SMEFT predictions for flavour physics and effects beyond SMEFT

Siddhartha Karmakar

Tata Institute of Fundamental Research, Mumbai, India

Based on : arXiv:2404.10061 and arXiv: 2305.16007

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

Frontiers in Particle Physics 2024, CHEP, IISc

Motivation:

Standard Model Effective Field Theory (SMEFT) :

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

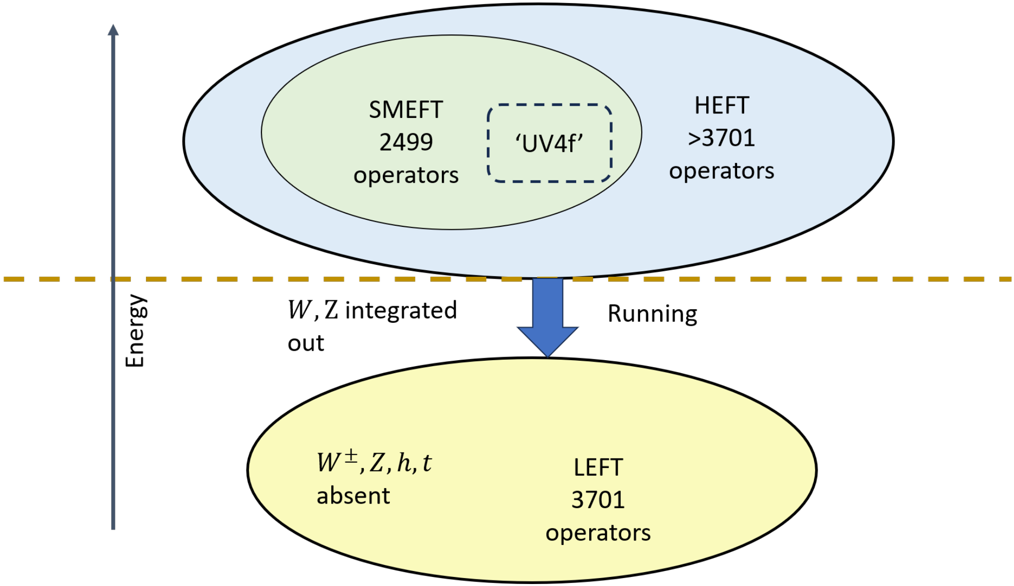
- Includes SM fields only.
- Follows $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Electroweak (EW) symmetry linearly realized.

Current uncertainties in Higgs coupling measurements 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

- 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 LEFT than in SMEFT $\Longrightarrow$ relations among LEFT WCs
- Relations among LEFT WCs $\Longrightarrow$ indirect bounds
- Violation of these relations $\Longrightarrow$ physics beyond SMEFT

Outline:

- SMEFT-predicted relations among LEFT/HEFT Wilson coefficients

- SMEFT-predicted constraints on LEFT Wilson coefficients

- Violations of SMEFT-predicted relation.
  - Effects beyonds SMEFT in charged-current semileptonic processes.
  - Effects beyond SMEFT in neutral-current semileptonic processes.

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:

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

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

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

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

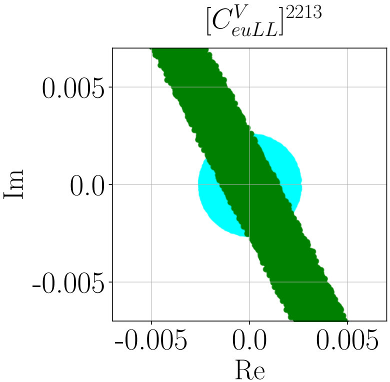
Resulting relations among HEFT $LLLL$ Wilson Coefficients

