SMEFT Restrictions on Exclusive $b \to ul\nu$ Decays

Based on [Greljo, JS, Smolkovic, Stangl: 2306.09401]

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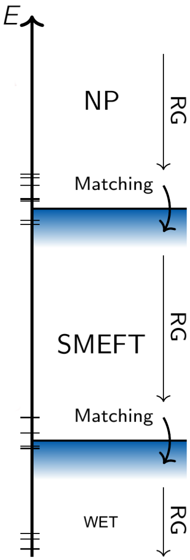
Introduction

$b \to ul\nu$ = sandbox for CKM and form factor determination

Any room for new physics?

Introduction



Part III
Finite number of tree level mediators matching to Dim-6 SMEFT *[de Blas et.al. 1711.10391]*

Part II
SM works well as an EFT
Scale separation $\Lambda_{\text{NP}} \gg v_{\text{EW}}$
WCs encode generic NP above EW scale
Systematic approach at each EFT and loop order

Part I
B decays described in WET

Part I: WET

WET: setup

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} + \frac{4G_F}{\sqrt{2}} V_{ub} \sum_{i,l} C_i^{(l)} O_i^{(l)} + \text{h.c.}$$

$$O_{V_L}^{(l)} = (\bar{u}_L \gamma^\mu b_L)(\bar{l}_L \gamma_\mu \nu_{lL}) \qquad O_{V_R}^{(l)} = (\bar{u}_R \gamma^\mu b_R)(\bar{l}_L \gamma_\mu \nu_{lL})$$

$$O_{S_L}^{(l)} = (\bar{u}_R b_L)(\bar{l}_R \nu_{lL}) \qquad O_{S_R}^{(l)} = (\bar{u}_L b_R)(\bar{l}_R \nu_{lL})$$

$$O_T^{(l)} = (\bar{u}_R \sigma^{\mu\nu} b_L)(\bar{l}_R \sigma_{\mu\nu} \nu_{lL})$$

- $C_{V_L}^{(l)\text{SM}} = 1 + \frac{\alpha_e}{\pi} \log(\frac{m_Z}{\mu_b})$
- numerical analysis using `flavio` *[1810.08132]* and `smelli` *[1810.07698, 2012.12211]*

WET: data

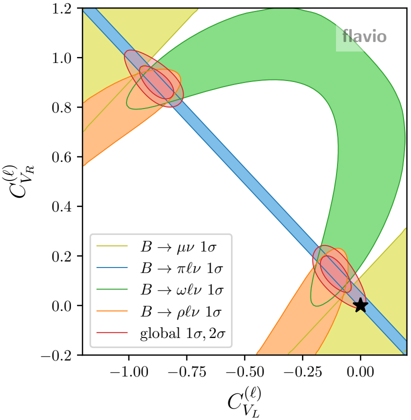
- $B \to l\nu$ sensitive to $C_P = C_{S_R} - C_{S_L}$ and $C_A = C_{V_R} - C_{V_L}$

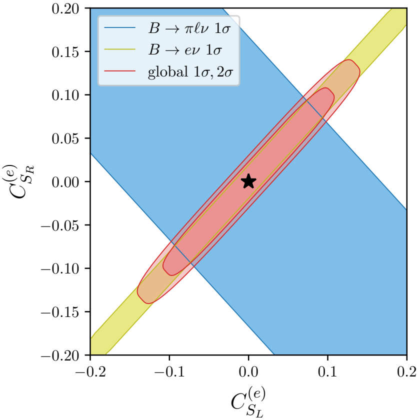
$\text{BR}(B \to e\nu)$ *[Belle: 0611045]*
$\text{BR}(B \to \mu\nu)$ *[Belle: 0611045, 1911.03186]*
$\text{BR}(B \to \tau\nu)$ *[PDG average]*

