CP-Violating Invariants in the SMEFT

Emanuele Gendy Abd El Sayed
DESY & Universität Hamburg

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Based on: Q. Bonnefoy, E.G., C. Grojean, J. Ruderman: 2112.03889

Motivation

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- Explore CP-Violation beyond the Standard Model

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- Define a flavor-independent formalism for CPV

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- Characterize the parameter space of CP-violating observables at order $1/\Lambda^2$ in the EFT expansion

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- Review: CP-Violation in the Standard Model and the Standard Model Effective Field Theory

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- Counting CP-odd flavor-invariants at order $1/\Lambda^2$
- Collectivity and suppression in the SMEFT

CP-Violation in the Standard Model

In the Electroweak sector, CP violation is encoded in the CKM matrix

Taken from: Matthew D. Schwartz, “Quantum Field Theory and the Standard Model”

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$$\mathcal{L}_{\text{mix}} = \frac{e}{\sqrt{2}\sin\theta_w}\left[\bar{u}_L V \not{W}^+ d_L \; + \; \bar{d}_L V^\dagger \not{W}^- u_L\right]$$

$$= \frac{e}{\sqrt{2}\sin\theta_w}\left[W_\mu^+ \bar{u} V \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) d \; + W_\mu^- \bar{d} V^\dagger \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u\right]$$

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Under CP:

$$\mathcal{L}_{\text{mix}} \to \frac{e}{\sqrt{2}\sin\theta_w}\left[W_\mu^+ \bar{u}\,(V^\dagger)^T \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) d + W_\mu^- \bar{d} V^T \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u\right]$$

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so a complex CKM matrix breaks CP

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CP-Violation must thus have a flavor-independent meaning. In the SM, this is provided by the Jarlskog Invariant

$$J_4 \equiv \mathrm{Im}\,\mathrm{Tr}\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]^3 = 6(y_t^2 - y_c^2)(y_t^2 - y_u^2)(y_c^2 - y_u^2)(y_b^2 - y_s^2)(y_b^2 - y_d^2)(y_s^2 - y_d^2)\mathcal{J}$$

where $\mathcal{J} = s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin(\delta_{\mathrm{CKM}})$

In the standard parametrization

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

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

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We will focus on operators of dimension 6 in the Warsaw basis (B. Grzadkowski et al. arXiv:1008.4884)

CP violation in the SMEFT

As we know from the SM, the presence of phases alone does not necessary imply CPV.

Take a SMEFT with just one generation and only turn on the modified Yukawa $\mathcal{O}_{uH}$ operator

