SMEFT predictions for semileptonic processes

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Standard Model Effective Field Theory (SMEFT) :

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda} C^{(5)} O^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right).$$

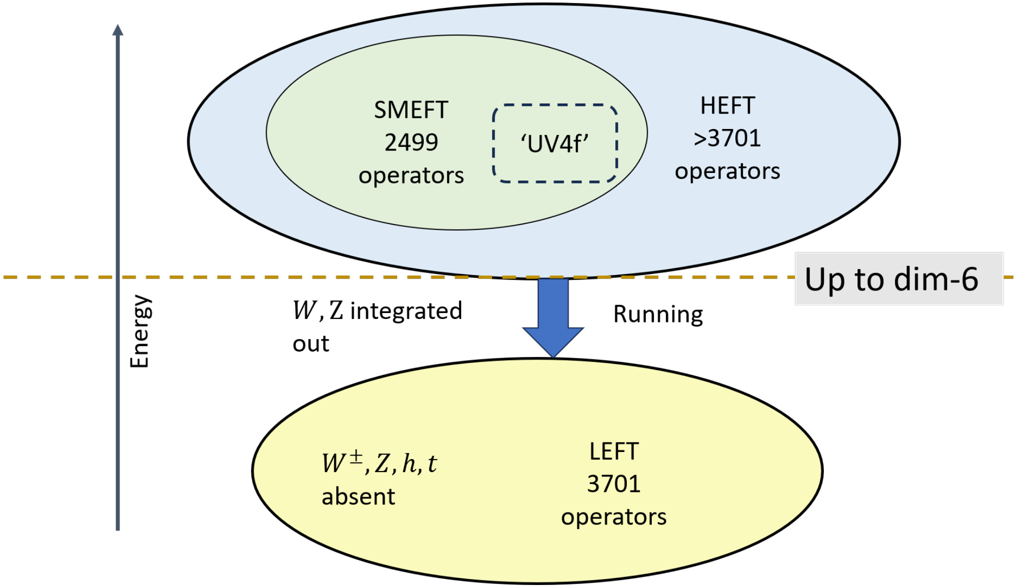
- Includes SM fields only.
- Follows $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Electroweak (EW) symmetry is linearly realized.

More general EFTs e.g. **Higgs Effective Field Theory (HEFT)**, are also possible. In HEFT:

- $SU(2)_L \times U(1)_Y$ non-linearly realized.
- In the unitary gauge, HEFT reduces to the most general $U(1)_{em}$ invariant Lagrangian.
- Higgs boson is not embedded in a $SU(2)_L$-doublet: $\longrightarrow$ More general coupling of Higgs.
- HEFT $\supset$ SMEFT $\supset$ SM *[Buchalla and Cata, 2012]*

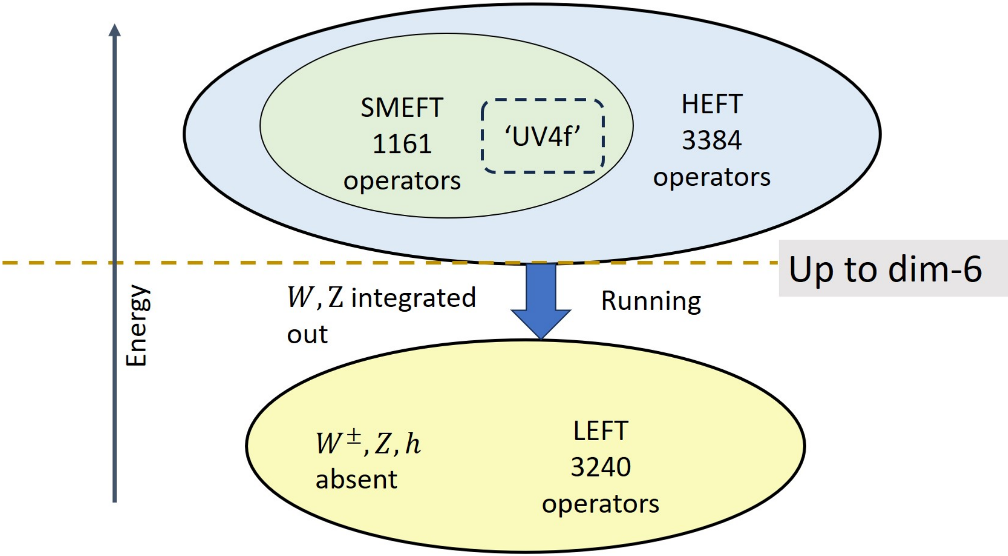
- In the energy scale much below the EW symmetry breaking, the relevant EFT is **Low Energy Effective Field Theory (LEFT)**
- LEFT can be derived from HEFT by integrating out the heavier particles – $W^{\pm}$, Z, Higgs and top quark. *[Jenkins, Manohar and Stoffer, 2018]*