- $B \to \pi$ sensitive to $C_S = C_{S_R} + C_{S_L}$, $C_V = C_{V_R} + C_{V_L}$ and C_T
- $B \to \{\rho, \omega\}$ more complicated
- differential branching ratios of $B \to \{\pi, \rho, \omega\}\ell\nu$ measured:
  - *[Belle: 1012.0090, 1306.2781]*
  - *[BaBar: 1005.3288, 1208.1253, 1205.6245]*
  - combined in HFLAV *[2206.07501, 2104.05739]*
  - only combination of e and μ channels $\Rightarrow$ LFU in $\ell = e, \mu$ (when $B \to \ell\nu$ not relevant)
- form factors
  - $B \to \pi$: lattice + LCSR *[Leljak et.al. 2102.07233]*
  - $B \to \{\rho, \omega\}$: only LCSR *[Bharucha et.al. 1503.05534]*

WET: selected results

results compatible with *[Leljak et.al. 2302.05268]*





$$O_{V_L}^{(l)} = (\bar{u}_L \gamma^\mu b_L)(\bar{l}_L \gamma_\mu \nu_{lL})$$
$$O_{V_R}^{(l)} = (\bar{u}_R \gamma^\mu b_R)(\bar{l}_L \gamma_\mu \nu_{lL})$$

$$O_{S_L}^{(l)} = (\bar{u}_R b_L)(\bar{l}_R \nu_{lL})$$
$$O_{S_R}^{(l)} = (\bar{u}_L b_R)(\bar{l}_R \nu_{lL})$$

Part II: SMEFT

SMEFT: setup

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} Q_i$$

C_{V_L}	$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma_a l_r)(\bar{q}_s \gamma^\mu \sigma^a q_t)$
C_{S_R}	Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
C_{S_L}	$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
C_T	$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$
C_{V_L}	$Q_{\phi q}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu^a \phi)(\bar{q}_p \sigma_a \gamma^\mu q_r)$
C_{V_R}	$Q_{\phi ud}$	$(\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u}_p \gamma^\mu d_r)$

$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{\phi q}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_p \gamma^\mu q_r)$

- full set of Dim-6 operators relevant to $b \to u\ell\nu$ at the NP matching scale $\Lambda = 1$ TeV
- use `wilson` *[1804.05033]* for running and matching down to WET
- minimal flavour structure (e.g. 13 in quark sector)

SMEFT: complementary constraints

- $SU(2)$ relations $\Rightarrow b \to d\ell\ell$ and $b \to d\nu\nu$
  - $B \to ee$ *[LHCb: 2003.03999]*
  - $B \to \mu\mu$ *[LHCb: 2108.09283, 2108.09284, CMS: 2212.10311, ATLAS: 1812.03017]*
  - $B \to \pi ee$ *[Belle: 0804.3656]*, $B \to \pi\mu\mu$ *[LHCb: 1509.00414]*
  - $B_s \to K^{*0}\mu\mu$ *[LHCb: 1804.07167]*
  - $B \to \pi\nu\nu$, $B \to \rho\nu\nu$ *[Belle: 1303.3719, 1702.03224]*
  - see talk by A. Smolkovic tomorrow or [Greljo et.al. 2212.10497, Bause et.al. 2209.04457] for detailed WET studies of this sector

- high-mass Drell-Yan tails sensitive to contact interactions e.g. [Greljo et.al. 2212.10497, Allwicher et.al. 2207.10714]
  - differential spectra in both NC and CC by *[ATLAS: 2006.12946, 1906.05609]* and *[CMS: 2103.02708, 2202.06075]*

- B^0 mixing via double insertions of modified Z boson vertex OR RG running into 4-quark operators $C_{qq}^{(1)}$ and $C_{qq}^{(3)}$.
  - ΔM_d and $S_{\psi K}$ *[HFLAV: 2206.07501]*