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

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

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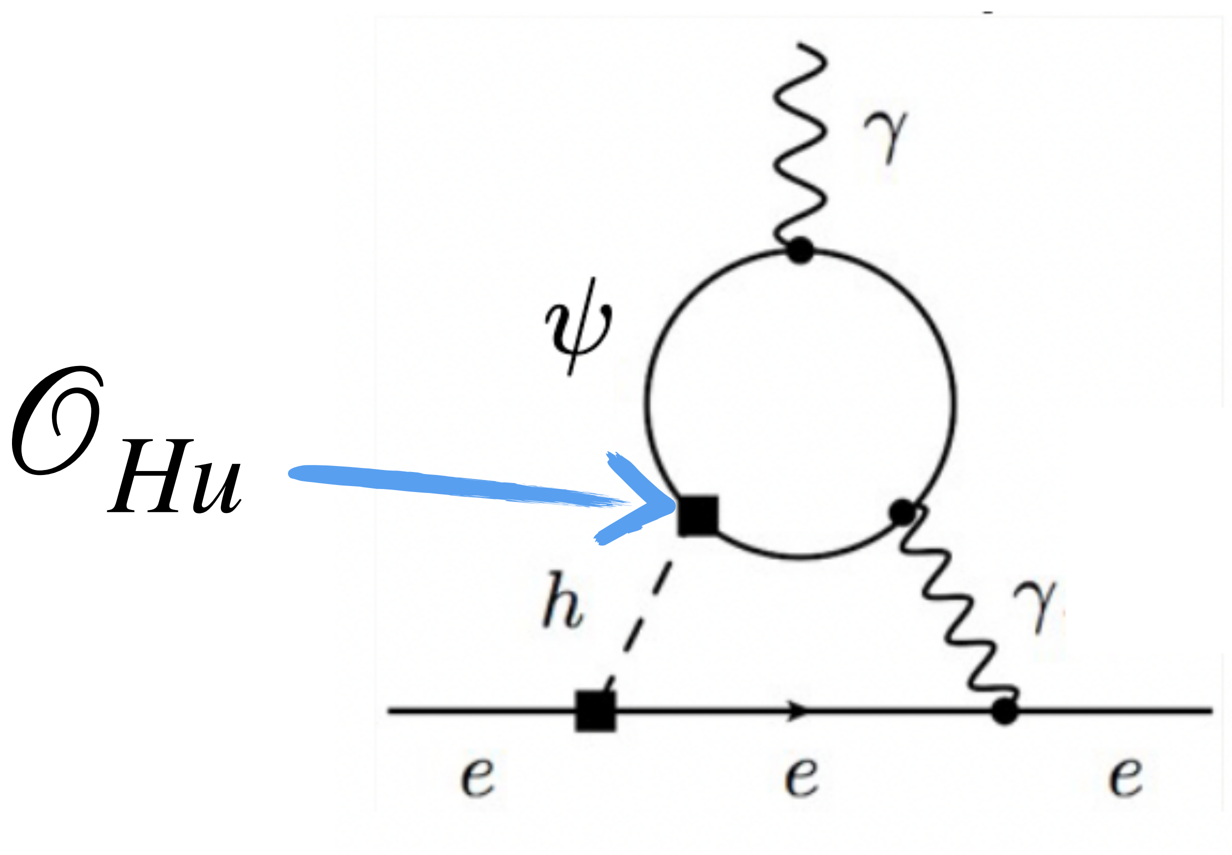

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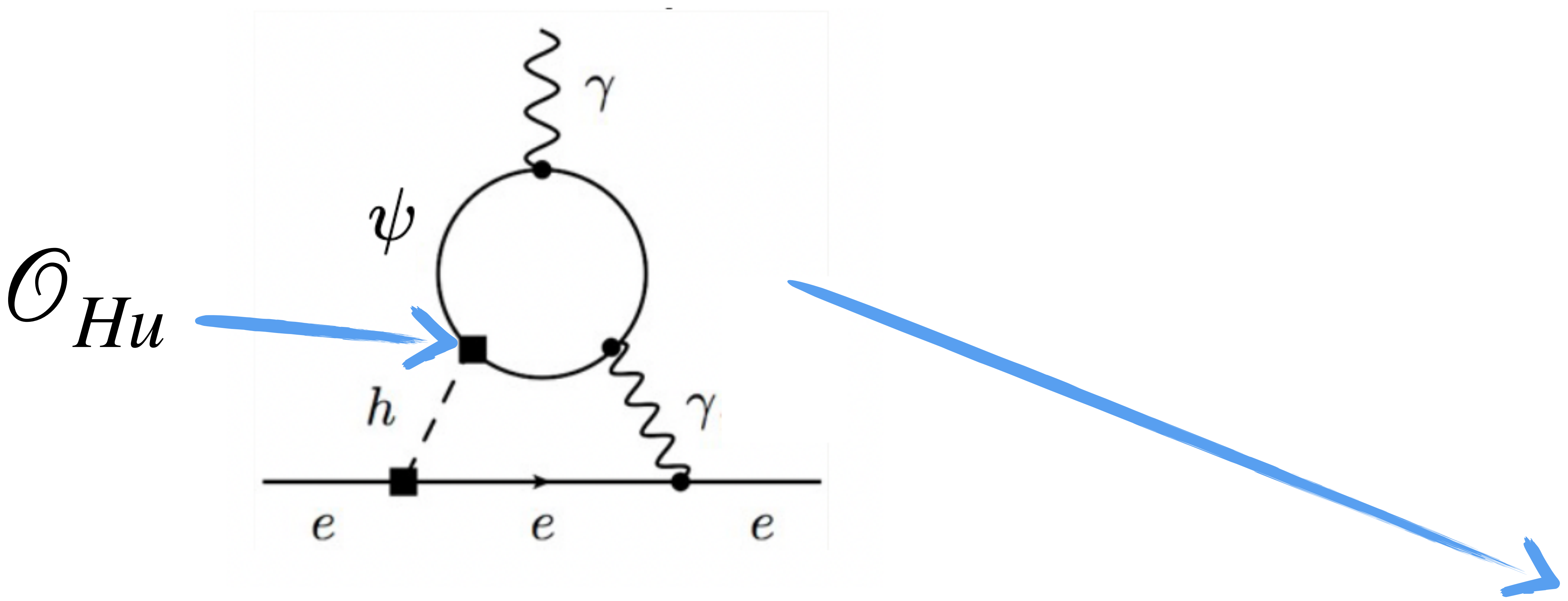