HEFT, SMEFT and LEFT



- More number of operator in HEFT/LEFT than in SMEFT $\implies$ relations among HEFT/LEFT WCs
- Relations among HEFT/LEFT WCs $\implies$ indirect bounds
- Violation of these relations $\implies$ physics beyond dimension-6 SMEFT

For semileptonic operators:



3384 – 1161 = 2223 Relations

- More number of operator in HEFT/LEFT than in SMEFT $\Longrightarrow$ relations among HEFT/LEFT WCs
- Relations among HEFT/LEFT WCs $\Longrightarrow$ indirect bounds
- Violation of these relations $\Longrightarrow$ physics beyond dimension-6 SMEFT

Outline:

- SMEFT-predicted relations among LEFT/HEFT Wilson coefficients

- SMEFT-predicted constraints on LEFT Wilson coefficients

- SMEFT-predicted hints of possible new physics signals.

An example derivation of relations among $U(1)_{em}$ invariant operators:

Vector operators $LLLL$ (HEFT)		
	NC	Count
$[\hat{\mathbf{c}}^{V}_{e_L d_L}]^{\alpha\beta ij}$	$(\bar{e}^{\alpha}_{L}\gamma_\mu e^{\beta}_{L})(\bar{d}^{i}_{L}\gamma^\mu \bar{d}^{j}_{L})$	81 (45)
$[\hat{\mathbf{c}}^{V}_{euLL}]^{\alpha\beta ij}$	$(\bar{e}^{\alpha}_{L}\gamma_\mu e^{\beta}_{L})(\bar{u}^{i}_{L}\gamma^\mu \bar{u}^{j}_{L})$	81 (45)
$[\hat{\mathbf{c}}^{V}_{\nu dLL}]^{\alpha\beta ij}$	$(\bar{\nu}^{\alpha}_{L}\gamma_\mu \nu^{\beta}_{L})(\bar{d}^{i}_{L}\gamma^\mu \bar{d}^{j}_{L})$	81 (45)
$[\hat{\mathbf{c}}^{V}_{\nu uLL}]^{\alpha\beta ij}$	$(\bar{\nu}^{\alpha}_{L}\gamma_\mu \nu^{\beta}_{L})(\bar{u}^{i}_{L}\gamma^\mu \bar{u}^{j}_{L})$	81 (45)
	CC	
$[\hat{\mathbf{c}}^{V}_{LL}]^{\alpha\beta ij}$	$(\bar{e}^{\alpha}_{L}\gamma_\mu \nu^{\beta}_{L})(\bar{u}^{i}_{L}\gamma^\mu \bar{d}^{j}_{L})$	162 (81)

$\hat{\mathbf{c}}$: WC in HEFT in mass basis

$\mathcal{C}$: WC in SMEFT in flavor basis

Vector operators $LLLL$ (SMEFT)		
	Operator	Count
$[\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta ij}$	$(\bar{l}^{\alpha}\gamma_\mu l^{\beta})(\bar{q}^{i}\gamma^\mu q^{j})$	81 (45)
$[\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta ij}$	$(\bar{l}^{\alpha}\gamma_\mu \tau^I l^{\beta})(\bar{q}^{i}\gamma^\mu \tau^I q^{j})$	81 (45)

$$q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix} \quad (1)$$

$$u^i_L \to (V^u_L)^{ij} u^j_L \,, \qquad u^i_R \to (V^u_R)^{ij} u^j_R \,,$$
$$d^i_L \to (V^d_L)^{ij} d^j_L \,, \qquad d^i_R \to (V^d_R)^{ij} d^j_R \,,$$
$$V_{\rm CKM} = (V^u_L)^\dagger V^d_L \,.$$

SMEFT predictions for semileptonic processes: Relations among LEFT WCs

Matching among SMEFT and HEFT:

$$[\hat{\mathbf{c}}^V_{\nu uLL}]^{\alpha\beta ij} = (V_L^{u\dagger})^{im}(V_L^u)^{nj}\left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta mn} + [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta mn}\right),$$

$$[\hat{\mathbf{c}}^V_{euLL}]^{\alpha\beta ij} = (V_L^{u\dagger})^{im}(V_L^u)^{nj}\left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta mn} - [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta mn}\right),$$

$$[\hat{\mathbf{c}}^V_{\nu dLL}]^{\alpha\beta ij} = (V_L^{d\dagger})^{im}(V_L^d)^{nj}\left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta mn} - [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta mn}\right),$$

$$[\hat{\mathbf{c}}^V_{edLL}]^{\alpha\beta ij} = (V_L^{d\dagger})^{im}(V_L^d)^{nj}\left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta mn} + [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta mn}\right),$$

$$[\hat{\mathbf{c}}^V_{LL}]^{\alpha\beta ij} = 2\,(V_L^{u\dagger})^{im}(V_L^d)^{nj}\,[\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta mn}$$

