Implications of SMEFT for semileptonic processes

Based on : arXiv:2404.10061

In collaboration with Prof. Amol Dighe, and Dr. Rick S. Gupta.

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Siddhartha Karmakar

Tata Institute of Fundamental Research, Mumbai, India

Motivation:

Standard Model Effective Field Theory (SMEFT) :

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

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

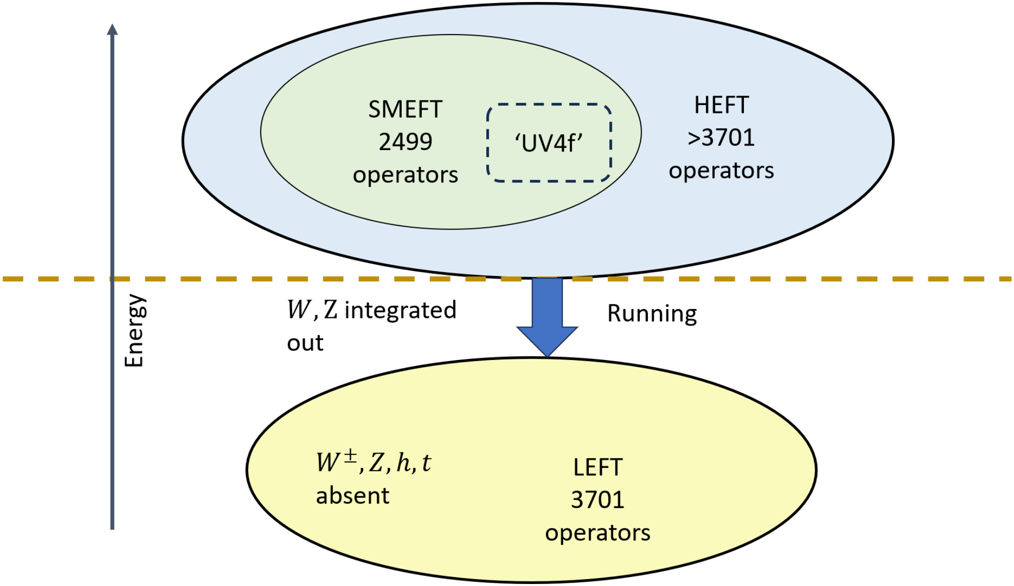
Current uncertainties in Higgs coupling measurements can allow more generalized EFTs e.g. **Higgs Effective Field Therory (HEFT)**. In HEFT:

- $SU(2)_L \times U(1)_Y$ non-linearly realized.
- Higgs boson is not embedded in a $SU(2)_L$-doublet: $\longrightarrow$ More general coupling of Higgs.
- HEFT $\supset$ SMEFT $\supset$ SM

[G. Buchalla and O. Cata, JHEP 07 (2012) 101]
[A. Falkowski, R. Rattazzi, JHEP 10 (2019) 255]

- 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.

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 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
$[\mathbf{c}^V_{e_L d_L}]^{\alpha\beta ij}$	$(\bar{e}^\alpha_L \gamma_\mu e^\beta_L)(\bar{d}^i_L \gamma^\mu d^j_L)$	81 (45)
$[\mathbf{c}^V_{euLL}]^{\alpha\beta ij}$	$(\bar{e}^\alpha_L \gamma_\mu e^\beta_L)(\bar{u}^i_L \gamma^\mu u^j_L)$	81 (45)
$[\mathbf{c}^V_{\nu dLL}]^{\alpha\beta ij}$	$(\bar{\nu}^\alpha_L \gamma_\mu \nu^\beta_L)(\bar{d}^i_L \gamma^\mu d^j_L)$	81 (45)
$[\mathbf{c}^V_{\nu uLL}]^{\alpha\beta ij}$	$(\bar{\nu}^\alpha_L \gamma_\mu \nu^\beta_L)(\bar{u}^i_L \gamma^\mu u^j_L)$	81 (45)
	CC	
$[\mathbf{c}^V_{LL}]^{\alpha\beta ij}$	$(\bar{e}^\alpha_L \gamma_\mu \nu^\beta_L)(\bar{u}^i_L \gamma^\mu d^j_L)$	162 (81)

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)

$$C^{(1)\alpha\beta ij}_{lq} O^{(1)\alpha\beta ij}_{lq} = C^{(1)\alpha\beta ij}_{lq} (\bar{l}^\alpha \gamma_\mu l^\beta)(\bar{u}^i_L \gamma^\mu u^j_L + \bar{d}^i_L \gamma^\mu d^j_L)$$

Matching among SMEFT and HEFT:

$$[\mathbf{c}^V_{\nu uLL}]^{\alpha\beta ij} = \left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta ij} + [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta ij} \right), \quad [\mathbf{c}^V_{euLL}]^{\alpha\beta ij} = \left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta ij} - [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta ij} \right),$$

$$[\mathbf{c}^V_{\nu dLL}]^{\alpha\beta ij} = \left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta ij} - [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta ij} \right), \quad [\mathbf{c}^V_{edLL}]^{\alpha\beta ij} = \left([\mathcal{C}^{(1)}_{\ell q}]^{\alpha\beta ij} + [\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta ij} \right),$$

$$[\mathbf{c}^V_{LL}]^{\alpha\beta ij} = 2\,[\mathcal{C}^{(3)}_{\ell q}]^{\alpha\beta ij}\ .$$

[J. Aebischer, A. Crivellin, M. Fael and C. Greub, JHEP 05 (2016) 037]
[E.E. Jenkins, A.V. Manohar and P. Stoffer, JHEP 03 (2018) 016]

$$u_L^i \to S^u_{L\,ij} u_L^j \,, \qquad u_R^i \to S^u_{R\,ij} u_R^j \,,$$
$$d_L^i \to S^d_{L\,ij} d_L^j \,, \qquad d_R^i \to S^d_{R\,ij} d_R^j \,,$$
$$V_{\rm CKM} = (S^u_L)^\dagger S^d_L \,.$$

Resulting relations among HEFT/LEFT $LLLL$ Wilson Coefficients

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)
	$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{LL}]^{\alpha\beta kj} = [\hat{\mathbf{c}}^V_{edLL}]^{\alpha\rho ij}\,U^\dagger_{\rho\beta} - U^\dagger_{\alpha\sigma}\,[\mathbf{c}^V_{\nu dLL}]^{\sigma\beta ij}$	162 (81)

[S. Karmakar, A. Dighe, R. S. Gupta, arXiv:2404.10061]

- These relations are independent of any assumptions for the flavor structure in NP.
- We derive 17 classes of such relations (2223 relations with explicit flavor indices).
- In the scenario when SMEFT only contains four-fermionic operators i.e. the 'UV4f' scenario, the above relations will be applicable for WCs in LEFT as well.

