01 & 0.006
\end{pmatrix}$$

- Assume $\Lambda_{BSM} \sim 1\,\mathrm{TeV}$. Very loosely, using Phys.Lett.B 726 (2013) 697-702
  $V_{\mathrm{EFT}} \sim \frac{\pi^6}{720}\left(\frac{(4\pi)}{\mathrm{TeV}^2}\right)^3\left(\frac{(4\pi)^2}{\mathrm{TeV}^2}\right)^8\left(\frac{(4\pi)^3}{\mathrm{TeV}^2}\right)$

- Experimental constraints reduce it to a tiny fraction $(\sim 10^{-31})$

Applications to UV model I: tau-philic S_1

- $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{+1/3}$
- $\mathcal{L} \supset \lambda_{t\tau}\, \bar{q}_3^c i\sigma_2 l_3\, S_1 + \text{h.c.}$,
  - $C_{lq}^{(1),33} = -C_{lq}^{(3),33} = \frac{|\lambda_{t\tau}|^2}{4M_{S_1}^2}, \quad C_{qq}^{(1)} = C_{qq}^{(3)} = -\frac{|\lambda_{t\tau}|^4}{256\pi^2 M_{S_1}^2}$



Applications to UV models II: Cabibbo anomalies

- Assume a Cabibbo tensions are new physics hints. Can they (at least partially) be accommodated in top-philic set-up?

- $[C_{lq}^{(3),22}]^{\rm Cabibbo} = (0.19 \pm 0.06)\,{\rm TeV}^{-2}$. What is pulling this?
- Dominated by

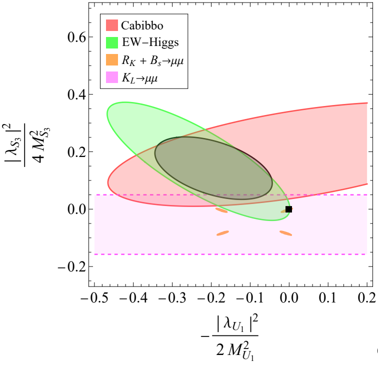
$$\Delta_{\rm CKM} \equiv |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 \approx -2v^2\,(|V_{ud}|^2 C_{Hl}^{(3),22} - |V_{us}|^2(C_{Hl}^{(3),\ell\ell} - C_{Hl}^{(3),11} - C_{Hl}^{(3),22}))$$
$$\approx -2v^2\, C_{Hl}^{(3),22} \sim -\left[\frac{N_c}{2\pi^2}\frac{m_t^2}{\Lambda_{\rm UV}^2}\log\frac{\Lambda_{\rm UV}}{M_Z}\right]\Lambda_{\rm UV}^2 C_{lq}^{(3),22}(\Lambda_{\rm UV}^2)$$

- However... $[C_{lq}^{(3),22}]^{\rm EW/Higgs} = (-0.11 \pm 0.06)\,{\rm TeV}^{-2}$ Why?
- EW fit prefers $G_\mu < G_F$. Oversimplifying

$$M_W^{2,EW} \sim \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_\mu M_Z^2}}\right) < M_W^2$$

Applications to UV models II: anomalies

- Reduce G_μ by also switching on $[C_{lq}^{(3),11}]$? Stringent bounds on δg_L^{Ze}
- Unless $[C_{lq}^{(3),11}] = [C_{lq}^{(1),11}]$ ($\sim U_1$) Take also $C_{lq}^{(1),22} \approx 3C_{lq}^{(3),22}$ ($\sim S_3$)



95% CL

- B/K physics avoided if top-philic condition in the down-quark basis