[Aebischer, Crivellin, Fael and Greub, 2016]
[Jenkins, Manohar and Stoffer, 2018]

V_L^u : $V_{\rm CKM}^\dagger$ for down-aligned basis or $\mathbf{1}$ for up-aligned basis
V_L^d : $V_{\rm CKM}$ for up-aligned basis or $\mathbf{1}$ for down-aligned basis

Eliminating SMEFT WCs from the above relations:

Category	Analytic relations	Count
$LLLL$	$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{euLL}]^{\alpha\beta kl}\,V_{\ell j} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu dLL}]^{\rho\sigma ij}\,U_{\sigma\beta}$	81 (45)
	$V_{ik}\,[\hat{\mathbf{c}}^V_{edLL}]^{\alpha\beta kl}\,V^\dagger_{\ell j} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu uLL}]^{\rho\sigma ij}\,U_{\sigma\beta}$	81 (45)
	$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{LL}]^{\alpha\beta kj} = [\hat{\mathbf{c}}^V_{edLL}]^{\alpha\rho ij}\,U^\dagger_{\rho\beta} - U^\dagger_{\alpha\sigma}\,[\hat{\mathbf{c}}^V_{\nu dLL}]^{\sigma\beta ij}$	162 (81)

- These relations are independent of the SMEFT flavor basis choice.
- The WCs in HEFT here are in the mass basis and are, in principle, measurable. Thus, relations among them do not depend on the SMEFT basis choice.

- We find **all** the SMEFT-predicted relations among the WCs of semileptonic HEFT operators:
  - 7 sets of relations for vector operators (5×81 for neutral current, 2×162 for charged current)
  - 9 sets of relations for scalar and tensor operators (4×162 for scalars, 5×162 for tensors)
  - 2 sets of relations for to $Z, W^{\pm}$ couplings (1×18 for quarks and 1×18 for leptons)

$$(5 \times 81) + (2 \times 162) + (4 \times 162) + (5 \times 162) + 18 + 18 = 2223$$

- These **relations** are powerful, basis-independent expressions of the implications of SMEFT gauge invariance on flavor physics observables.

Category	Analytic relations	Count
$LLLL$	$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{euLL}]^{\alpha\beta kl}\,V_{\ell j} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu dLL}]^{\rho\sigma ij}\,U_{\sigma\beta}$	81 (45)
	$V_{ik}\,[\hat{\mathbf{c}}^V_{edLL}]^{\alpha\beta kl}\,V^\dagger_{\ell j} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu uLL}]^{\rho\sigma ij}\,U_{\sigma\beta}$	81 (45)
	$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{LL}]^{\alpha\beta kj} = [\hat{\mathbf{c}}^V_{edLL}]^{\alpha\rho ij}\,U^\dagger_{\rho\beta} - U^\dagger_{\alpha\sigma}\,[\hat{\mathbf{c}}^V_{\nu dLL}]^{\sigma\beta ij}$	162 (81)
$RRRR$	No relations	
$LLRR$	$[\hat{\mathbf{c}}^V_{edLR}]^{\alpha\beta ij} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu dLR}]^{\rho\sigma ij}\,U_{\rho\beta}$	81 (45)
	$[\hat{\mathbf{c}}^V_{euLR}]^{\alpha\beta ij} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu uLR}]^{\rho\sigma ij}\,U_{\rho\beta}$	81 (45)
	$[\hat{\mathbf{c}}^V_{LR}]^{\alpha\beta ij} = 0$	162 (81)
$RRLL$	$[\hat{\mathbf{c}}^V_{edRL}]^{\alpha\beta ij} = V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{euRL}]^{\rho\sigma kl}\,V_{lj}$	81 (45)
Scalar (d_R)	$V_{ik}\,[\hat{\mathbf{c}}^S_{ed,RLLR}]^{\alpha\beta kj} = [\hat{\mathbf{c}}^S_{RLLR}]^{\alpha\rho ij}\,U_{\rho\beta}$	162 (81)
	$[\hat{\mathbf{c}}^S_{ed,RLRL}]^{\alpha\beta ij} = 0$	162 (81)
Scalar (u_R)	$[\hat{\mathbf{c}}^S_{eu,RLRL}]^{\alpha\beta ik}\,V_{kj} = -[\hat{\mathbf{c}}^S_{RLRL}]^{\alpha\rho ij}\,U_{\rho\beta}$	162 (81)
	$[\hat{\mathbf{c}}^S_{eu,RLLR}]^{\alpha\beta ij} = 0$	162 (81)
Tensor (d_R)	$[\hat{\mathbf{c}}^T_{ed,\,\mathrm{all}}]^{\alpha\beta ij} = 0$	324 (162)
	$[\hat{\mathbf{c}}^T_{RLLR}]^{\alpha\beta ij} = 0$	162 (81)
Tensor (u_R)	$[\hat{\mathbf{c}}^T_{eu,RLRL}]^{\alpha\beta ik}\,V_{kj} = -[\hat{\mathbf{c}}^T_{RLRL}]^{\alpha\rho ij}\,U_{\rho\beta}$	162 (81)
	$[\hat{\mathbf{c}}^T_{eu,RLLR}]^{\alpha\beta ij} = 0$	162 (81)
Z and $W^\pm$	$[\hat{\mathbf{c}}_{ud_L W}]^{ij} = \frac{1}{\sqrt{2}}\cos\theta_w\,([\hat{\mathbf{c}}_{u_L Z}]^{ik}\,V_{kj} - V_{ik}\,[\hat{\mathbf{c}}_{d_L Z}]^{kj})$	18 (9)
	$[\hat{\mathbf{c}}_{e\nu_L W}]^{\alpha\rho}\,U_{\rho\beta} = \frac{1}{\sqrt{2}}\cos\theta_w\,([\hat{\mathbf{c}}_{e_L Z}]^{\alpha\beta} - U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}_{\nu_L Z}]^{\rho\sigma}\,U_{\sigma\beta})$	18 (9)