$$u_L^i \to S^u_{L\,ij} u_L^j\,, \qquad u_R^i \to S^u_{R\,ij} u_R^j\,,$$
$$d_L^i \to S^d_{L\,ij} d_L^j\,, \qquad d_R^i \to S^d_{R\,ij} d_R^j\,,$$
$$V_{\rm CKM} = (S_L^u)^\dagger S_L^d\,.$$

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	$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{LL}]^{\alpha\beta kj} = [\hat{\mathbf{c}}^V_{edLL}]^{\alpha\rho ij}\,U^\dagger_{\rho\beta} - U^\dagger_{\alpha\sigma}\,[\mathbf{c}^V_{\nu dLL}]^{\sigma\beta ij}$	162 (81)

[S. Karmakar, A. Dighe, R. S. Gupta, arXiv:2404.10061]

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

- 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.

$$\begin{aligned}
Y_1 &= a_1X_1 + b_1X_2 + c_1X_3 + d_1X_4 + e_1X_5 + f_1X_6 + g_1X_7 + h_1X_8 + i_1X_9\\
Y_2 &= a_2X_1 + b_2X_2 + c_2X_3 + d_2X_4 + e_2X_5 + f_2X_6 + g_2X_7 + h_2X_8 + i_2X_9\\
Y_3 &= a_3X_1 + b_3X_2 + c_3X_3 + d_3X_4 + e_3X_5 + f_3X_6 + g_3X_7 + h_3X_8 + i_3X_9\\
Y_4 &= a_4X_1 + b_4X_2 + c_4X_3 + d_4X_4 + e_4X_5 + f_4X_6 + g_4X_7 + h_4X_8 + i_4X_9\\
Y_5 &= a_5X_1 + b_5X_2 + c_5X_3 + d_5X_4 + e_5X_5 + f_5X_6 + g_5X_7 + h_5X_8 + i_5X_9\\
Y_6 &= a_6X_1 + b_6X_2 + c_6X_3 + d_6X_4 + e_6X_5 + f_6X_6 + g_6X_7 + h_6X_8 + i_6X_9\\
Y_7 &= a_7X_1 + b_7X_2 + c_7X_3 + d_7X_4 + e_7X_5 + f_7X_6 + g_7X_7 + h_7X_8 + i_7X_9\\
Y_8 &= a_8X_1 + b_8X_2 + c_8X_3 + d_8X_4 + e_8X_5 + f_8X_6 + g_8X_7 + h_8X_8 + i_8X_9\\
Y_9 &= a_9X_1 + b_9X_2 + c_9X_3 + d_9X_4 + e_9X_5 + f_9X_6 + g_9X_7 + h_9X_8 + i_9X_9
\end{aligned}$$

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

$K\to\pi\nu\nu$

$$\mathrm{Re}\left([C^V_{\nu dLL}]^{2212}\right),\ \mathrm{Im}\left([C^V_{\nu dLL}]^{2212}\right),\ \mathrm{Re}\left([C^V_{\nu dLL}]^{2213}\right),$$

$B\to\pi\nu\nu$

$$\mathrm{Im}\left([C^V_{\nu dLL}]^{2213}\right),\ \mathrm{Re}\left([C^V_{\nu dLL}]^{2223}\right),\ \mathrm{Im}\left([C^V_{\nu dLL}]^{2223}\right),$$