SMEFT: selected results

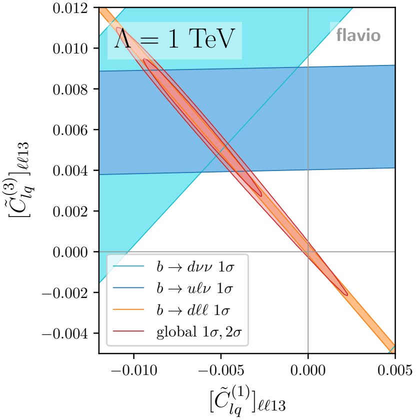
- WET motivated:
  - Scenario 1: $(C_{V_L}, C_{V_R}) \Rightarrow (C_{lq}^{(3)}$ and $C_{lq}^{(1)}, C_{\phi ud})$
  - Scenario 2: $(C_{V_L}, C_{V_R}) \Rightarrow (C_{\phi q}^{(3)}$ and $C_{\phi q}^{(1)}, C_{\phi ud})$
- Scenario 3: $(C_{lequ}^{(1)}, C_{lequ}^{(3)})$ and C_{ledq} considered separately

SMEFT: selected results

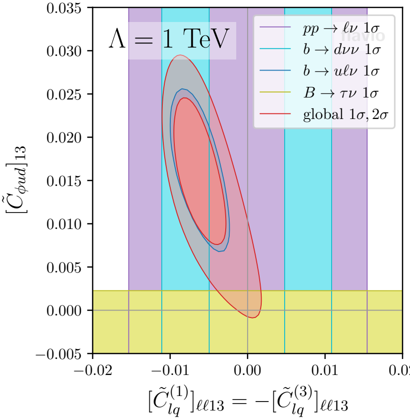
Scenario 1: $(C_{lq}^{(1)}, C_{lq}^{(3)}, C_{\phi ud})$

SMEFT: selected results

$(C_{lq}^{(1)}$ vs. $C_{lq}^{(3)})$, profiling over $C_{\phi ud}$



$(C_{lq}^{(1)} = -C_{lq}^{(3)}$ vs $C_{\phi ud})$



$$[Q_{lq}^{(1)}]_{\ell\ell 13} = (\bar{\ell}\gamma_\mu \ell)(\bar{q}_1 \gamma^\mu q_3)\,, \quad [Q_{lq}^{(3)}]_{\ell\ell 13} = (\bar{\ell}\gamma_\mu \sigma_a \ell)(\bar{q}_1 \gamma^\mu \sigma^a q_3)\,, \quad [Q_{\phi ud}]_{13} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u}\gamma^\mu b)$$

SMEFT: selected results

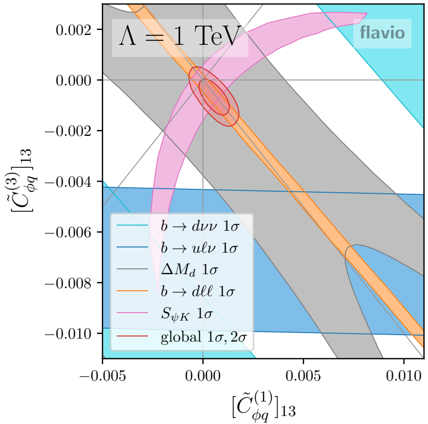
Scenario 2: $(C_{\phi q}^{(1)}, C_{\phi q}^{(3)}, C_{\phi ud})$

SMEFT: selected results

$(C_{\phi q}^{(1)}$ vs. $C_{\phi q}^{(3)})$, profiling over $C_{\phi ud}$

– dominated by complementary constraints

$$[Q_{\phi q}^{(1)}]_{13} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_1 \gamma^\mu q_3)$$
$$[Q_{\phi q}^{(3)}]_{13} = (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{q}_1 \sigma_a \gamma^\mu q_3)$$
$$[Q_{\phi ud}]_{13} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u} \gamma^\mu b)$$