Bause et al. 2020

Bause et al. 2020

SK, Dighe, Gupta 2024

Cata, Jung, 2015
Burges et al. 2021

Cata, Jung 2015

Pomarol 2015

We consider the 'UV4f' scenario, where UV physics only involve four-fermionic operators:
HEFT $\longrightarrow$ LFFT : $\hat{\mathbf{c}} \longrightarrow C$

$$V^{\dagger}_{ik}\, [\hat{\mathbf{c}}^{V}_{euLL}]^{22kl}\, V_{\ell j} = [\hat{\mathbf{c}}^{V}_{\nu dLL}]^{22ij}$$

- Six WCs on each sides, 3 complex and 3 real, total 18 parameters.
- We take the 9 whose direct bounds are the best and find indirect bounds for the others.

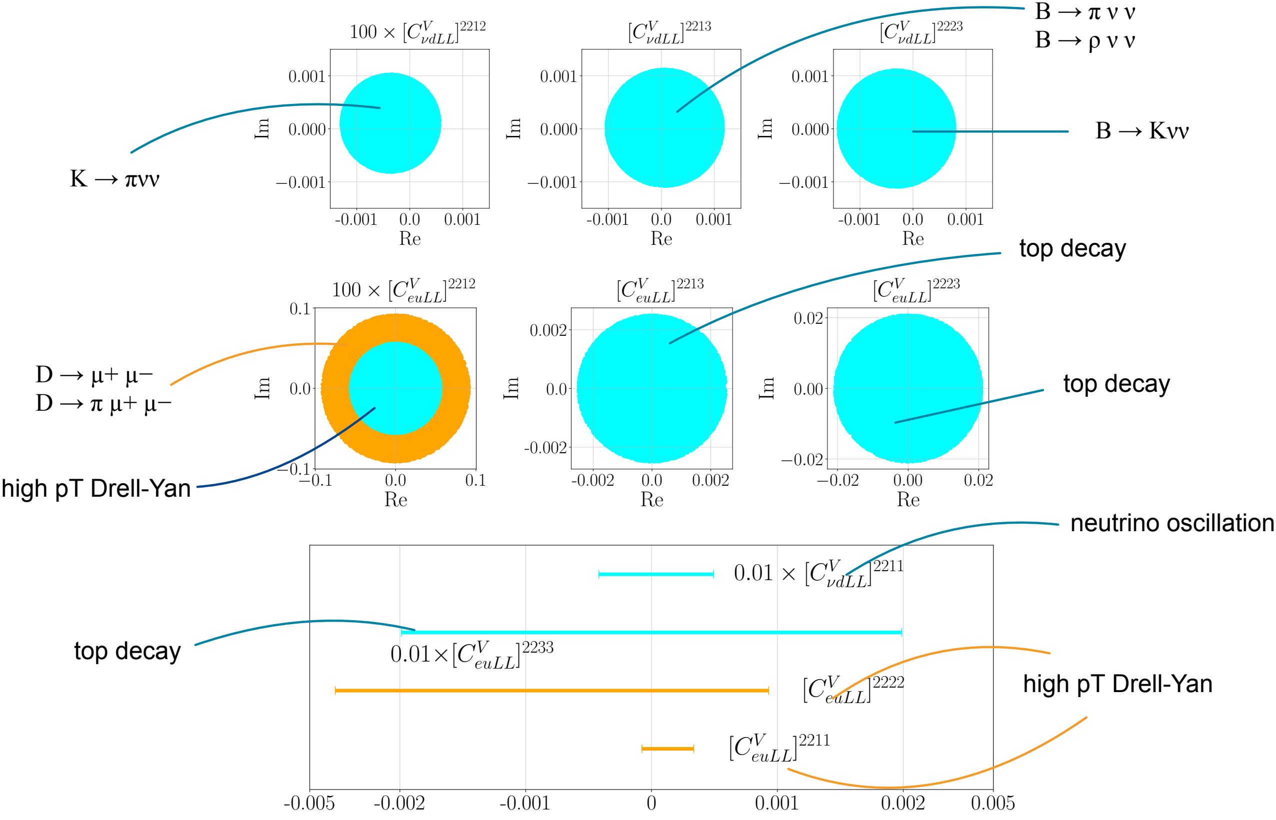
$$\begin{aligned}
Y_1 &= a_1 X_1 + b_1 X_2 + c_1 X_3 + d_1 X_4 + e_1 X_5 + f_1 X_6 + g_1 X_7 + h_1 X_8 + i_1 X_9 \\
Y_2 &= a_2 X_1 + b_2 X_2 + c_2 X_3 + d_2 X_4 + e_2 X_5 + f_2 X_6 + g_2 X_7 + h_2 X_8 + i_2 X_9 \\
Y_3 &= a_3 X_1 + b_3 X_2 + c_3 X_3 + d_3 X_4 + e_3 X_5 + f_3 X_6 + g_3 X_7 + h_3 X_8 + i_3 X_9 \\
&\ldots
\end{aligned}$$