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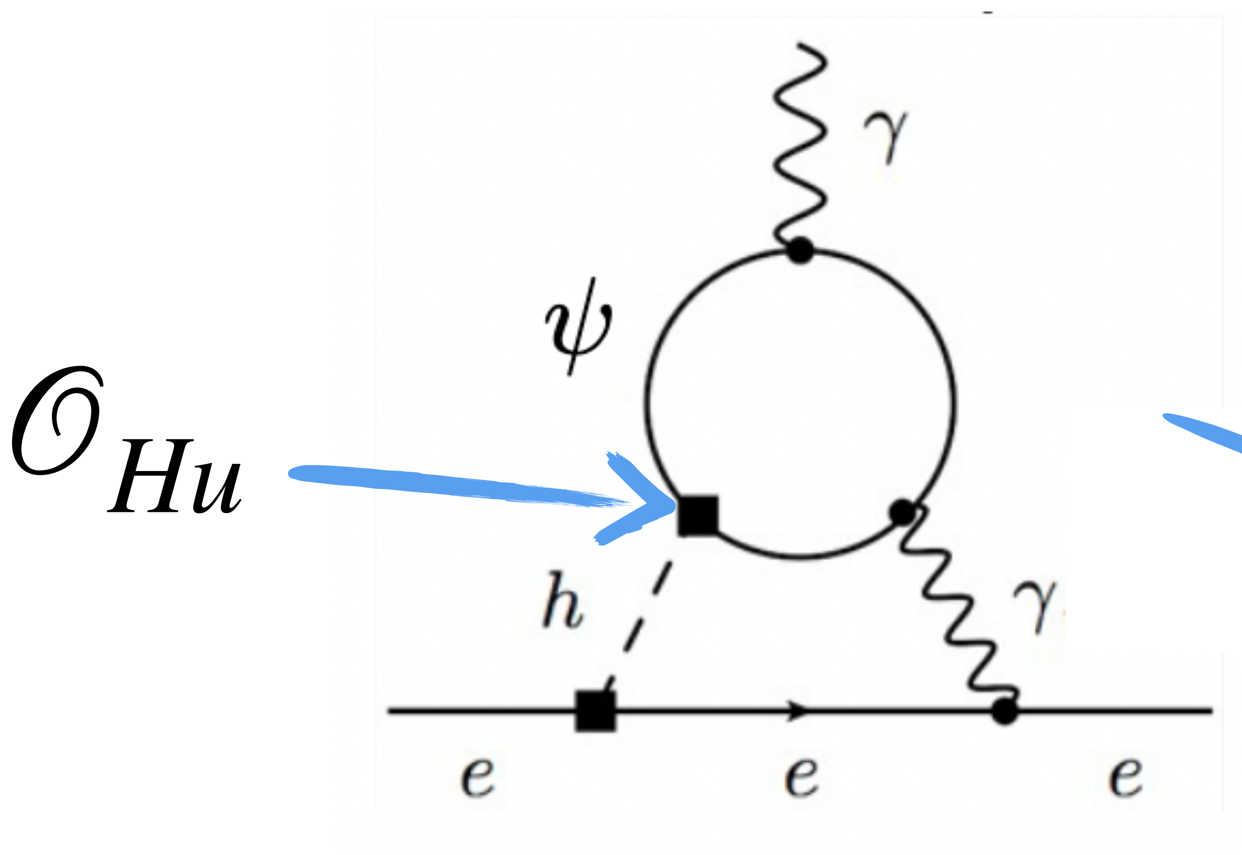

