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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

# CP–Violating Invariants in the SMEFT

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(based on 2112.03889, with Q. Bonnefoy, E.G., C. Grojean, J. Ruderman)

# CP–Violation in the Standard Model

CP–Violation must 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

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

# 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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More precisely, what are the order parameters of CP-Violation in the SMEFT?

# CP-odd invariants

Given a SMEFT dimension-6 operator containing fermions, we can build a set of CP-odd flavor invariants by giving it spurionic transformation properties.

For example turn on only $$\mathcal{O}_{uH} = \frac{C_{uH,ij}}{\Lambda^2}|H|^2\bar{Q}_{L,i}u_{R,j}\tilde{H}$$

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$C_{uH} \longrightarrow$

$$L_1^{uH} = \mathrm{Im\,Tr}\left[C_{uH} Y_u^\dagger\right] \quad L_2^{uH} = \mathrm{Im\,Tr}\left[C_{uH} Y_u^\dagger X_u\right] \quad L_3^{uH} = \mathrm{Im\,Tr}\left[C_{uH} Y_u^\dagger X_d\right]$$

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$$L_7^{uH} = \mathrm{Im\,Tr}\left[C_{uH} Y_u^\dagger X_d^2 X_u^2\right] \quad L_8^{uH} = \mathrm{Im\,Tr}\left[C_{uH} Y_u^\dagger X_u X_d^2 X_u^2\right] \quad L_9^{uH} = \mathrm{Im\,Tr}\left[C_{uH} Y_u^\dagger X_d X_u^2 X_d^2\right]$$

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CP is conserved **iff** $J_4 = L_i^{uH} = 0 \qquad i = 1,\ldots,9$

# CPV in the SM: a collective effect

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

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

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# CPV in the SMEFT: flavor assumptions

The SMEFT invariants are not as suppressed as $J_4$. Different flavor models affect the different number of new CP-violating observables

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Flavor degenerate assumption:

$$C_{uH,ij} = \begin{pmatrix} \rho_{11} + i\eta_{11} & \rho_{12} + i\eta_{12} & \rho_{13} + i\eta_{13} \\ \rho_{21} + i\eta_{21} & \rho_{22} + i\eta_{22} & \rho_{23} + i\eta_{23} \\ \rho_{31} + i\eta_{31} & \rho_{32} + i\eta_{32} & \rho_{33} + i\eta_{33} \end{pmatrix}$$

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↓

18 new parameters

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In Minimal Flavor Violation, the flavor structure is dictated by the Yukawa matrices

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3 new parameters at this order

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We can assume a $U(2)^5 = U(2)_L \otimes U(2)_Q \otimes U(2)_e \otimes U(2)_u \otimes U(2)_d$ flavor symmetry broken by the spurions

$$V_\ell \sim (2,1,1,1,1)\ , \qquad V_q \sim (1,2,1,1,1)\ ,$$
$$\Delta_e \sim (2,1,\bar{2},1,1)\ , \qquad \Delta_u \sim (1,2,1,\bar{2},1)\ , \qquad \Delta_d \sim (1,2,1,1,\bar{2})$$

whose vevs can be related to the SM Yukawa and CKM matrix entries. Up to $\mathcal{O}(V\Delta)$:

$$C_{uH,ij} = \begin{pmatrix} \lambda^5(\rho_1 + i\eta_1) & -\lambda^4(\rho_1 + i\eta_1) & 0 \\ \lambda^6(\rho_1 + i\eta_1) & \lambda^3(\rho_1 + i\eta_1) & \lambda^2(\rho_2 + i\eta_2) \\ \lambda^8(\rho_3 + i\eta_3) & \lambda^5(\rho_3 + i\eta_3) & \rho_4 + i\eta_4 \end{pmatrix}$$

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# CPV in the SMEFT

The number of independent CP-violating parameters in $C_{uH}$ at fixed order in the $\lambda$ expansion changes depending on the flavor assumption

| | Generic | MFV | $U(2)^5$ |
|---|---|---|---|
| Rank 1 | $\mathcal{O}(\lambda^0)$ | $\mathcal{O}(\lambda^0)$ | $\mathcal{O}(\lambda^0)$ |
| Rank 2 | $\mathcal{O}(\lambda^4)$ | $\mathcal{O}(\lambda^6)$ | $\mathcal{O}(\lambda^8)$ |
| Rank 3 | $\mathcal{O}(\lambda^8)$ | $\mathcal{O}(\lambda^8)$ | $\mathcal{O}(\lambda^{10})$ |