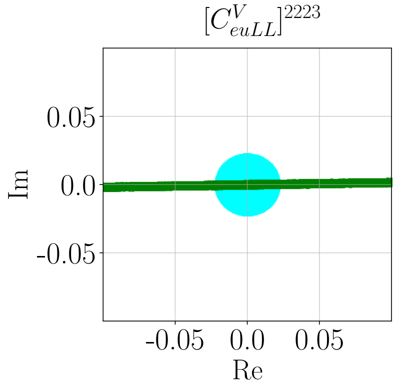
Category	Analytic relations	Count
$LLLL$	$V^\dagger_{ik}\,[\hat{\mathbf{c}}^V_{euLL}]^{\alpha\beta kl}\,V_{\ell j} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu dLL}]^{\rho\sigma ij}\,U_{\sigma\beta}$	81 (45)
	$V_{ik}\,[\hat{\mathbf{c}}^V_{edLL}]^{\alpha\beta kl}\,V^\dagger_{\ell j} = U^\dagger_{\alpha\rho}\,[\hat{\mathbf{c}}^V_{\nu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

- 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.

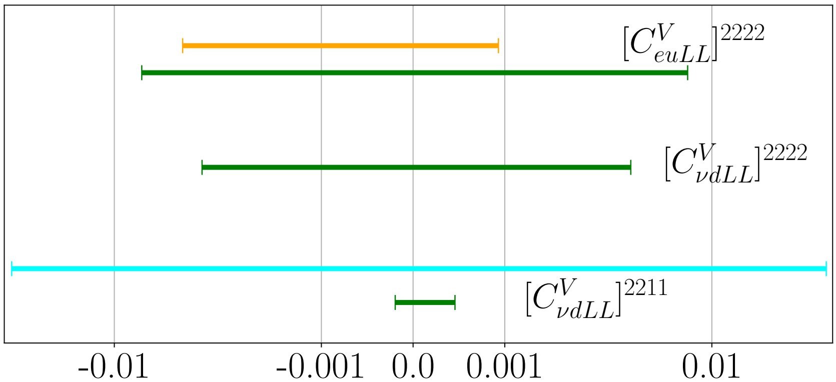
SMEFT predictions: Indirect bounds on $(\bar{\mu}\gamma^\sigma\mu)(\bar{u}\gamma_\sigma u)$, $(\bar{\nu}\gamma^\sigma\nu)(\bar{d}\gamma_\sigma d)$