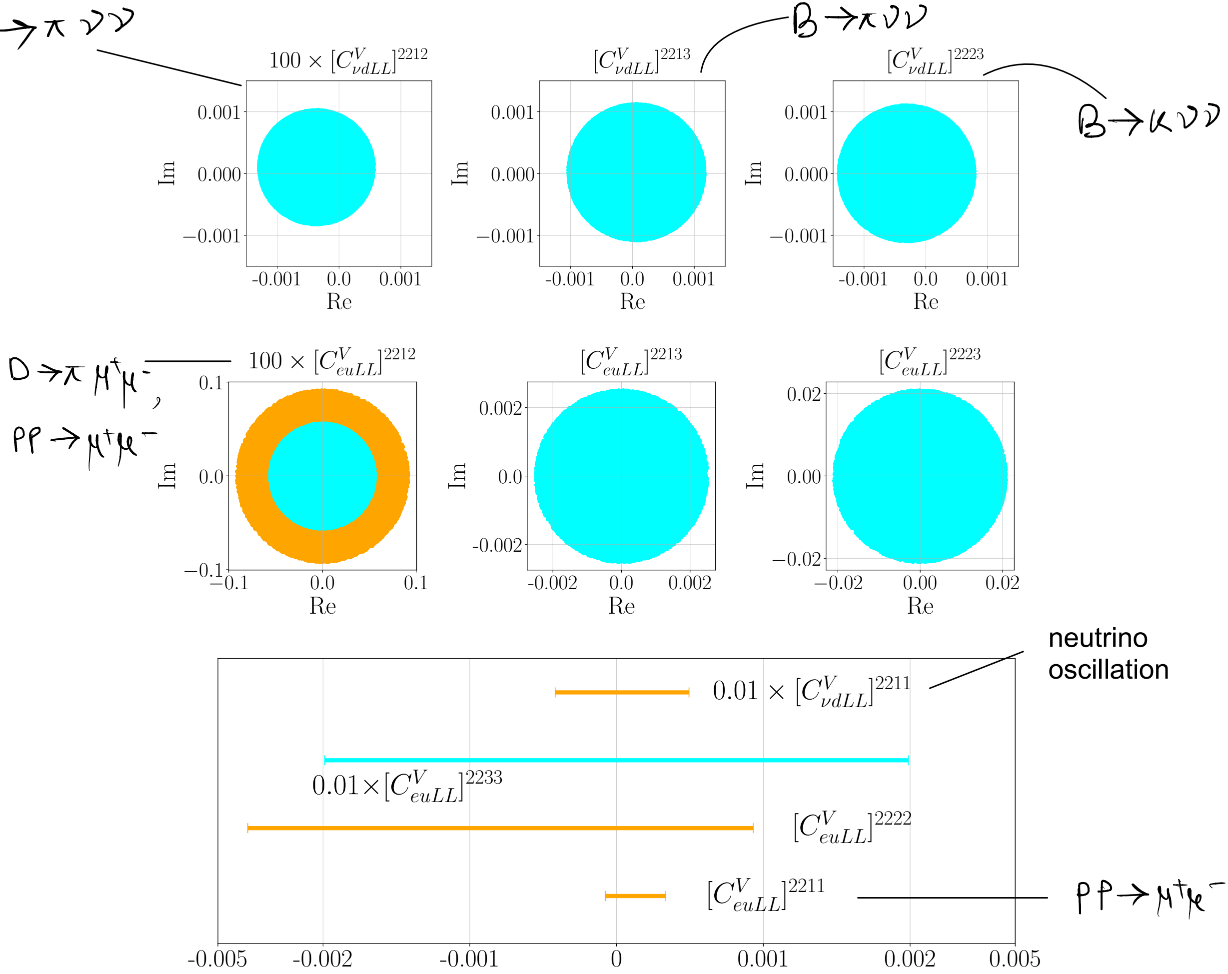
$B\to K\nu\nu$

$D\to\pi\mu^+\mu^-$

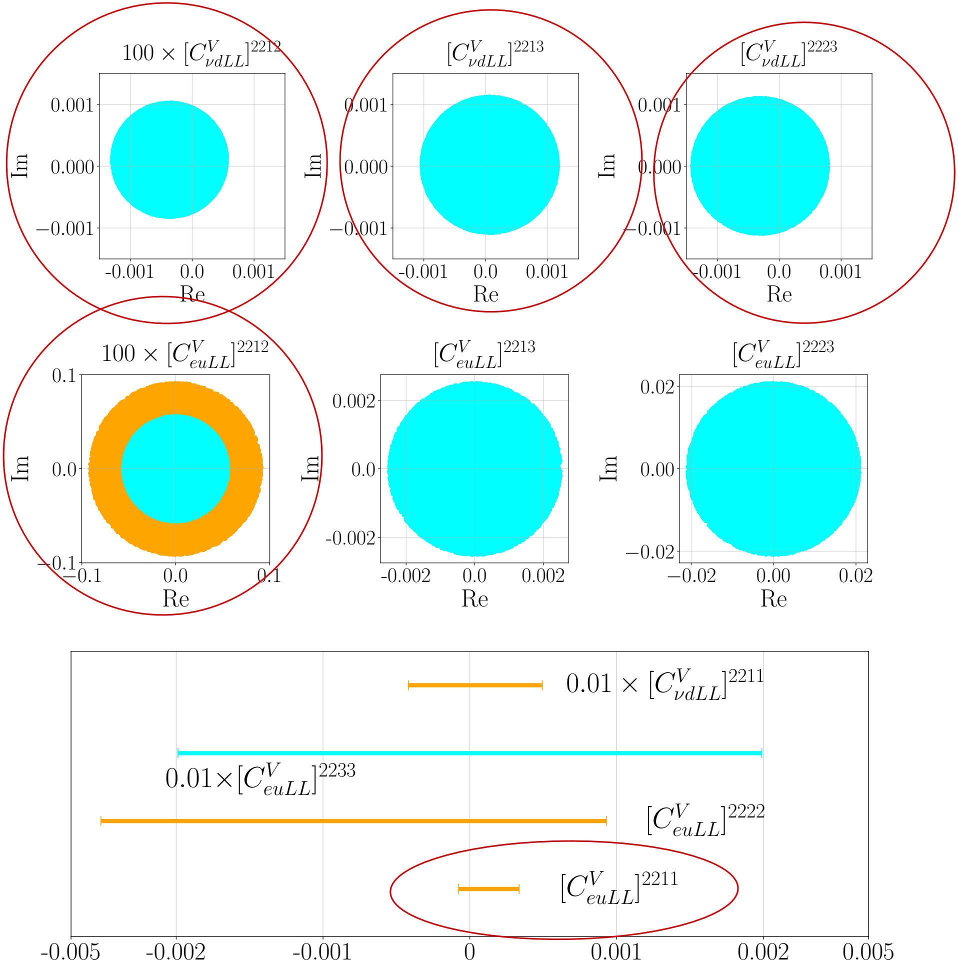
$$\mathrm{Re}\left([C^V_{euLL}]^{2212}\right),\ \mathrm{Im}\left([C^V_{euLL}]^{2212}\right)\ ,\ [C^V_{euLL}]^{2211}$$

$pp\to\mu^+\mu^-$

Direct bounds on C^V_{euLL} and $C^V_{\nu dLL}$

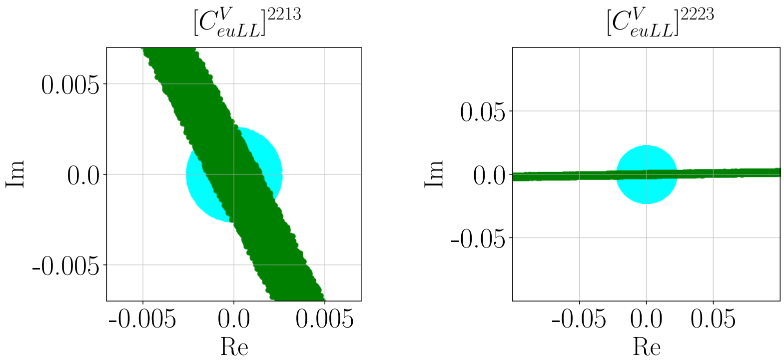


Direct bounds on C^V_{euLL} and $C^V_{\nu dLL}$

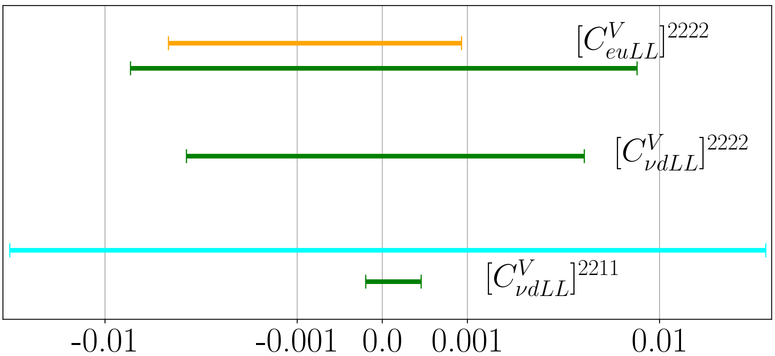


SMEFT predictions: Indirect bounds on $(\bar{\mu}\gamma^\sigma \mu)(\bar{u}\gamma_\sigma u)$, $(\bar{\nu}\gamma^\sigma \nu)(\bar{d}\gamma_\sigma d)$