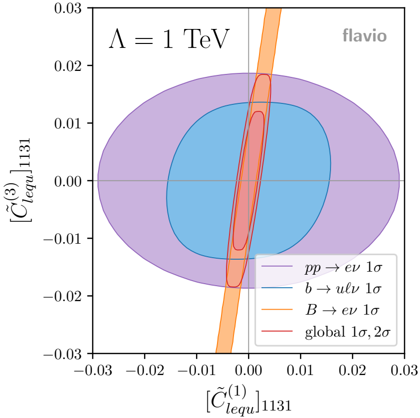


SMEFT: selected results

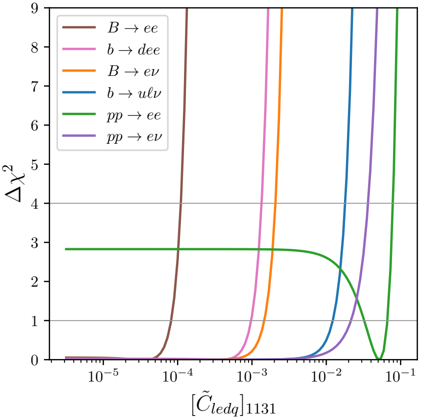
Scenario 3: $(C^{(1)}_{lequ}, C^{(3)}_{lequ})$ **and** C_{ledq}

SMEFT: selected results

$(C^{(1)}_{lequ}$ vs. $C^{(3)}_{lequ})$



C_{ledq}



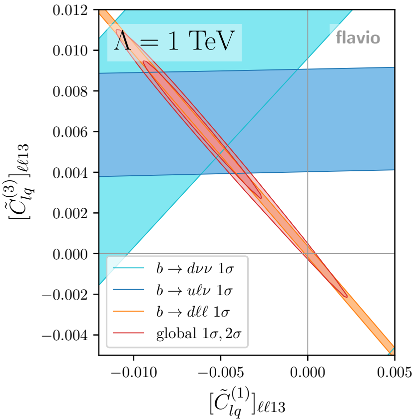
$$[Q^{(1)}_{lequ}]_{1131} = (\bar{\ell}^j_1 e)\varepsilon_{jk}(\bar{q}^k_3 u)\,, \quad [Q^{(3)}_{lequ}]_{1131} = (\bar{\ell}^j_1 \sigma_{\mu\nu} e)\varepsilon_{jk}(\bar{q}^k_3 \sigma^{\mu\nu} u)\,, \quad [Q_{ledq}]_{1131} = (\bar{\ell}^j_1 e)(\bar{b} q_{1j})$$

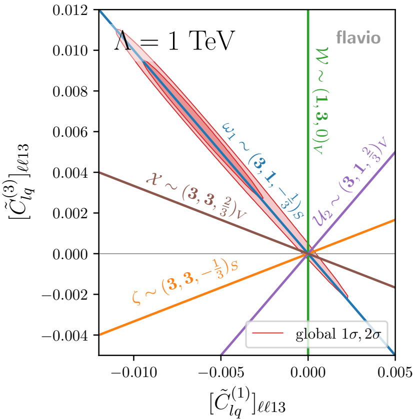
Part III: Models

Models: tree level mediators

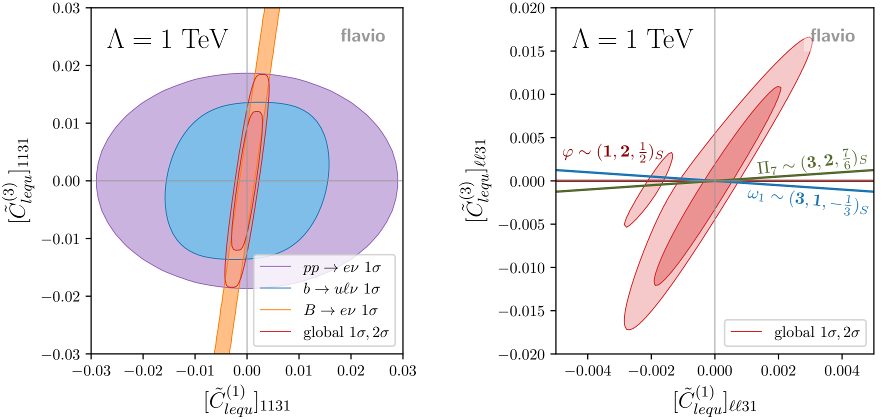
- finite number of NP single mediators matching at tree level
- only a subset (4 scalars, 5 fermions or 5 vectors) could play a role for $b \to u\ell\nu$
- each requires two independent couplings $\Rightarrow$ correlations with other observables
- notation and matching from *[de Blas et.al. 1711.10391]*