$$\frac{d_e}{e} = -\frac{1}{48\pi^2}\frac{v m_e m_u}{m_h^2}\frac{\mathrm{Im}(C_{uH})}{\Lambda^2}F_1\left(\frac{m_u^2}{m_h^2},0\right)$$

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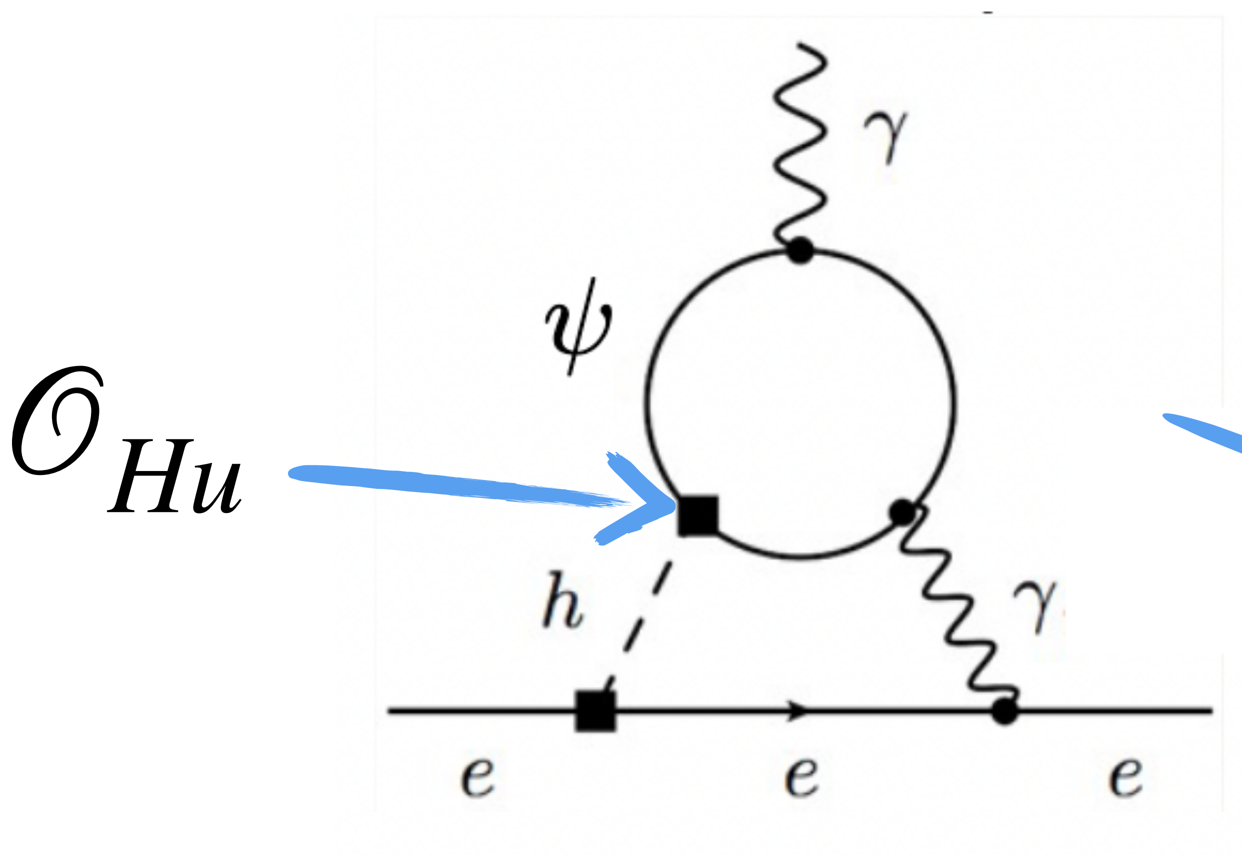