Indirect bounds on C^V_{euLL} and $C^V_{\nu dLL}$



$t \to u\mu\mu$
$t \to c\mu\mu$

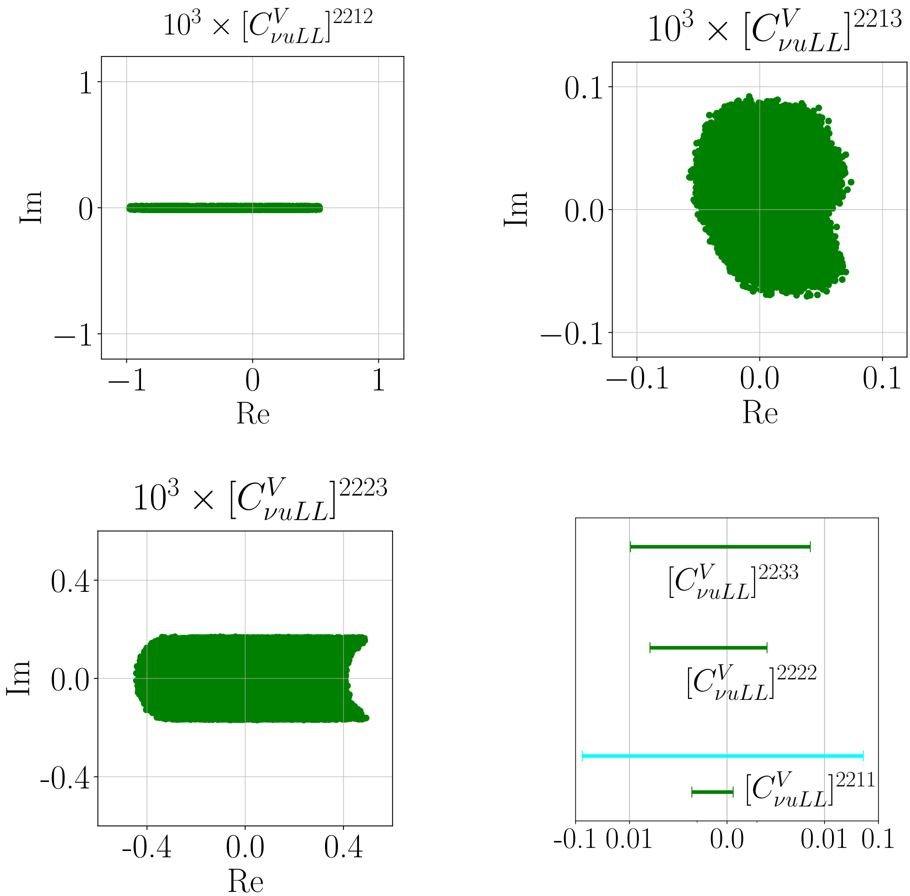


$cc \to \mu\mu$
$ss \to \nu\nu$
$dd \to \nu\nu$

Cyan and *orange* are for direct bounds. *Green* is for indirect bounds

SMEFT predictions: Indirect bounds on $(\bar{\nu}\gamma^{\sigma}\nu)(\bar{u}\gamma_{\sigma}u)$

Indirect bounds on $C^{V}_{\nu uLL}$



$D \to \pi\nu\nu$

$t \to u\nu\nu$

$t \to c\nu\nu$

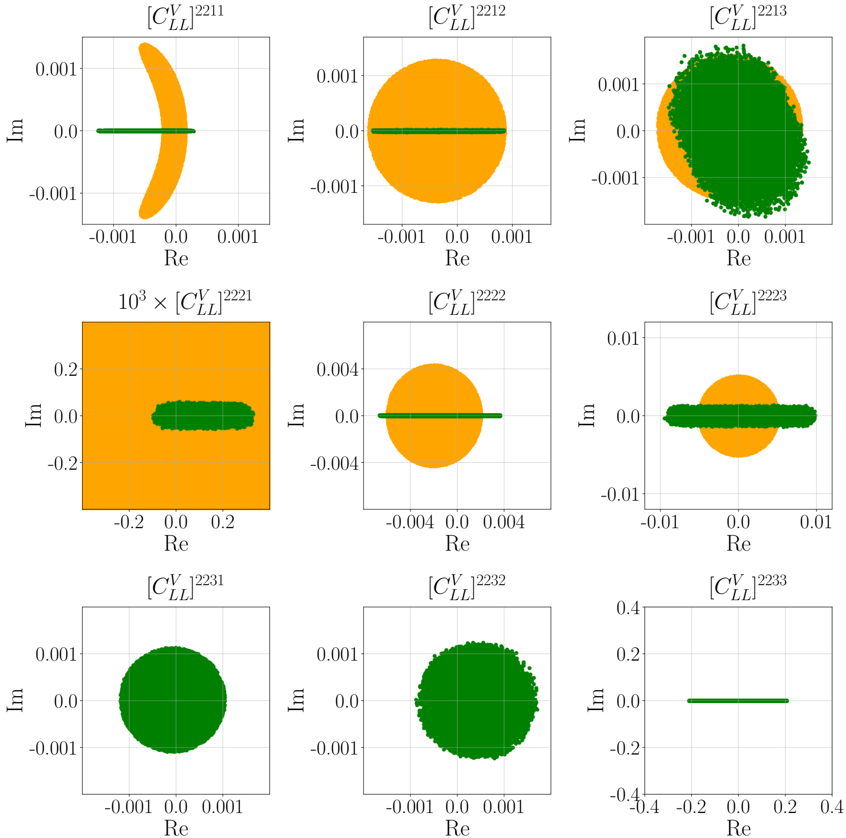
$tt \to \nu\nu$

$cc \to \nu\nu$

$uu \to \nu\nu$

SMEFT predictions: Indirect bounds on $(\bar{\mu}\gamma^{\sigma}\nu)(\bar{u}\gamma_{\sigma}d)$

Indirect bounds on C_{LL}^{V}



$\pi \to \mu\nu$
$K \to \pi\mu\nu$
$B \to \pi\mu\nu$

$D \to \pi\mu\nu$
$D \to K\mu\nu$
$B \to D\mu\nu$

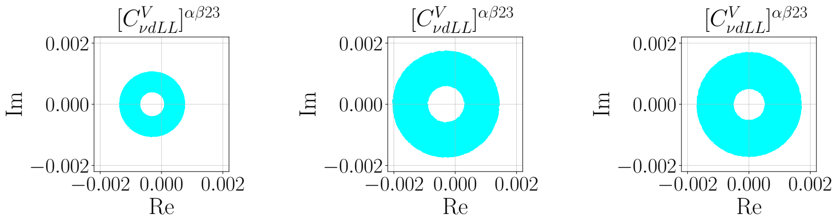
$t \to d\mu\nu$
$t \to s\mu\nu$
$t \to b\mu\nu$

[S. Karmakar, A. Dighe, R. S. Gupta, arXiv:2404.10061]

Comments on the SMEFT-predicted indirect bounds

- The indirect bounds are derived from leading order matching at dimension 6
- The relations and hence the indirect bounds will get modified when
  - RG running and one loop matching are included,
  - large contributions from dimension 8 operators are considered.
- The indirect bounds do not depend on any NP flavour assumption.
- In principle the method of getting the indirect bounds can be iterated to get stronger constraints. Here we presented the bounds at the leading order only.