Direct bound: Bounds calculated directly based on the observed data (X_i)
Indirect bound: Bounds derived using the SMEFT-predicted relations (Y_i)

In this case the best direct bounds are there for the following WCs

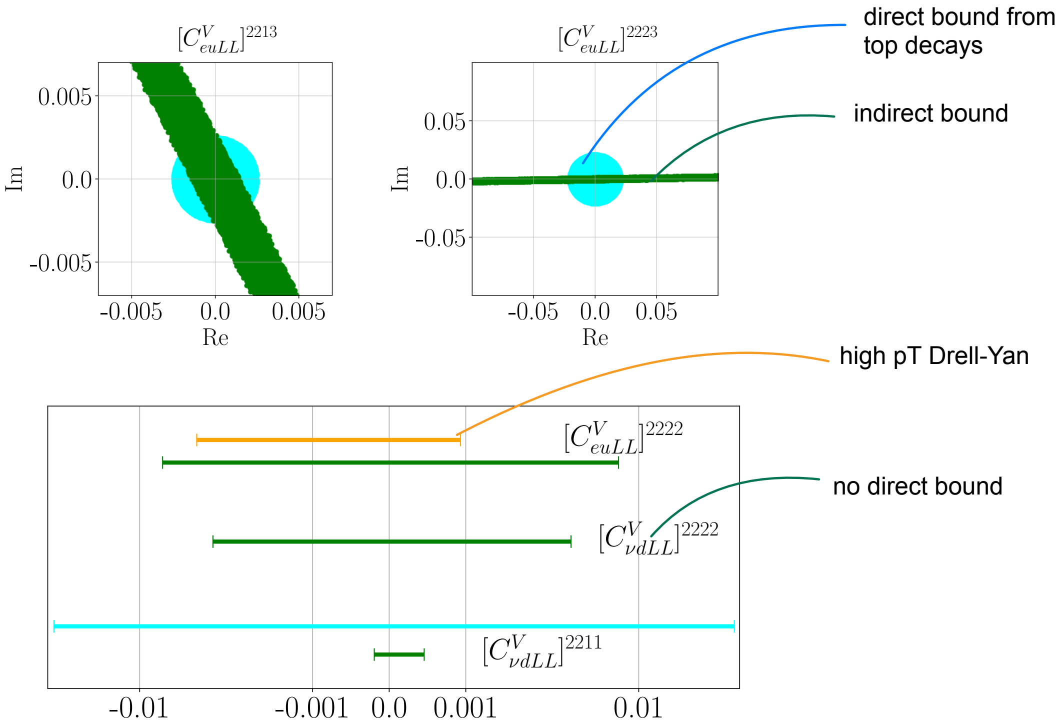
$$\begin{aligned}
&\mathrm{Re}\left([C^{V}_{\nu dLL}]^{2212}\right),\ \mathrm{Im}\left([C^{V}_{\nu dLL}]^{2212}\right),\ \mathrm{Re}\left([C^{V}_{\nu dLL}]^{2213}\right), \\
&\mathrm{Im}\left([C^{V}_{\nu dLL}]^{2213}\right),\ \mathrm{Re}\left([C^{V}_{\nu dLL}]^{2223}\right),\ \mathrm{Im}\left([C^{V}_{\nu dLL}]^{2223}\right), \\
&\mathrm{Re}\left([C^{V}_{euLL}]^{2212}\right),\ \mathrm{Im}\left([C^{V}_{euLL}]^{2212}\right)\ ,\ [C^{V}_{euLL}]^{2211}
\end{aligned}$$