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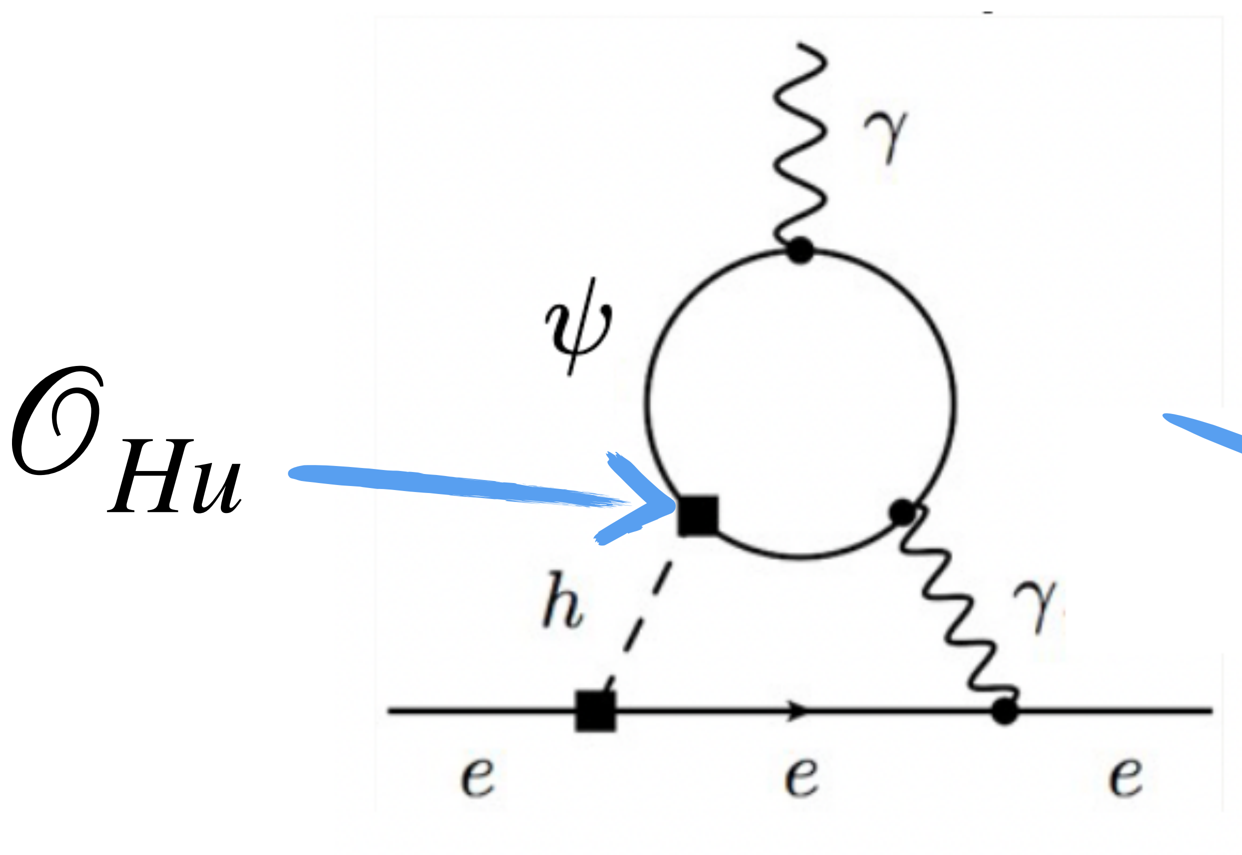

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CP violation in the SMEFT

Which phases are physical for 3 flavors? When does the SMEFT break CP?

$$\mathcal{A} = \mathcal{A}^{(4)} + \mathcal{A}^{(6)} + \ldots \Rightarrow |\mathcal{A}^{(4)}|^2 + 2\mathrm{Re}\left(\mathcal{A}^{(4)}\mathcal{A}^{(6)*}\right)$$

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What are the order parameters of CP-Violation in the SMEFT?