Observed excess in $\mathbf{B} \to \mathbf{K}\nu\nu$:



(LFU) $\alpha = \beta$ (LFUV) $\alpha \neq \beta$ (LFV)

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

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

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

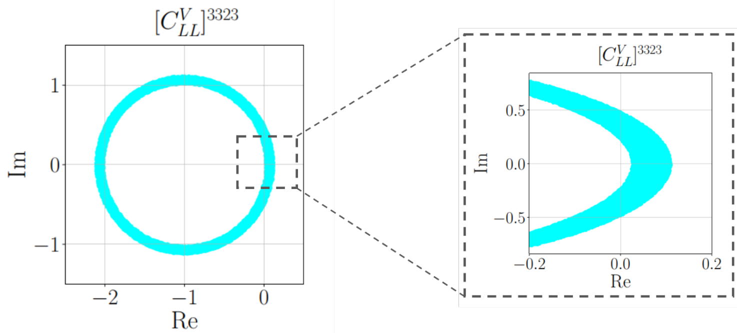
$\Rightarrow$ Possible excess in $t \to ce^\alpha e^\beta$, $t \to ue^\alpha e^\beta$

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

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

[R. Bause, H. Gisbert, and G. Hiller, PhysRevD.109.015006]
[S. Bhattacharya, S. Jahedi, S. Nandi and A. Sarkar, arXiv:2312.14872]
[S. Karmakar, A. Dighe, R. S. Gupta, arXiv:2404.10061]

$\mathbf{R}(\mathbf{D}^{(*)})$ annomalies:



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

- 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.

[R. Alonso, B. Grinstein and J. Martin Camalich, JHEP10(2015)184]
[A. Crivellin, D. Müller and T. Ota, JHEP09(2017)040]
[A. Greljo, J. Salko, A. Smolkovic and P. Stangl, JHEP 11 (2023) 023]
[S. Karmakar, A. Dighe, R. S. Gupta, arXiv:2404.10061]

SMEFT predictions for semileptonic processes: key points

SMEFT predictions for correlated LEFT WCs were explored earlier in:
- *[R. Bause, H. Gisbert, M. Golz and G. Hiller, Eur.Phys.J.C 82(2022)164]*
- *[J. Fuentes-Martin, A. Greljo, J. Martin Camalich and J.D. Ruiz-Alvarez, JHEP 11 (2020) 080]*
- *[A. Greljo, J. Salko, A. Smolkovič and P. Stangl, JHEP 05 (2023) 087]*
- *[A. Greljo, J. Salko, A. Smolkovic and P. Stangl, JHEP 11 (2023) 023]*
- *And others ...*

Our focus for this analysis:

- Classification of the correlations in LEFT space of WCs.
- Exploration of relations among all semileptonic LEFT WCs in a systematic manner. (Connecting B, D, K semileptonic decays, high-p$_T$ dilepton and single-lepton searches, neutrino oscillations, top decays etc.)
- Full CKM expansion is considered.
- Relations and indirect bounds on WCs are calculated independent of any UV flavor assumption.

Challenges and limitations of the analysis

- The relations are based on leading order matching to SMEFT.
- Effects from dimension-8 and higher will break the relations.
- One-loop matching and RG running effects will modify the relations.
- So, any signal showing deviations from the mentioned relations may not necessarily mean signal beyond SMEFT.
- A more systematic power-counting is required to consider the effects of small CKM elements and weaker direct bounds.

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 any NP flavour assumption.
- 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 generalized power counting can be implemented to consider the effects of RG running, one-loop matching and suppressed CKM elements.
- Calculation of indirect bounds can be extended to include, scalar, tensor and right handed vector operators.
- It might be interesting to look at a similar analysis for four-quark operators.

Summary and outlook

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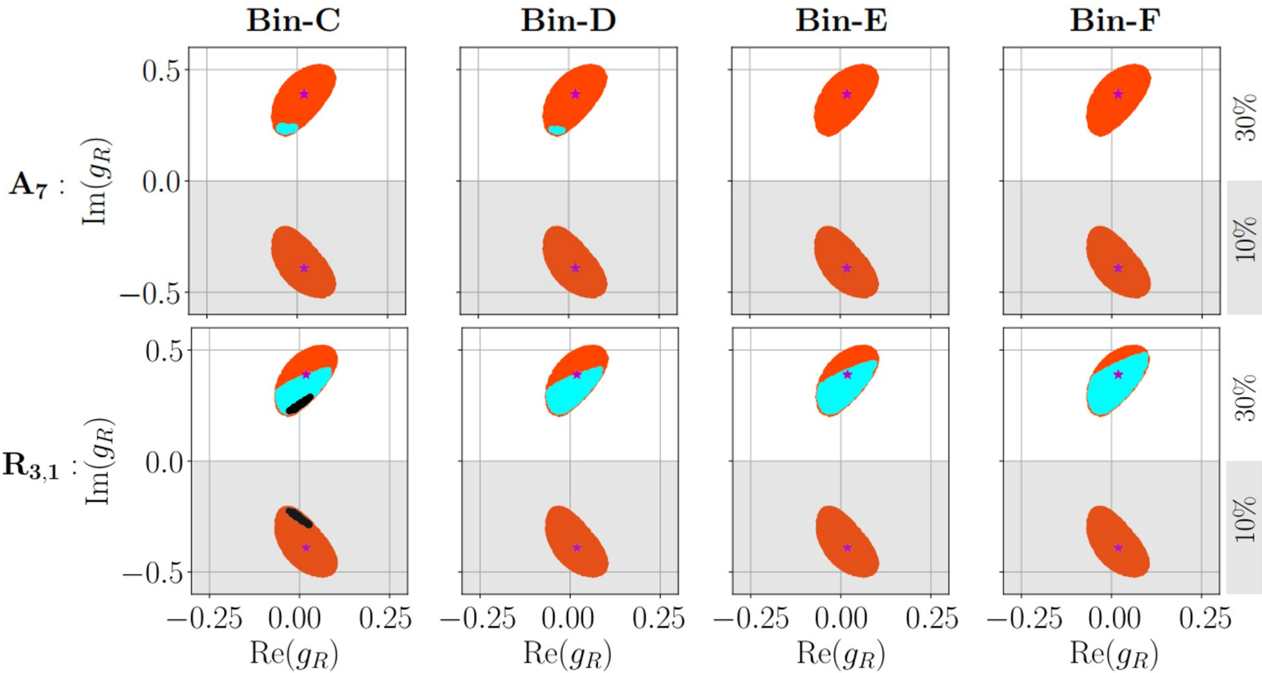
Thank you for your attention!