$\vdots$

More generically, fixing the flavor symmetry allows us to count the number of independent CPV parameters that can appear in observables

| | Bilinears | | | | 4-Fermi | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Flavour symmetries of the quark sector of the SM | $C_{eH}$<br>$C_{eW}$<br>$C_{eB}$ | $C_{uH}$<br>$C_{uG}$<br>$C_{uW}$<br>$C_{uB}$<br>$C_{dH}$<br>$C_{dG}$<br>$C_{dW}$<br>$C_{dB}$<br>$C_{Hud}$ | $C_{HL}^{1,3}$<br>$C_{He}$ | $C_{HQ}^{1,3}$<br>$C_{Hu}$<br>$C_{Hd}$ | $C_{LL}$<br>$C_{ee}$ | $C_{Le}$ | $C_{QQ}^{1,3}$<br>$C_{uu}$<br>$C_{dd}$ | $C_{LQ}^{1,3}$<br>$C_{Qe}$<br>$C_{Lu}$<br>$C_{eu}$<br>$C_{Ld}$<br>$C_{ed}$ | $C_{ud}^{1,8}$<br>$C_{Qu}^{1,8}$<br>$C_{Qd}^{1,8}$ | $C_{LedQ}$<br>$C_{LeQu}^{1,3}$ | $C_{QuQd}^{1,8}$ |
| $U(1)_B$ | 3 | 9 | 0 | 3 | 0 | 3 | 18 | 9 | 36 | 27 | 81 |
| $U(1)_B \times U(1)_{u_R}$ | 3 | $6^4, 9^4, 6$ | 0 | 3,1,3 | 0 | 3 | 18,6,18 | $9^2, 3^2, 9^2$ | $18^2, 36$ | 27,18 | 54 |
| $U(1)_B \times U(1)_{u_R} \times U(1)_{d_R}$ | 3 | $6^8, 4$ | 0 | $3,1^2$ | 0 | 3 | $18,6^2$ | $9^2, 3^4$ | $8, 18^2$ | $18^2$ | 36 |
| $U(1)_B \times U(2)_{u_R}$ | 3 | $3^4, 9^4, 3$ | 0 | 3,0,3 | 0 | 3 | 18,0,18 | $9^2, 0^2, 9^2$ | $6^2, 36$ | 27,9 | 27 |
| $U(1)_B \times U(2)_{u_R} \times U(1)_{d_R}$ | 3 | $3^4, 6^4, 2$ | 0 | 3,0,1 | 0 | 3 | 18,0,6 | $9^2, 0^2, 3^2$ | 2, 6, 18 | 18,9 | 18 |
| $U(1)^2$ | 3 | 5 | 0 | 1 | 0 | 3 | 5 | 3 | 12 | 15 | 33 |
| $U(1)^2 \times U(1)_{u_R}$ | 3 | $(3 \text{ or } 4)^4, 5^4, 3 \text{ or } 4$ | 0 | 1,0 or 1,1 | 0 | 3 | 5,0 or 5,5 | $3^2,(0 \text{ or } 3)^2,3^2$ | $(5 \text{ or } 8)^2,12$ | 15,9 or 12 | 21 or 24 |
| $U(1)^2 \times U(1)_{u_R} \times U(1)_{d_R}$ | 3 | $(3 \text{ or } 4)^8, 2 \text{ or } 4$ | 0 | $1,(0 \text{ or } 1)^2$ | 0 | 3 | $5,(0 \text{ or } 5)^2$ | $3^2,(0 \text{ or } 3)^4$ | $1 \text{ or } 3 \text{ or } 8,(5 \text{ or } 8)^2$ | 9 or 12 | 12 or 13 or 16 |
| $U(1)^2 \times U(2)_{u_R}$ | 3 | $(1 \text{ or } 2)^4, 5, 1 \text{ or } 2$ | 0 | 1,0,1 | 0 | 3 | 5,0,5 | $3^2, 0^2, 3^2$ | $2^2,12$ | 15,3 | 12 |
| $U(1)^2 \times U(2)_{u_R} \times U(1)_{d_R}$ | 3 | $(1 \text{ or } 2)^4,(3 \text{ or } 4)^4,0 \text{ or } 1 \text{ or } 2$ | 0 | 1,0,0 or 1 | 0 | 3 | 5,0,0 or 5 | $3^2,0^2,(0 \text{ or } 3)^2$ | 0 or 2,2,5 or 8 | 9 or 12,3 | 8 |
| $U(1)^2 \times U(2)_{u_R} \times U(2)_{d_R}$ | 3 | $(1 \text{ or } 2)^8, 0 \text{ or } 1$ | 0 | $1,0^2$ | 0 | 3 | $5,0^2$ | $3^2, 0^4$ | $0,2^2$ | 3 or 6 | 4 |
| $U(1)^3$ | 3 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 3 | 9 | 15 |
| $U(1)^3 \times U(1)_{u_R}$ | 3 | $2^4, 3^4, 2$ | 0 | 0 | 0 | 3 | 0 | 0 | $1^2, 3$ | 9,6 | 10 |
| $U(1)^3 \times U(1)_{u_R} \times U(1)_{d_R}$ | 3 | $2^8, 1 \text{ or } 2$ | 0 | 0 | 0 | 3 | 0 | 0 | $0 \text{ or } 1,1^2$ | 6 | 7 or 8 |