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$$L_1^{HQ(1)} = \mathrm{Im}\mathrm{Tr}(Y_u Y_u^\dagger Y_d Y_d^\dagger C_{HQ}^{(1)})$$

$$L_2^{HQ(1)} = \mathrm{Im}\mathrm{Tr}((Y_u Y_u^\dagger)^2 (Y_d Y_d^\dagger)^2 C_{HQ}^{(1)})$$

$$L_3^{HQ(1)} = \mathrm{Im}\mathrm{Tr}(Y_u Y_u^\dagger Y_d Y_d^\dagger (Y_u Y_u^\dagger)^2 (Y_d Y_d^\dagger)^2 C_{HQ}^{(1)})$$

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CP is conserved **iff** $J_4 = L_1^{HQ(1)} = L_2^{HQ(1)} = L_3^{HQ(1)} = 0$

CP-odd invariants

How many conditions?

	Type of op.	# of ops	# real	# im.	# CP-odd invariants
bilinears	Yukawa	3	27	27	21
	Dipoles	8	72	72	60
	current-current	8	51	30	21
	all bilinears	19	150	129	102
4-Fermi	LLLL	5	171	126	54
	RRRR	7	255	195	126
	LLRR	8	360	288	174
	LRRL	1	81	81	27
	LRLR	4	324	324	216
	all 4-Fermi	25	1191	1014	597
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CP-odd observables at $\mathcal{O}(1/\Lambda^2)$

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.

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

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

CPV in the SM: a collective effect

In the Standard Model, the smallness of the phenomenological parameters from all three generations conspire to produce a non-zero but small J_4

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Using the Wolfenstein parametrization

$$Y_u = \mathrm{diag}(a_u\lambda^8,\ a_c\lambda^4, a_t\lambda^0)$$
$$Y_d = V_{\mathrm{CKM}}\mathrm{diag}(a_d\lambda^7,\ a_c\lambda^4, a_b\lambda^3)$$
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

with $\lambda \approx 0.2$, $a_i = \mathcal{O}(1)$

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

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CPV in the SM: a collective effect

In the Standard Model, the smallness of the phenomenological parameters from all three generations conspire to produce a non-zero but small J_4

$$J_4 \equiv \mathrm{Im}\,\mathrm{Tr}\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]^3 = 6(y_t^2 - y_c^2)(y_t^2 - y_u^2)(y_c^2 - y_u^2)(y_b^2 - y_s^2)(y_b^2 - y_d^2)(y_s^2 - y_d^2)\mathcal{J}$$

Using the Wolfenstein parametrization

$$Y_u = \mathrm{diag}(a_u\lambda^8,\ a_c\lambda^4, a_t\lambda^0)$$
$$Y_d = V_{\mathrm{CKM}}\mathrm{diag}(a_d\lambda^7,\ a_c\lambda^4, a_b\lambda^3)$$
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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

with $\lambda \approx 0.2$, $a_i = \mathcal{O}(1)$

How suppressed are the SMEFT invariants?