Backup: Relations among the HEFT/LEFT WCs in UV4f scenario

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)

Category	Analytic relations	Count
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 $W^\pm$	$[\hat{\mathbf{c}}_{ud_L W}]^{ij} = \frac{1}{\sqrt{2}}\cos\theta_w\left([\hat{\mathbf{c}}_{u_L Z}]^{ik}\,V_{kj} - V_{ik}\,[\hat{\mathbf{c}}_{d_L Z}]^{kj}\right)$	18 (9)
	$[\hat{\mathbf{c}}_{e\nu_L W}]^{\alpha\rho}\,U_{\rho\beta} = \frac{1}{\sqrt{2}}\cos\theta_w\left([\hat{\mathbf{c}}_{e_L Z}]^{\alpha\beta} - U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}_{\nu_L Z}]^{\rho\sigma}\,U_{\sigma\beta}\right)$	18 (9)



$B \to K^*$ form factors from *[A. Bharucha, D.M. Straub and R. Zwicky - 2015]*
$\Lambda_b \to \Lambda_c$ form factors from *[W. Detmold, C. Lehner and S. Mein - 2015]*

Identifying effects beyond SMEFT in $b \to s\tau\tau$

EFT for processes involving $b \to s\tau\tau$ channel

$$\mathcal{H}^{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \left(\sum_i C_i O_i + \sum_j C'_j O'_j \right),$$

where the scalar and pseudoscalar operators are

$$O_S^{(\prime)} = \left[\bar{s} P_R(L) b\right] \left[\ell\ell\right], \quad O_P^{(\prime)} = \left[\bar{s} P_R(L) b\right] \left[\ell\gamma_5\ell\right].$$

SMEFT predictions : $C_S = -C_P\,, \quad \text{and} \quad \mathrm{C'_S} = \mathrm{C'_P}.$

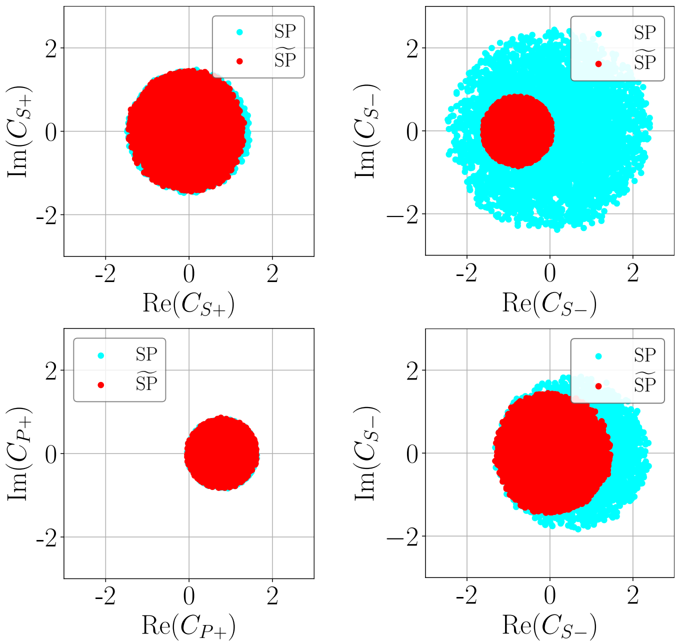
[O. Catà and M. Jung, PhysRevD.92.055018]

Non-SMEFT effect can be parameterized as

$$\mathcal{C}_S + \mathcal{C}_P \equiv \Delta\mathcal{C}\ , \quad \mathcal{C}'_S - \mathcal{C}'_P \equiv \Delta\mathcal{C}'\ .$$

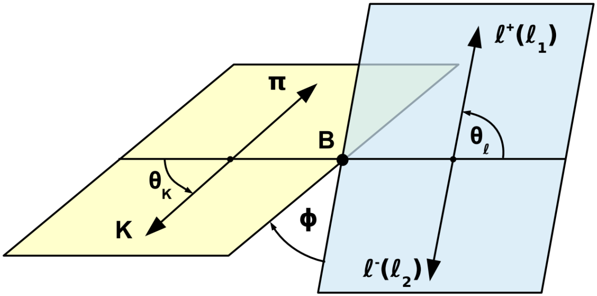
We consider the following scenarios

1. SM,
2. VA: where NP is present only in vector operators,
3. SP: where NP is present only in scalar operators with, $\Delta\mathcal{C}^{(\prime)} = 0$
4. $\widetilde{\mathrm{SP}}$: where NP is present only in scalar operators with $\Delta\mathcal{C}^{(\prime)} \neq 0$.



Projected bounds for the complex parameters C_{S-}, C_{P-}, C_{S+}, and C_{P+} from the expected upper bound on $\mathcal{B}(B_s \to \tau\tau)$ and the expected measurement of $\mathcal{B}(B^+ \to K^+\tau\tau)$ at HL-LHC/FCC-ee. Note that the SP regions (red) are subsets of $\widetilde{\mathrm{SP}}$ region (cyan), i.e. all the red regions have cyan regions underneath.

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_V\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_V, \phi)\,,$$



$$\begin{aligned}
& I(q^2, \theta_l, \theta_V, \phi) \\
&= I_1^s \sin^2\theta_V + \boxed{I_1^c \cos^2\theta_V} \\
&+ (I_2^s \sin^2\theta_V + I_2^c \cos^2\theta_V) \cos 2\theta_l \\
&+ I_3 \sin^2\theta_V \sin^2\theta_l \cos 2\phi \\
&+ I_4 \sin 2\theta_V \sin 2\theta_l \cos\phi \\
&+ I_5 \sin 2\theta_V \sin\theta_l \cos\phi \\
&+ \boxed{(I_6^s \sin^2\theta_V + I_6^c \cos^2\theta_V) \cos\theta_l} \\
&+ \boxed{I_7 \sin 2\theta_V \sin\theta_l \sin\phi} + I_8 \sin 2\theta_V \sin 2\theta_l \sin\phi \\
&+ I_9 \sin^2\theta_V \sin^2\theta_l \sin 2\phi\,,
\end{aligned}$$

[J. Gratrex, M. Hopfer and R. Zwicky , Phys.Rev.D 93(2016)054008]