Models: tree level mediators





$$[Q^{(1)}_{lq}]_{\ell\ell 13} = (\bar{\ell}\gamma_\mu \ell)(\bar{q}_1 \gamma^\mu q_3)\,, \quad [Q^{(3)}_{lq}]_{\ell\ell 13} = (\bar{\ell}\gamma_\mu \sigma_a \ell)(\bar{q}_1 \gamma^\mu \sigma^a q_3)\,, \quad [Q_{\phi ud}]_{13} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u}\gamma^\mu b)$$



$$[Q^{(1)}_{lequ}]_{1131} = (\bar{\ell}^j_1 e)\varepsilon_{jk}(\bar{q}^k_3 u)\,, \quad [Q^{(3)}_{lequ}]_{1131} = (\bar{\ell}^j_1 \sigma_{\mu\nu} e)\varepsilon_{jk}(\bar{q}^k_3 \sigma^{\mu\nu} u)$$

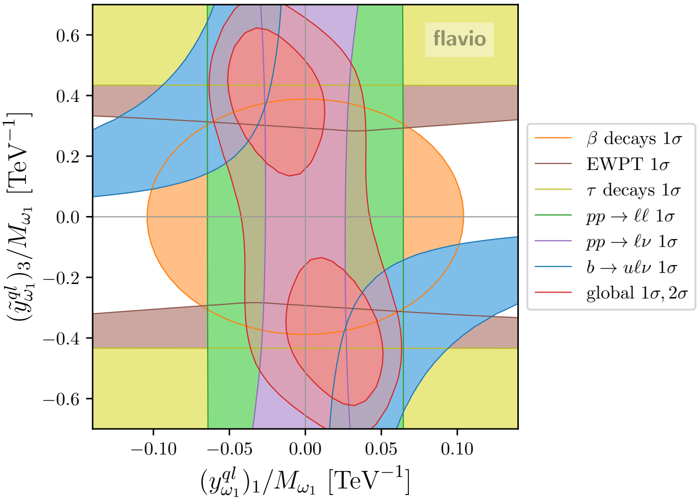
Models: LQ + VLQ

- consider ω_1 (scalar singlet leptoquark) and Q_1 (vector-like partner of the quark doublet)
- ω_1 assumed to be a doublet under leptonic $SU(2)$ to generate LFU SMEFT operators

$$-\mathcal{L}^{\leq 4} \supset (y^{ql}_{\omega_1})_1 \; \omega^\dagger_{1\ell} \bar{q}^c_1 i\sigma_2 l_\ell + (y^{ql}_{\omega_1})_3 \; \omega^\dagger_{1\ell} \bar{q}^c_3 i\sigma_2 l_\ell + \text{h.c.}$$
$$+ (\lambda^u_{Q_1})_1 \; \bar{Q}_{1L} \tilde{\phi} u_1 + (\lambda^d_{Q_1})_3 \; \bar{Q}_{1L} \phi d_3 + \text{h.c.}$$

- LQ generates $[C^{(1)}_{lq}]_{prst} = -[C^{(3)}_{lq}]_{prst}$ with $prst = \{\ell\ell 13, \ell\ell 11, \ell\ell 33\}$
- VLQ generates $[C_{\phi ud}]_{13}$, $[C_{\phi u}]_{11}$, $[C_{\phi d}]_{33}$ (also $Q_{u\phi}$ and $Q_{d\phi}$)