| $U(1)^3 \times U(2)_{u_R}$ | 3 | $1^4, 3^4, 1$ | 0 | 0 | 0 | 3 | 0 | 0 | $0^2, 3$ | 9,3 | 5 |
| $U(1)^3 \times U(2)_{u_R} \times U(1)_{d_R}$ | 3 | $1^4, 2^4, 0 \text{ or } 1$ | 0 | 0 | 0 | 3 | 0 | 0 | $0^2, 1$ | 6,3 | 3 or 4 |
| $U(1)^3 \times U(2)_{u_R} \times U(2)_{d_R}$ | 3 | $1^8, 0 \text{ or } 1$ | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 2 |
| $U(1)^3 \times U(3)_{u_R}$ | 3 | $0^4, 3^4, 0$ | 0 | 0 | 0 | 3 | 0 | 0 | $0^2, 3$ | 9,0 | 0 |
| $U(1)^3 \times U(3)_{u_R} \times U(1)_{d_R}$ | 3 | $0^4, 2^4, 0$ | 0 | 0 | 0 | 3 | 0 | 0 | $0^2, 1$ | 6,0 | 0 |
| $U(2) \times U(1)$ | 3 | 2 | 0 | 0 | 0 | 3 | 0 | 0 | 1 | 6 | 7 |
| $U(2) \times U(1) \times U(1)_{u_R}$ | 3 | $1^4, 2^4, 1$ | 0 | 0 | 0 | 3 | 0 | 0 | $0^2, 1$ | 6,3 | 3 |
| $U(2) \times U(1) \times U(1)_{u_R} \times U(1)_{d_R}$ | 3 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 1 or 2 |
| $U(2) \times U(1) \times U(2)_{u_R}$ | 3 | $1^4, 2^4, 1$ | 0 | 0 | 0 | 3 | 0 | 0 | $0^2, 1$ | 6,3 | 3 |
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| $U(2) \times U(1) \times U(2)_{u_R} \times U(2)_{d_R}$ | 3 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 1 |
| $U(2) \times U(1) \times U(3)_{u_R}$ | 3 | $0^4, 2^4, 0$ | 0 | 0 | 0 | 3 | 0 | 0 | $0^2, 1$ | 6,0 | 0 |
| $U(2) \times U(1) \times U(3)_{u_R} \times U(1)_{d_R}$ | 3 | $0^4, 1^4, 0$ | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3,0 | 0 |
| $U(2) \times U(1) \times U(3)_{u_R} \times U(2)_{d_R}$ | 3 | $0^4, 1^4, 0$ | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3,0 | 0 |
| $U(3)$ | 3 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 2 |
| $U(3) \times U(3)_{u_R}$ | 3 | $0^4, 1^4, 0$ | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3,0 | 0 |
| $U(3) \times U(3)_{u_R} \times U(3)_{d_R}$ | 3 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| Two degenerate electron-type leptons | $\times\frac{2}{3}$ | $\times 1$ | | $\times 1$ | | $\times\frac{2}{3}$ | $\times 1$ | $\times\frac{2}{3}$ | $\times 1$ | $\times\frac{2}{3}$ | $\times 1$ |
| All electron-type leptons degenerate | $\times\frac{1}{3}$ | $\times 1$ | | $\times 1$ | | $\times\frac{1}{3}$ | $\times 1$ | $\times\frac{1}{3}$ | $\times 1$ | $\times\frac{1}{3}$ | $\times 1$ |
| One vanishing electron-type mass | $\times\frac{2}{3}$ | $\times 1$ | | $\times 1$ | | $\times\frac{1}{3}$ | $\times 1$ | $\times 1$ | $\times 1$ | $\times\frac{2}{3}$ | $\times 1$ |
| Two vanishing electron-type masses | $\times\frac{1}{3}$ | $\times 1$ | | $\times 1$ | | 0 | $\times 1$ | $\times\frac{2}{3}$ | $\times 1$ | $\times\frac{1}{3}$ | $\times 1$ |
| All electron-type masses vanishing | 0 | $\times 1$ | | $\times 1$ | | 0 | $\times 1$ | $\times\frac{1}{3}$ | $\times 1$ | 0 | $\times 1$ |