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





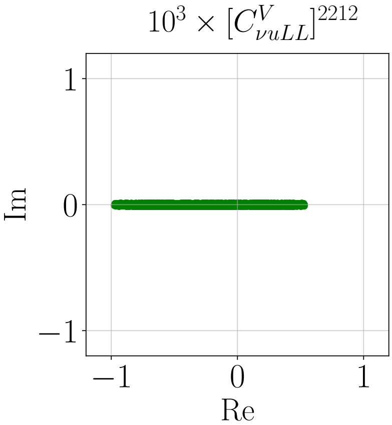
$t \to u\mu\mu$
$t \to c\mu\mu$

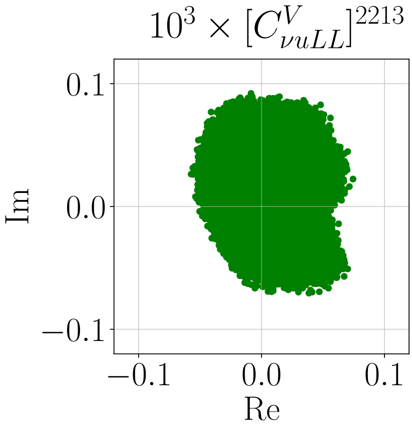


$cc \to \mu\mu$
$ss \to \nu\nu$
$dd \to \nu\nu$

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

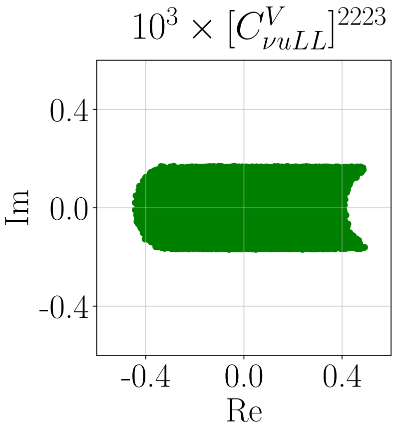
Indirect bounds on $C^V_{\nu uLL}$

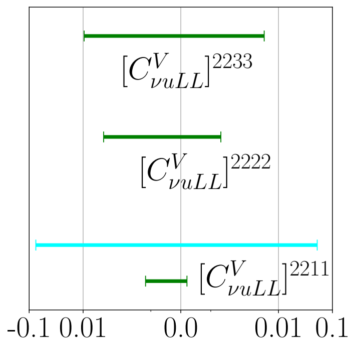




$D \to \pi\nu\nu$

$t \to u\nu\nu$





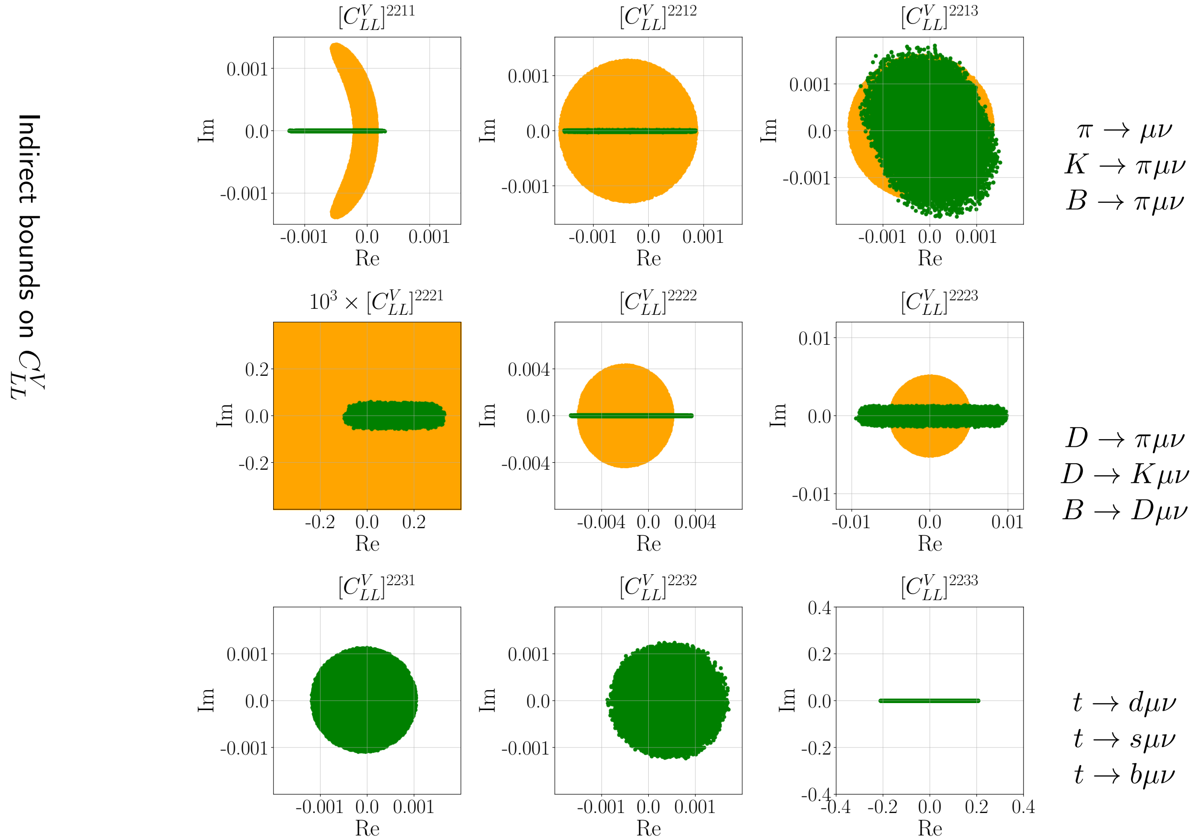
$t \to c\nu\nu$

$tt \to \nu\nu$

$cc \to \nu\nu$

$uu \to \nu\nu$

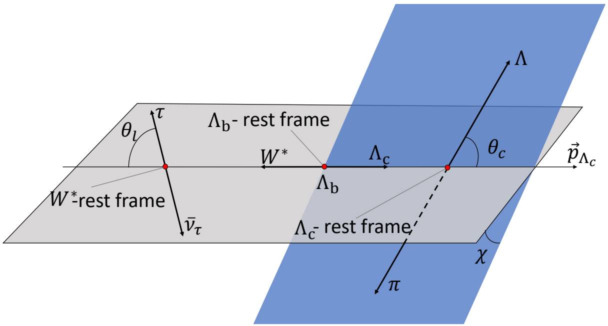
SMEFT predictions: Indirect bounds on $(\bar{\mu}\gamma^{\sigma}\nu)(\bar{u}\gamma_{\sigma}d)$



SMEFT predictions for semileptonic processes: key points

- Systematic exploration of SMEFT predictions for all semileptonic operators taking the full expansion of the CKM matrix.