Direct bounds on WCs of $(\bar{\nu}_L\gamma_\sigma\nu_L)(\bar{d}_L\gamma^\sigma d_L)$ and $(\bar{\mu}_L\gamma_\sigma\mu_L)(\bar{u}_L\gamma^\sigma u_L)$



Meson decays | ν-oscillations, top production and decays | High-p_T

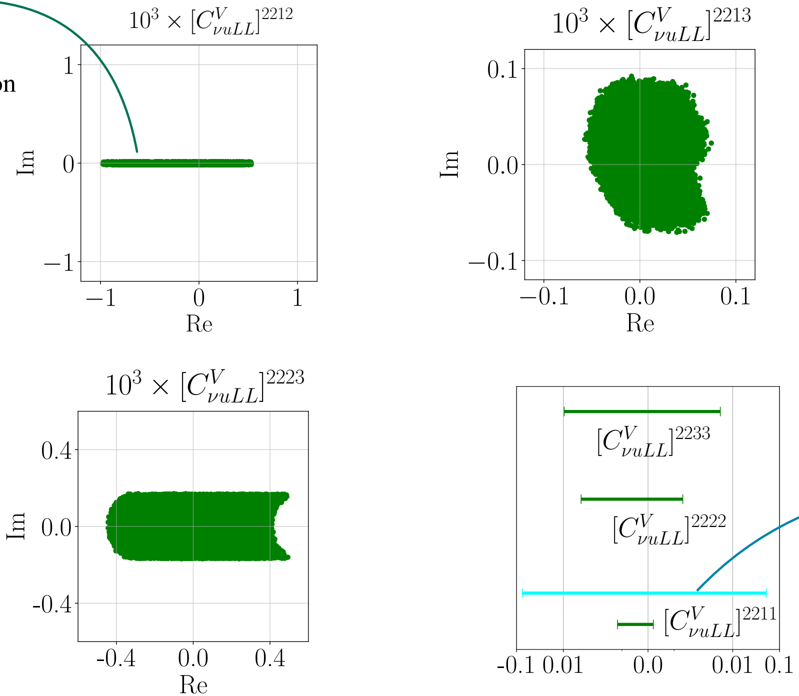
$$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{euLL}]^{22kl}\,V_{\ell j} = [\hat{\mathbf{c}}^V_{\nu dLL}]^{22ij}$$



Meson decays ; ν-oscillations , top production and decays ; High-p_T ; Indirect bounds

$$V_{ik}\,[\hat{\mathbf{c}}^V_{edLL}]^{22kl}\,V^\dagger_{\ell j} = [\hat{\mathbf{c}}^V_{\nu uLL}]^{22ij}$$

