CP-Violation in SMEFT

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Motivation and Outline

Motivation:

- Explore CP-Violation beyond the Standard Model
- Define a basis-independent formalism
- Check whether BSM could give CP-violating contributions comparable to SM ones

Outline:

- CP-Violation in the Standard Model: the Jarlskog invariant
- The collective nature of CP-violation
- CP violation in SMEFT: building dimension-6 invariants
- Accidentally small breaking
- A flavor model: MFV
- Summary

CP-Violation in the SM

In the Standard Model, CP breaking can be reduced, through flavor transformations, to a single phase in the CKM matrix

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta_{\rm CKM}} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CKM}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CKM}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CKM}} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta_{\rm CKM}} & c_{13}c_{23} \end{pmatrix} \approx$$

Standard parametrization

$$\approx \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4\left(1+4A^2\right) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^5)$$

Wolfenstein parametrization ($\lambda \approx 0.2$)

In a flavor invariant way, CP-Violation is parametrized by a combination of the Yukawa matrices Y_u, Y_d, the **Jarlskog Invariant:**

$$J_4 = \mathrm{ImTr}\left([Y_u^\dagger Y_u, Y_d^\dagger Y_d]^3\right) =$$

$$= (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin(\delta_{\rm CKM}) \sim \mathcal{O}(\lambda^{36})$$

CP in the Standard Model is conserved **iff** $J_4 = 0$

CP-Violation in SMEFT

The Standard Model is generally intended as the renormalizable part of a larger description, that includes the effects from heavy resonances that cannot be produced on-shell.

Deviations from the dimension-4 SM are parametrized via higher dimensional, gauge invariant operators, built with SM field

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_{n \geq 5} \frac{c_n}{\Lambda^{n-4}} \mathcal{O}^{(n)}$$

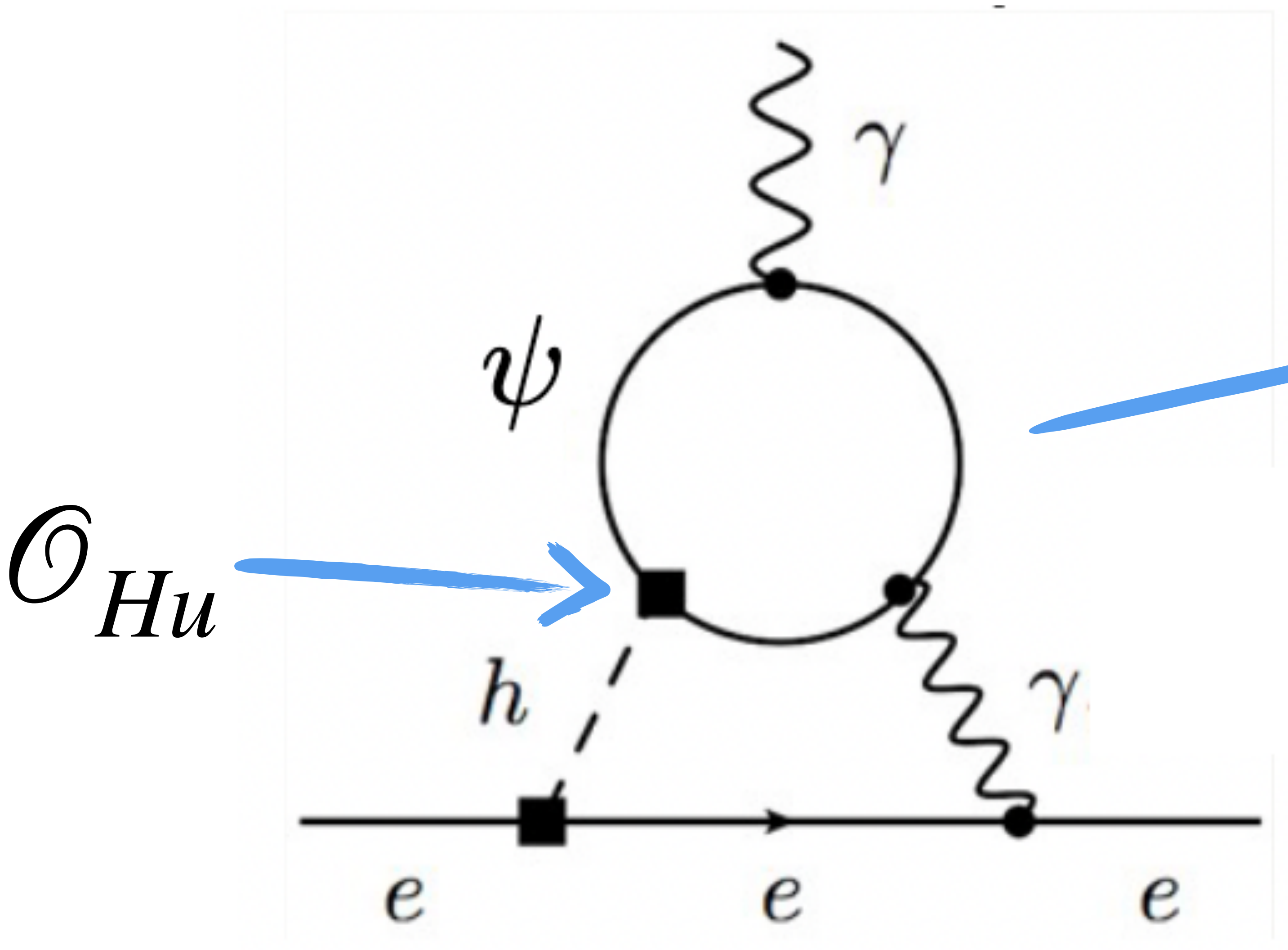
Generically, the Wilson Coefficients of the $\mathcal{O}^{(n)}$ will contain new phases, and thus new possible sources of CP-violation.