- These prediction are independent of any assumptions about the alignment of the mass and flavor bases for the quarks.

- Implications of the violation of SMEFT predictions:
  - Physics beyond UV4f
  - Large contribution from dimension-8 SMEFT operators
  - Physics beyond SMEFT

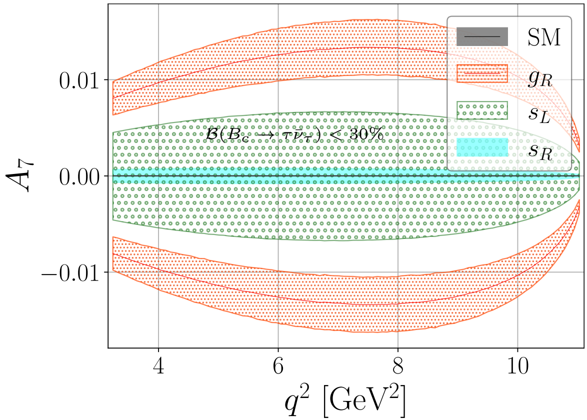


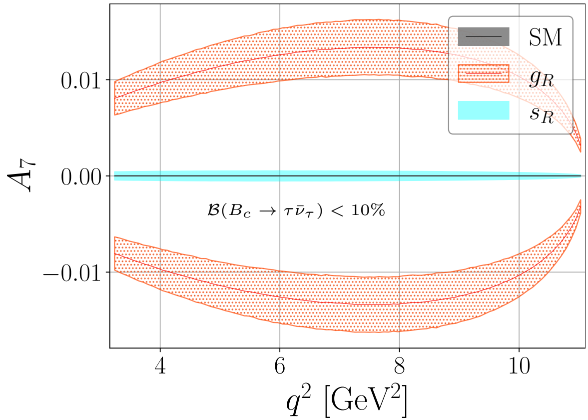
$$\frac{1}{(d\Gamma/dq^2)}\frac{d\Gamma}{dq^2\, d\cos\theta_c\, d\cos\theta_l\, d\chi}$$
$$= A_0 + A_1\,\cos\theta_c + A_2\,\cos\theta_l$$
$$+ A_3\,\cos\theta_c\,\cos\theta_l + A_4\,\cos^2\theta_l$$
$$+ A_5\,\cos\theta_c\cos^2\theta_l$$
$$+ A_6\,\sin\theta_c\sin\theta_l\cos\chi$$
$$+ A_7\,\sin\theta_c\sin\theta_l\sin\chi$$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

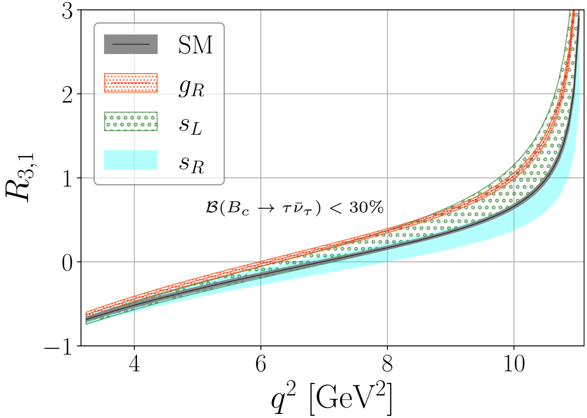
$$O_V^{LR} \equiv (\bar{\tau}\gamma^\mu P_L \nu_\tau)(\bar{c}\gamma_\mu P_R b)$$