Models: LQ + VLQ

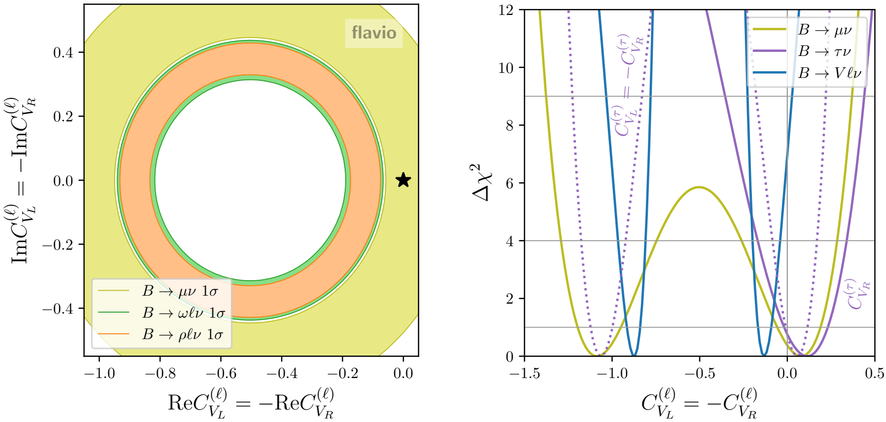


Summary

- most WET operators best constrained by semileptonic decays except for the pseudoscalar operators constrained by the fully leptonic decays
- SMEFT implies important correlations with NC b decays, B^0 mixing and high-mass Drell-Yan tails
- $b \to u\ell\nu$ important for $([Q_{lq}^{(1)}]_{\ell\ell 13} = -[Q_{lq}^{(3)}]_{\ell\ell 13}, [Q_{\phi ud}]_{13})$ parameter space
- a limited number of tree level mediators matching onto the SMEFT operators relevant for $b \to u\ell\nu$ all constrained primarily by complementary constraints
- exception of $\omega_1 \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})_S$, $Q_1 \sim (\mathbf{3}, \mathbf{2}, \frac{1}{6})_F$ and $\mathcal{B} \sim (\mathbf{1}, \mathbf{1}, 1)_V$

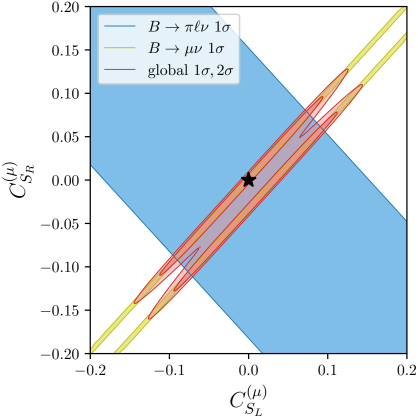
Thank you for you attention

Backup: WET results - $C_{V_L} = -C_{V_R}$



$$O_{V_L}^{(l)} = (\bar{u}_L \gamma^\mu b_L)(\bar{l}_L \gamma_\mu \nu_{lL}), \quad O_{V_R}^{(l)} = (\bar{u}_R \gamma^\mu b_R)(\bar{l}_L \gamma_\mu \nu_{lL})$$

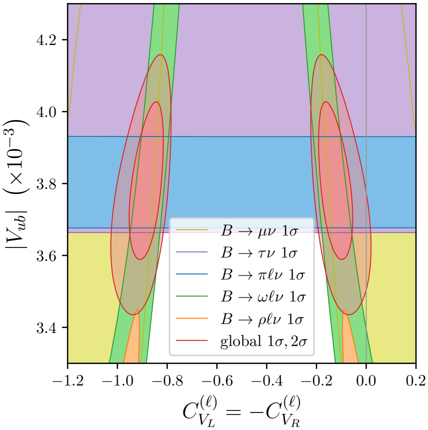
Backup: WET results - $C_{S_L}^{(\mu)}$ vs. $C_{S_R}^{(\mu)}$



$$O_{S_L}^{(l)} = (\bar{u}_R b_L)(\bar{l}_R \nu_{lL})\,, \quad O_{S_R}^{(l)} = (\bar{u}_L b_R)(\bar{l}_R \nu_{lL})$$