CP-Violation is a collective effect

An invariant perspective is needed, as CP violation exhibits properties of collectivity in SMEFT as it does in the SM

Consider with one flavor $$\mathcal{L} = \mathcal{L}_{SM} + \frac{C_{uH}}{\Lambda^2}|H|^2\bar{Q}_L u_R \tilde{H}$$

After EWSB this operator produces a correction to the electron EDM via a Barr-Zee type diagram



$$\frac{d_e}{e} = -\frac{1}{48\pi^2}\frac{v m_e m_u}{m_h^2}\frac{\mathrm{Im}(C_{uH})}{\Lambda^2}F_1\left(\frac{m_u^2}{m_h^2},0\right)$$

Can we remove this contribution transforming $u_R \to e^{-i\arg(C_{Hu})}u_R$?

NO! It will pop up again in the mass term: $\mathcal{L} \supset -m\bar{u}_L u_R$

Actual **invariant** result $$\frac{d_e}{e} = -\frac{1}{48\pi^2}\frac{v m_e}{m_h^2}\frac{\mathrm{Im}(m_u^* C_{uH})}{\Lambda^2}F_1\left(\frac{|m_u|^2}{m_h^2},0\right)$$

CP-Violating flavor invariants

In general, for three families of fermions, the Wilson Coefficients of SMEFT operators built with fermions will contain new phases, and thus new sources of CP violation.

To build the Jarlskog Invariant, one promotes the Yukawa matrices to spurions, with transformation properties

	$SU(3)_Q$	$SU(3)_u$	$SU(3)_d$	$SU(3)_L$	$SU(3)_e$
Y_u	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Y_d	$\mathbf{3}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$
Y_e	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$

Analogously, we promote dimension-6 Wilson Coefficients to flavor spurions and look for CP-Violating invariants that are <u>linear</u> in the coefficients

$$\mathcal{O}_{HQ}^{(1)} = C_{HQ,mn}^{(1)} \left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{Q}_m \gamma^\mu Q_n \longrightarrow \begin{cases} K_1^{HQ(1)} = \mathrm{Im}\,\mathrm{Tr}\left(\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right] C_{HQ}^{(1)}\right) \\ K_2^{HQ(1)} = \mathrm{Im}\,\mathrm{Tr}\left(\left[(Y_u Y_u^\dagger)^2, Y_d Y_d^\dagger\right] C_{HQ}^{(1)}\right) \\ K_3^{HQ(1)} = \mathrm{Im}\,\mathrm{Tr}\left(\left[Y_u Y_u^\dagger, (Y_d Y_d^\dagger)^2\right] C_{HQ}^{(1)}\right) \end{cases}$$

↑ Hermitian 3x3 matrix → 3 phases

CP is conserved iff $J_4 = K_1^{HQ(1)} = K_2^{HQ(1)} = K_3^{HQ(1)} = 0$

Counting CP-Violating parameters

Working at $\mathcal{O}(1/\Lambda^2)$ reduces the number of CP-violating parameters. Let us start from the up-basis

$$Y_u = \mathrm{diag}(y_u, y_c, y_t) \qquad Y_d = V_{\mathrm{CKM}}\mathrm{diag}(y_d, y_s, y_b) \qquad Y_e = \mathrm{diag}(y_e, y_\mu, y_\tau)$$

In the lepton sector, this choice breaks the $U(3)_L \times U(3)_e$ of the free Lagrangian down to the $U(1)^3$ described by the transformation

$$(L, e) \to \mathrm{diag}(e^{i\delta_1}, e^{i\delta_2}, e^{i\delta_3})(L, e)$$

This has to be a symmetry of all observables.