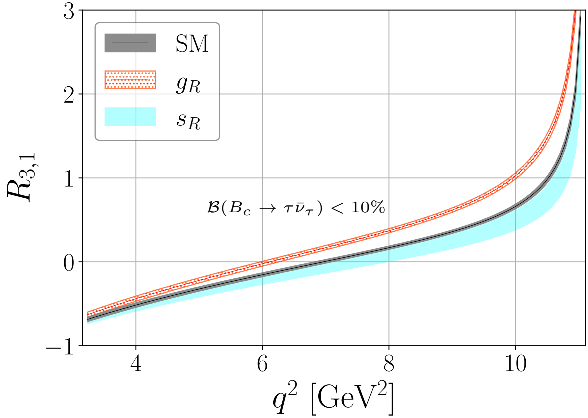
- Large contribution coming from O_V^{LR} would imply effects beyond SMEFT.
- Our goal is to find angular observables in $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu_\tau$n that can distinguish effects of large O_V^{LR}.

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









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

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

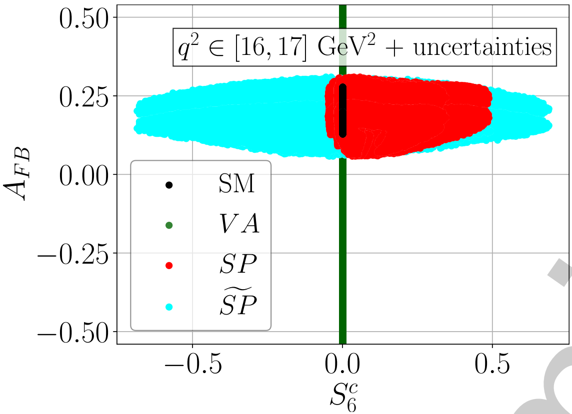
SMEFT predictions : $C_S = -C_P\,, \quad \text{and} \quad \mathrm{C'_S} = \mathrm{C'_P}.$
Non-SMEFT effect can be parameterized as

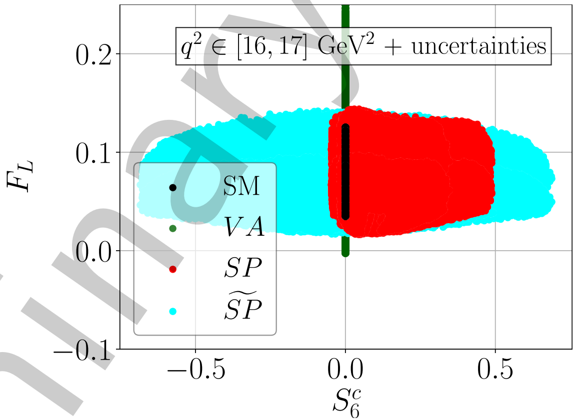
$$\mathcal{C}_S + \mathcal{C}_P \equiv \Delta\mathcal{C}\ , \quad \mathcal{C}_S' - \mathcal{C}_P' \equiv \Delta\mathcal{C}'\ .$$

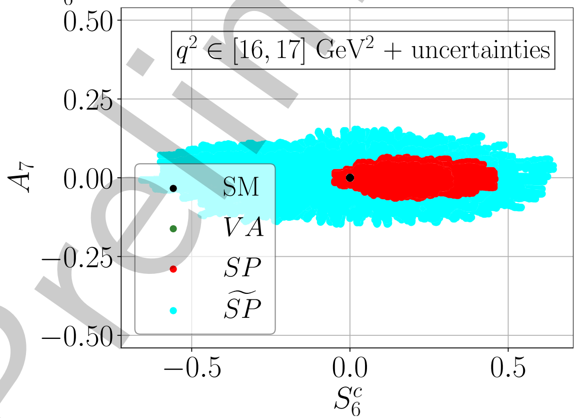
We consider the following scenarios

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 $\Delta\mathcal{C}^{(\prime)} \neq 0$.