no direct bound available, this is indirect bound on c → u ν ν



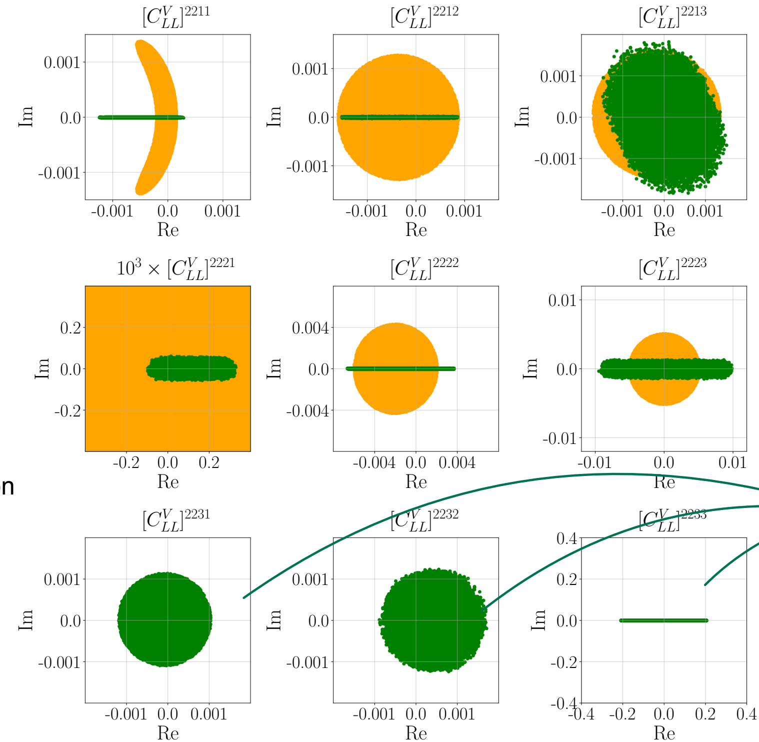
neutrino oscillation

ν-oscillations, Indirect bounds

Indirect bounds on WCs of $(\bar{\mu}_L \gamma^\sigma \nu_L)(\bar{u}_L \gamma_\sigma d_L)$

$$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{LL}]^{22kj} = [\hat{\mathbf{c}}^V_{edLL}]^{22ij} - [\hat{\mathbf{c}}^V_{\nu dLL}]^{22ij}$$

high pT single muon searches



no direct bound available

[**SK**, *Dighe, Gupta, arXiv:2404.10061*]

High-p_T Indirect bounds

SMEFT implications for observed deviations and anomalies

- The SMEFT-predicted relations implies that it is in general not consistent to assume a single non-zero WC to explain an excess in a certain channel.
- For certain operators a non-zero WC must be accompanied by multiple other WCs that are non-vanishing.

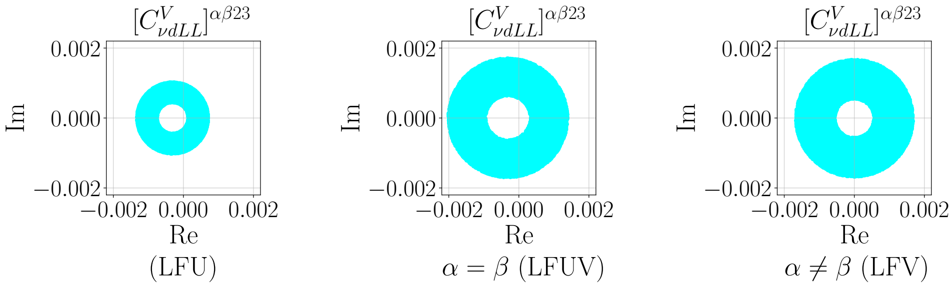
$$[\hat{\mathbf{c}}^V_{\nu uLL}]^{22ij} = V_{ik}\,[\hat{\mathbf{c}}^V_{edLL}]^{22kl}\,V^\dagger_{\ell j}$$

For the above relation, there are 6 linear relation among 12 in general complex WCs (say C_1 to C_{12}). If one of these WCs, (say C_1) is found to be nonzero, we can write:

$$\begin{aligned}
C_7 &= a_1C_1 + b_1C_2 + c_1C_3 + d_1C_4 + e_1C_5 + f_1C_6\\
C_8 &= a_2C_1 + b_2C_2 + c_2C_3 + d_2C_4 + e_2C_5 + f_2C_6\\
C_9 &= a_3C_1 + b_3C_2 + c_3C_3 + d_3C_4 + e_3C_5 + f_3C_6\\
C_{10} &= a_4C_1 + b_4C_2 + c_4C_3 + d_4C_4 + e_4C_5 + f_4C_6\\
C_{11} &= a_5C_1 + b_5C_2 + c_5C_3 + d_5C_4 + e_5C_5 + f_5C_6\\
C_{12} &= a_6C_1 + b_6C_2 + c_6C_3 + d_6C_4 + e_6C_5 + f_6C_6
\end{aligned}$$

- Then, as long as the coefficient of C_1 is nonzero in all these equations, all the 6 coefficients C_7 to C_{12} also have to be nonzero.
- Thus, the nonvanishing nature of C_1 necessarily implies that overall at least 7 WCs are nonvanishing in principle.