Backup: V_{ub}

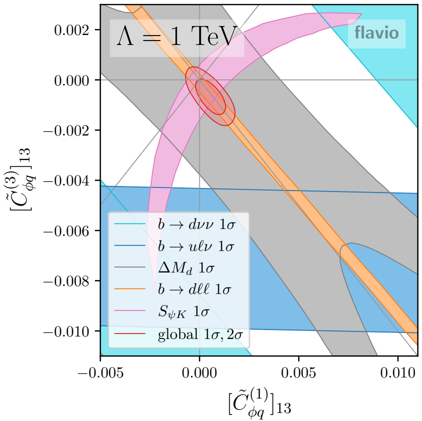
- concerning the tension in C_A, we fit $|V_{ub}|$ and C_A simultaneously
- in case of vector, scalar and tensor operators, $|V_{ub}|$ can be fixed by $\Delta F = 2$ processes



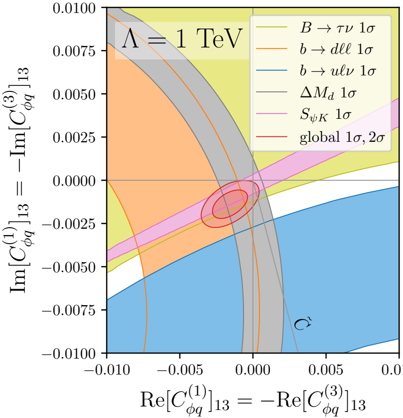
$$O_{V_L}^{(l)} = (\bar{u}_L \gamma^\mu b_L)(\bar{l}_L \gamma_\mu \nu_{lL}), \quad O_{V_R}^{(l)} = (\bar{u}_R \gamma^\mu b_R)(\bar{l}_L \gamma_\mu \nu_{lL})$$

Backup: SMEFT results - VC in complex plane

$(C_{\phi q}^{(1)}$ vs. $C_{\phi q}^{(3)})$, profiling over $C_{\phi ud}$



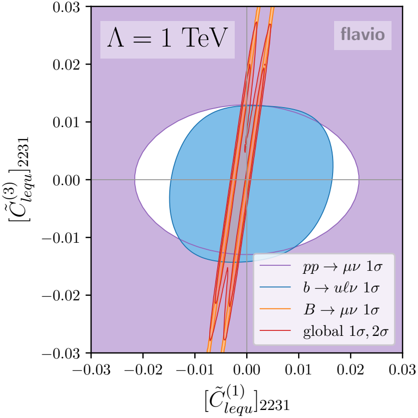
$(C_{\phi q}^{(1)} = -C_{\phi q}^{(3)}$ vs $C_{\phi ud})$



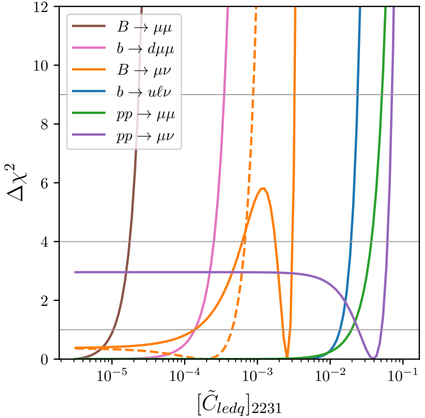
$$[Q_{\phi q}^{(1)}]_{13} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_1 \gamma^\mu q_3)\,, \quad [Q_{\phi q}^{(3)}]_{13} = (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{q}_1 \sigma_a \gamma^\mu q_3)\,, \quad [Q_{\phi ud}]_{13} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u}\gamma^\mu b)$$

Backup: SMEFT results - scalars and tensors in μ channel

$(C_{lequ}^{(1)}$ vs. $C_{lequ}^{(3)})$



$C_{ledq}^{(1)}$



$$[Q_{lequ}^{(1)}]_{1131} = (\bar{\ell}_1^j e)\varepsilon_{jk}(\bar{q}_3^k u)\,, \quad [Q_{lequ}^{(3)}]_{1131} = (\bar{\ell}_1^j \sigma_{\mu\nu} e)\varepsilon_{jk}(\bar{q}_3^k \sigma^{\mu\nu} u)\,, \quad [Q_{ledq}]_{1131} = (\bar{\ell}_1^j e)(\bar{b} q_{1j})$$