Beyond-SMEFT effects in $B \to K^{*0}\tau^+\tau^-$ angular observables







Summary

- 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.
- Violation of these relations implies existence of physics beyond SMEFT.
- Effects beyond SMEFT can be probed indirectly in low energy flavour physics observables.
- We find the effectiveness of different angular observables in $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu_\tau$ and $B \to K^*\tau^+\tau^-$ decay, which can distinguish non-SMEFT effects from other NP scenarios present within SMEFT.

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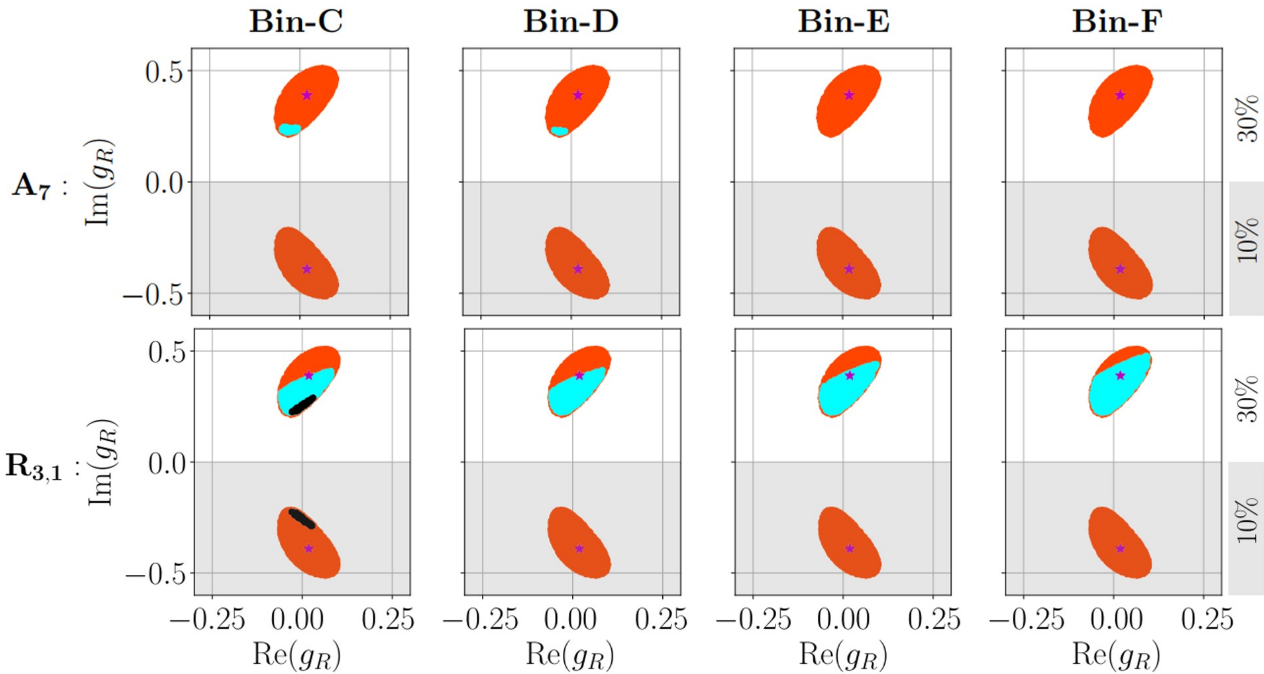
Thank you for your attention!


Bin-C
Bin-D
Bin-E
Bin-F
$\mathbf{A_7}$:
$\mathbf{R_{3,1}}$:
$\mathrm{Im}(g_R)$
$\mathrm{Re}(g_R)$
0.5
0.0
−0.5
−0.25
0.00
0.25
30%
10%