CPV in the SMEFT: a collective effect

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For the invariants of $C_{HQ}^{(1)}$ at first non-zero order

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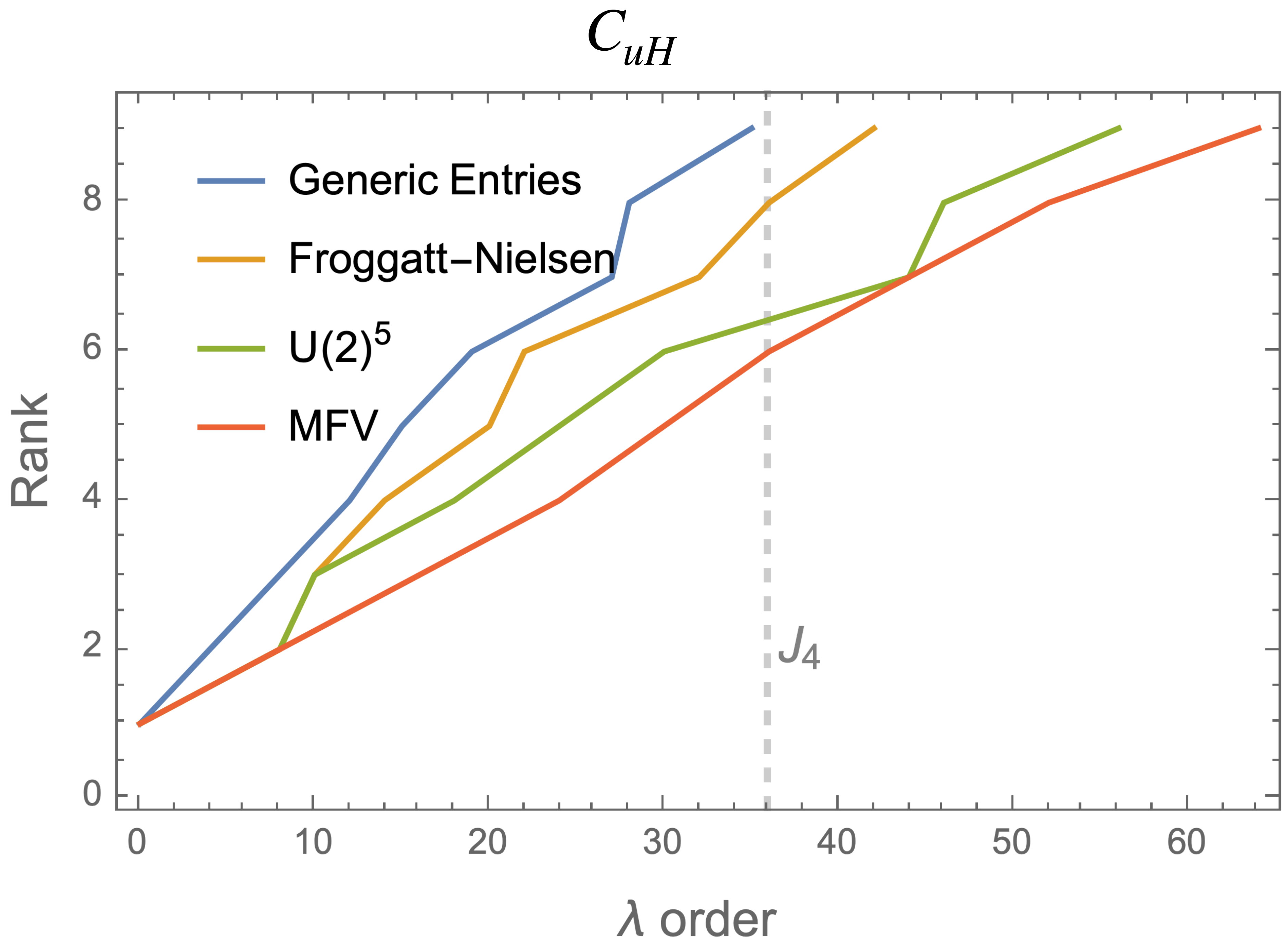
This depends on the assumption we make on the flavor structure of the dimension-six operator coefficient.



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- Not all new phases contained in the operator coefficients break CP at order $\mathcal{O}(1/\Lambda^2)$. Using invariants straightforwardly provides the correct counting
- The invariants can be used to check the suppression of CPV coming from SMEFT operators

Thank you