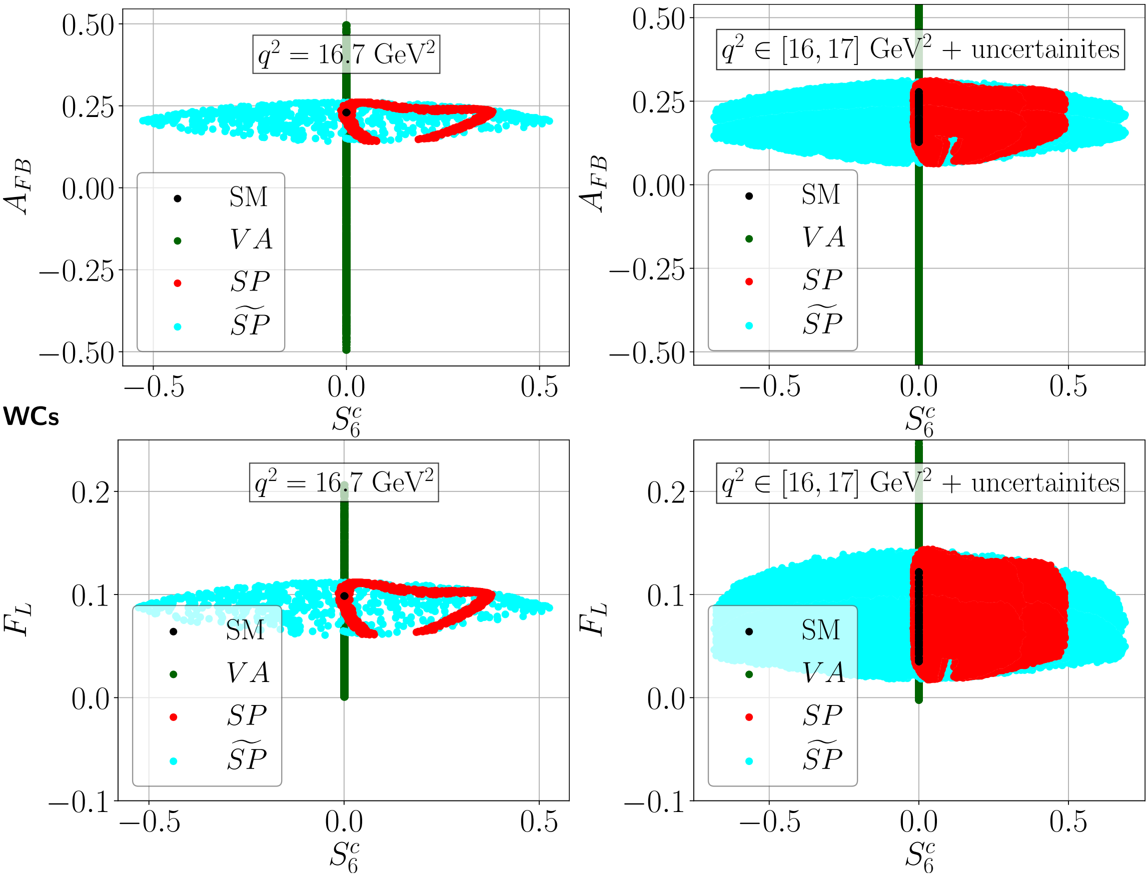
$$\mathcal{C}_S + \mathcal{C}_P \equiv \Delta\mathcal{C}\,, \quad \mathcal{C}'_S - \mathcal{C}'_P \equiv \Delta\mathcal{C}'\,.$$

$$S_i^{(a)} = \frac{(I_i^{(a)} + \bar{I}_i^{(a)})}{d(\Gamma + \bar{\Gamma})/dq^2}\,,$$

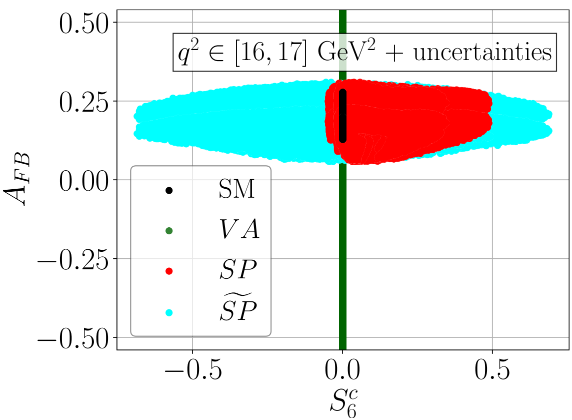
$$A_{FB} = \frac{3}{8}(2S_6^s + S_6^c)\,, \quad F_L = S_1^c\,.$$

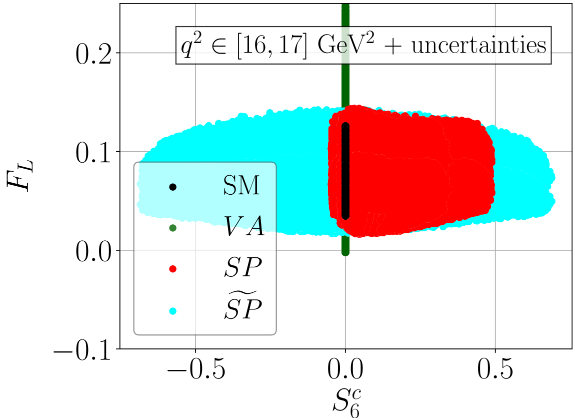
NP WCs	Sensitive observables
$C_9^{(\prime)}$, $C_{10}^{(\prime)}$	$S_1^{s,c}$, $S_2^{s,c}$, S_3, S_4, S_5, S_6^s, A_7 A_{FB}, $\mathcal{B}(B \to K^*\tau^+\tau^-)$
C_{S-}	$S_1^c + S_2^c$, S_6^c, A_{FB} $\mathcal{B}(B_s \to \tau^+\tau^-)$
C_{P-}	F_L $\mathcal{B}(B_s \to \tau^+\tau^-)$
C_{S+}, C_{P+}	$\mathcal{B}(B \to K\tau^+\tau^-)$

Real WCs

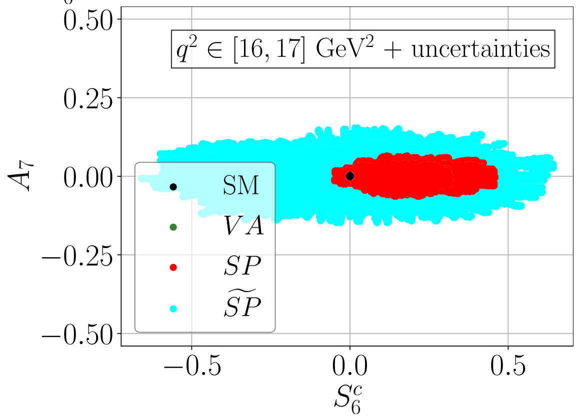


[S. Karmakar, A. Dighe, arXiv:2408.13069]

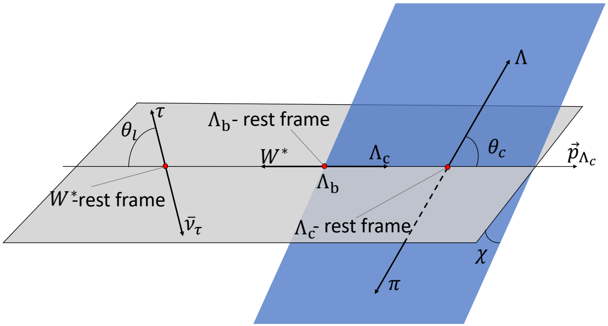




Complex WCs



[S. Karmakar, A. Dighe, arXiv:2408.13069]