Backup: running

– flat direction $C_{\phi q}^{(1)} = -C_{\phi q}^{(3)}$ unstable under RG effects

– the two operators run differently due to y_t-enhanced contributions of diagrams with Higgs attached to one fermion and emmiting another Higgs from inside the loop *[Jenkins at.al. 1310.4838]*

$$\left[\dot{C}_{\phi q}^{(1)}\right]_{pr} \propto \frac{3}{2}\left[C_{\phi q}^{(1)}\right]_{pt}[Y_u^\dagger Y_u]_{tr} - \frac{9}{2}\left[C_{\phi q}^{(3)}\right]_{pt}[Y_u^\dagger Y_u]_{tr}$$
$$\left[\dot{C}_{\phi q}^{(3)}\right]_{pr} \propto \frac{1}{2}\left[C_{\phi q}^{(3)}\right]_{pt}[Y_u^\dagger Y_u]_{tr} - \frac{3}{2}\left[C_{\phi q}^{(1)}\right]_{pt}[Y_u^\dagger Y_u]_{tr}$$

– $C_{\phi q}^{(1)}$ and $C_{\phi q}^{(3)}$ also run into $C_{qq}^{(1)}$ and $C_{qq}^{(3)}$ by closing the Higgs loop by two insertions of top Yukawas *[Jenkins at.al. 1310.4838]*

$$\begin{aligned}\left[\dot{C}_{qq}^{(1)}\right]_{prst} &\propto \frac{1}{2}[Y_u^\dagger Y_u]_{pr}\left[C_{\phi q}^{(1)}\right]_{st} + \frac{1}{2}[Y_u^\dagger Y_u]_{st}\left[C_{\phi q}^{(1)}\right]_{pr} \\ \left[\dot{C}_{qq}^{(3)}\right]_{prst} &\propto -\frac{1}{2}[Y_u^\dagger Y_u]_{pr}\left[C_{\phi q}^{(3)}\right]_{st} - \frac{1}{2}[Y_u^\dagger Y_u]_{st}\left[C_{\phi q}^{(3)}\right]_{pr}\end{aligned} \tag{1}$$

– the RGE contribution to the B^0 mixing will be non-vanishing even the case $C_{\phi q}^{(1)} = -C_{\phi q}^{(3)}$ when the Z vertex does not get modified

Backup: LQ+VLQ model matching to the SMEFT

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{(y^{ql}_{\omega_1})^*_1 (y^{ql}_{\omega_1})_3}{4M^2_{\omega_1}} \left([Q^{(1)}_{lq}]_{\ell\ell 13} - [Q^{(3)}_{lq}]_{\ell\ell 13} \right) + (\ell\ell 11 + \ell\ell 33)$$
$$+ \frac{(\lambda^d_{Q_1})_3 (\lambda^u_{Q_1})^*_1}{M^2_{Q_1}} [Q_{\phi ud}]_{13} - \frac{|(\lambda^u_{Q_1})_1|^2}{2M^2_{Q_1}} [Q_{\phi u}]_{11} + \frac{|(\lambda^d_{Q_1})_3|^2}{2M^2_{Q_1}} [Q_{\phi d}]_{33}$$
$$+ \frac{\hat{y}^{u*}_{1i} |(\lambda^u_{Q_1})_1|^2}{2M^2_{Q_1}} [Q_{u\phi}]_{i1} + \frac{\hat{y}^{d*}_{3i} |(\lambda^d_{Q_1})_3|^2}{2M^2_{Q_1}} [Q_{d\phi}]_{i3}$$

- with the index i running over all three generations
- notation and matching from *[de Blas et.al. 1711.10391]*