At dimension 6, operators containing leptons are charged under this symmetry, e.g.

$$\mathcal{O}_{He} = \frac{1}{\Lambda^2} C_{He,mn} \,(H^\dagger i \overleftrightarrow{D}_\mu H)\, \bar{e}_m \gamma^\mu e_n \quad \longrightarrow \quad C_{He,mn} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{12}^* & c_{22} & c_{23} \\ c_{13}^* & c_{23}^* & c_{33} \end{pmatrix} \xrightarrow{U(1)^3} \begin{pmatrix} c_{11} & c_{12}e^{i(\delta_2-\delta_1)} & c_{13}e^{i(\delta_3-\delta_1)} \\ c_{12}^* e^{-i(\delta_2-\delta_1)} & c_{22} & c_{23}e^{i(\delta_3-\delta_2)} \\ c_{13}^* e^{-i(\delta_3-\delta_1)} & c_{23}^* e^{-i(\delta_3-\delta_2)} & c_{33} \end{pmatrix}$$

Off-diagonal coefficients are charged under such $U(1)^3$, so at $\mathcal{O}(1/\Lambda^2)$ <u>no invariant containing them can be built</u>

Counting CP-Violating parameters

The difference between the naive counting, relying on the total number of phases, and the actual number of parameters that break CP at leading order is accounted for automatically by the invariants formalism

	Type of op.	# of ops	# real	# im.	inv. under $U(1)_{e_i} - U(1)_{e_j}$ # real	# im.
bilinears	Yukawa	3	27	27	21	21
	Dipoles	8	72	72	60	60
	current-current	8	51	30	42	21
	all bilinears	19	150	129	123	102
4-Fermi	LLLL	5	171	126	99	54
	RRRR	7	255	195	186	126
	LLRR	8	360	288	246	174
	LRRL	1	81	81	27	27
	LRLR	4	324	324	216	216
	all 4-Fermi	25	1191	1014	774	597
	all		1341	1143	897	699

An accidentally small symmetry breaking

The Jarlskog invariant is built by looking for the smallest flavor-invariant, CP-violating object. To capture all three generations, it needs 6 powers of the Yukawa matrices.

Then, the phenomenological smallness of the Yukawa entries induce an extremely small breaking parameter

$$J_4 \approx \lambda^{36}$$

where $\lambda = sin(\theta_C) \approx 0.2$ is the sine of the Cabibbo angle

Even if the dimension-6 Wilson coefficients are all real, they can mix with the Standard Model CP-violating phase, in a way not necessarily proportional to J_4

$$\mathcal{O}_{HQ}^{(1)} = C_{HQ,mn}^{(1)} \left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{Q}_m \gamma^\mu Q_n \xrightarrow{\text{real WC}} C_{HQ,mn}^{(1)} = \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} \\ \rho_{21} & \rho_{22} & \rho_{23} \\ \rho_{31} & \rho_{32} & \rho_{33} \end{pmatrix}$$

$$\longrightarrow \quad K_1^{HQ(1)} = \mathrm{Im}\,\mathrm{Tr}\left(\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right] C_{HQ}^{(1)}\right) \approx \rho_{13}\eta\lambda^9$$

in the up-basis.

This does not mean this is the suppression that accompanies observables.

A flavorful example: MFV

The Minimal Flavor Violation ansatz requires all flavor structure in the Wilson Coefficients of operators containing fermions to be specified by the Yukawa matrices:

$$\mathcal{O}_{uH} = \frac{C_{uH,mn}}{\Lambda^2}|H|^2\bar{Q}_{L,m}u_{R,m}\tilde{H} \quad \xrightarrow{\text{MFV}} \quad C_{uH,mn} = (\rho + i\eta)(Y_u)_{mn} \quad \text{at leading order}$$

The invariants can be used to capture the overall phase η

$$L_1^{uH} = \mathrm{Im}\mathrm{Tr}\left(C_{uH}Y_u^\dagger\right) = y_t^2\eta$$

However, here, a real overall coefficient can mix with the SM CP-Violating phase only through the Jarlskog Invariant

$$C_{uH,mn} = \rho \times (Y_u)_{mn} \quad \longrightarrow \quad L = \mathrm{Im}\mathrm{Tr}\left[(Y_dY_d^\dagger)(Y_uY_u^\dagger)^2(Y_dY_d^\dagger)^2C_{uH}Y_u^\dagger\right] = \frac{1}{2}\rho \times J_4$$

Summary

- CP-violation in the Standard Model Effective field theory inherits the collective nature of CP-violation in the renormalizable Standard Model,

- Wilson Coefficients of higher dimensional operators containing fermions can carry additional CP breaking, that can be consistently captured by flavor invariant objects, linear in the WCs,

- Not all phases contained in the higher-dimensional Wilson Coefficients break CP at leading order. Using invariants straightforwardly provides the correct counting,

- The huge suppression of CP-breaking in the Standard Model is accidental, and it is not in principle a characteristic of SMEFT, too,

- Specific flavor models, such as MFV, can be treated within the invariants formalism as well.

Thank you!