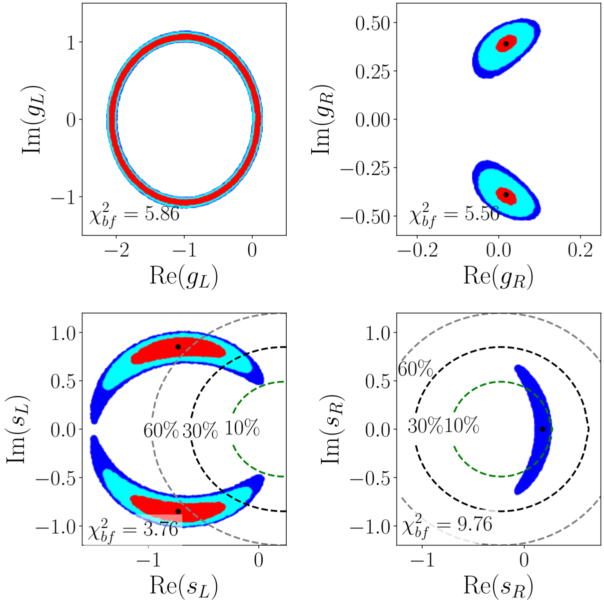
$$\frac{1}{(d\Gamma/dq^2)} \frac{d\Gamma}{dq^2\, d\cos\theta_c\, d\cos\theta_l\, d\chi}$$
$$= A_0 + A_1 \cos\theta_c + A_2 \cos\theta_l$$
$$+ A_3 \cos\theta_c \cos\theta_l + A_4 \cos^2\theta_l$$
$$+ A_5 \cos\theta_c \cos^2\theta_l$$
$$+ A_6 \sin\theta_c \sin\theta_l \cos\chi$$
$$+ A_7 \sin\theta_c \sin\theta_l \sin\chi$$
$$+ A_8 \sin\theta_c \sin\theta_l \cos\theta_l \cos\chi$$
$$+ A_9 \sin\theta_c \sin\theta_l \cos\theta_l \sin\chi\ .$$

$$O_V^{LR} \equiv (\bar{\tau}\gamma^\mu P_L \nu_\tau)(\bar{c}\gamma_\mu P_R b)$$

- Large contribution coming from O_V^{LR} would imply effects beyond SMEFT.
- Our goal is to find angular observables in $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu_\tau$ that can distinguish effects of large O_V^{LR}.

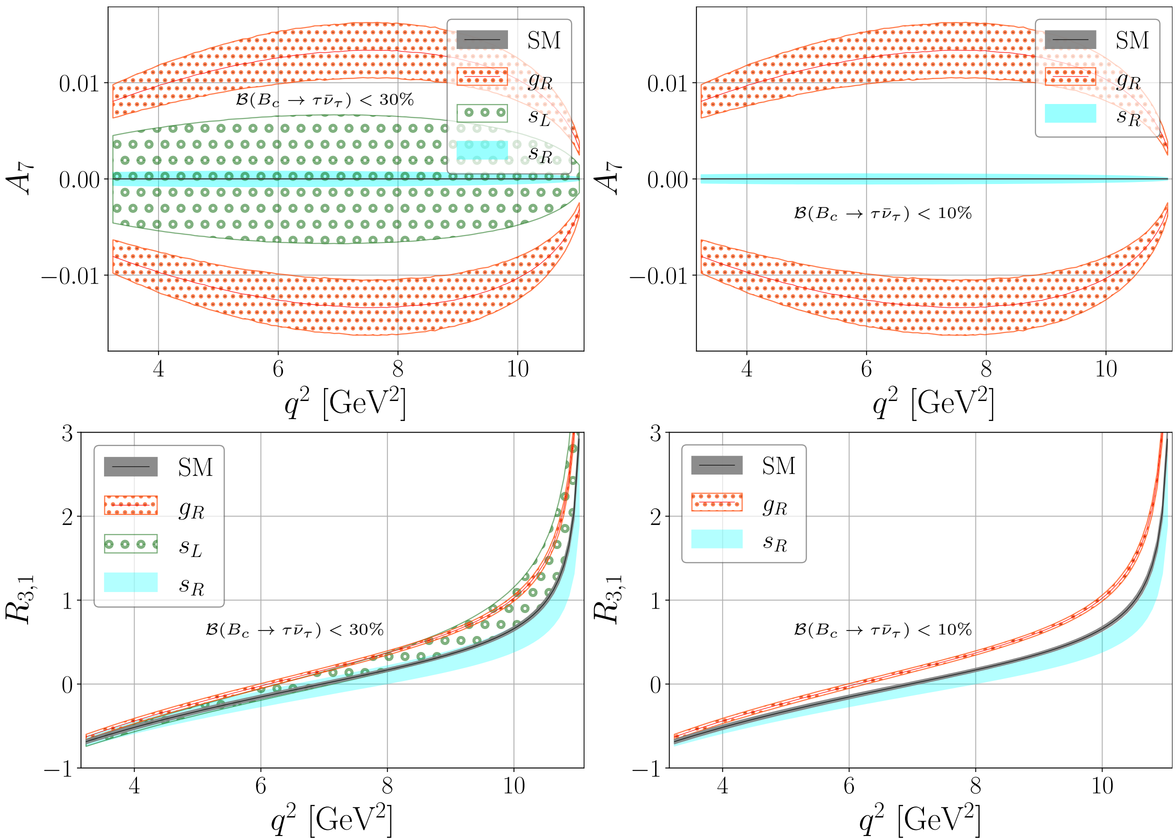
[C.P. Burgess, S. Hamoudou, J. Kumar and D. London, PhysRevD.105.073008]

$$\mathcal{L}_{\rm eff} = \frac{4\,G_F V_{cb}}{\sqrt{2}} \Big[(1+g_L)\mathcal{O}_V^{LL} + g_R \mathcal{O}_V^{LR} + g_S \mathcal{O}_S + g_P \mathcal{O}_P + g_T \mathcal{O}_T\Big] \, .$$



The red, cyan and blue regions are allowed at 1σ, 1.64σ and 2σ, respectively (5 d.o.f). The black dots represent the best-fit values of the NP parameters. The dashed (gray, black, green) contours indicate the allowed values of s_L and s_R corresponding to the upper bound $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < (60\%, 30\%, 10\%)$.

Beyond-SMEFT effects in angular observables in $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\bar{\nu}_\tau$



[S. Karmakar, S. Chattopadhyay, A. Dighe, PhysRevD.110.015010]