Assuming $[O^V_{\nu dLL}]^{\alpha\beta 23}$ as possible explanation of the observed excess in $B \to K\nu\nu$:



$$[C^V_{euLL}]^{\alpha\beta ij} = V_{i2}[C^V_{\nu dLL}]^{\alpha\beta 23}V^\dagger_{3j} + ...$$

For $i = 2,\ j = 3$, $\quad [C^V_{euLL}]^{\alpha\beta 23} \sim 0.97[C^V_{\nu dLL}]^{\alpha\beta 23}$.
For $i = 1,\ j = 3$, $\quad [C^V_{euLL}]^{\alpha\beta 13} \sim 0.22[C^V_{\nu dLL}]^{\alpha\beta 23}$

$\Rightarrow$ **Possible excess in $t \to ce^\alpha e^\beta$, $t \to ue^\alpha e^\beta$**

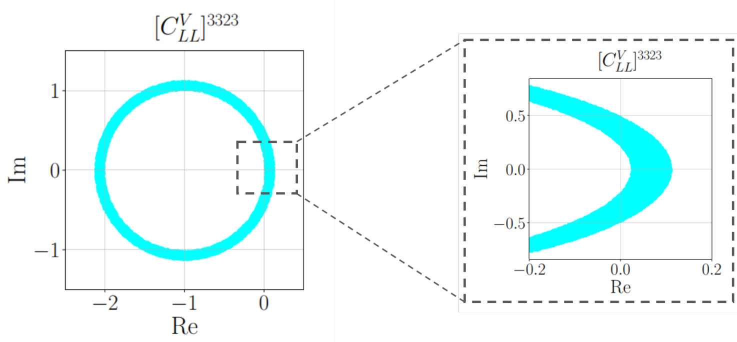
$$[C^V_{LL}]^{\alpha\beta i3} = V_{i2}([C^V_{edLL}]^{\alpha\beta 23} - [C^V_{\nu dLL}]^{\alpha\beta 23})V^\dagger_{3j}\ .$$

$\Rightarrow$ **Possible excess in $b \to c\ell\nu$, $b \to u\ell\nu$**

[Bause, Gisbert, and Hiller, 2024]
[Bhattacharya, Jahedi, Nandi and Sarkar, 2023]
*[**SK**, Dighe, Gupta, arXiv:2404.10061]*

Implications of $R(D^{(*)})$ anomalies

Assuming $[O_{LL}^V]^{3323}$ as possible explanation of $R(D^{(*)})$:



$$[C_{LL}^V]^{3323} = V_{cd}\left[[C_{edLL}^V]^{3313} - [C_{\nu dLL}^V]^{3313}\right] + V_{cs}\left[[C_{edLL}^V]^{3323} - [C_{\nu dLL}^V]^{3323}\right] + V_{cs}\left[[C_{edLL}^V]^{3333} - [C_{\nu dLL}^V]^{3333}\right]$$

- **Possible NP in** $b \to d\tau\tau$, $b \to s\tau\tau$, $b \to d\nu\nu$ and $b \to s\nu\nu$
- **These possible NP effects can manifest in** $B \to \tau\tau$, $B_s \to \tau\tau$, $B \to K^{(*)}\tau\tau$, $B \to K^{(*)}\nu\nu$ etc.

[Alonso, Grinstein and Camalich, 2015]
[Crivellin, Müller and Ota, 2017]
[Greljo, Salko, Smolkovic and Stangl, 2023]
*[**SK**, Dighe, Gupta, arXiv:2404.10061]*

Comments on the SMEFT-predicted relations and indirect bounds

- The relations are derived from leading order matching at dimension 6
- The relations and hence the indirect bounds will get modified when
  - If RG running and one loop matching effects are significant,
  - if there are large contributions from dimension 8 operators.
- A global-fit using the relations can give better indirect bounds. In our analysis, we focus on decoupling several connected sectors in flavor physics and get significant insight into the implications of SMEFT gauge invariance on flavor observables.

Summary and outlook

- We find 17 classes (2223 with generation indices) of relations among LEFT WCs based on the $SU(2)_L \times U(1)_Y$ invariance of SMEFT.
- Based on these relations, we find indirect bounds on WCs which are in some cases weakly constrained in direct experiments.
- The relations and the indirect bounds do not depend on choice of SMEFT flavor basis.
- Our indirect bounds on many di-neutrino operators e.g. $(\bar{\nu}\gamma_\mu\nu)(\bar{d}\gamma_\mu d)$, $(\bar{\nu}\gamma_\mu\nu)(\bar{u}\gamma_\mu u)$, $(\bar{\nu}\gamma_\mu\nu)(\bar{s}\gamma_\mu s)$ etc., are much better compared to the direct available bounds from atmospheric neutrino oscillations.
- From the observed excess in $B \to K\nu\nu$, we expect enhanced branching ratios for dilepton top decays and charged-current semileptonic B decays.
- From $R(D^{(*)})$, we predict enhancement for di-tauon and di-neutrino B decays.

- A further study can be done to consider the effects of RG running, one-loop matching and terms with suppressed CKM elements.
- Similar phenomenology analysis will also be interesting for other processes such as four-quark, charged LFV etc. with the inclusion of scalar, tensor and right handed operators,

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Thank you for your attention!