# For example, zooming on $U(2)^5$

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|---|---|---|---|---|---|---|---|---|---|---|---|
| Flavour symmetries of the quark sector of the SM | $C_{eH}$ $C_{eW}$ $C_{eB}$ | $C_{uH}$ $C_{uG}$ $C_{uW}$ $C_{uB}$ $C_{dH}$ $C_{dG}$ $C_{dW}$ $C_{dB}$ $C_{Hud}$ | $C_{HL}^{1,3}$ $C_{He}$ | $C_{HQ}^{1,3}$ $C_{Hu}$ $C_{Hd}$ | $C_{LL}$ $C_{ee}$ | $C_{Le}$ | $C_{QQ}^{1,3}$ $C_{uu}$ $C_{dd}$ | $C_{LQ}^{1,3}$ $C_{Qe}$ $C_{Lu}$ $C_{eu}$ $C_{Ld}$ $C_{ed}$ | $C_{ud}^{1,8}$ $C_{Qu}^{1,8}$ $C_{Qd}^{1,8}$ | $C_{LedQ}$ $C_{LeQu}^{1,3}$ | $C_{QuQd}^{1,8}$ |
| $\vdots$ | | | | | | | | | | | |
| $U(2) \times U(1) \times U(2)_{u_R} \times U(2)_{d_R}$ | 3 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 1 |
| $\vdots$ | | | | | | | | | | | |

To be compared with
(arxix:1802.07237)

| | |
|---|---|
| four heavy quarks | $11 + 2$ CPV |
| two light and two heavy quarks | 14 |
| two heavy quarks and bosons | $9 + 6$ CPV |
| two heavy quarks and two leptons | $(8 + 3 \text{ CPV}) \times 3$ lepton flavours |

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| ⋮ $U(2) \times U(1) \times U(2)_{u_R} \times U(2)_{d_R}$ ⋮ | 3 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 1 |

$\times 6$

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| | Bilinears | | | | 4-Fermi | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Flavour symmetries of the quark sector of the SM | $C_{eH}$ $C_{eW}$ $C_{eB}$ | $C_{uH}$ $C_{uG}$ $C_{uW}$ $C_{uB}$ $C_{dH}$ $C_{dG}$ $C_{dW}$ $C_{dB}$ $C_{Hud}$ | $C_{HL}^{1,3}$ $C_{He}$ | $C_{HQ}^{1,3}$ $C_{Hu}$ $C_{Hd}$ | $C_{LL}$ $C_{ee}$ | $C_{Le}$ | $C_{QQ}^{1,3}$ $C_{uu}$ $C_{dd}$ | $C_{LQ}^{1,3}$ $C_{Qe}$ $C_{Lu}$ $C_{eu}$ $C_{Ld}$ $C_{ed}$ | $C_{ud}^{1,8}$ $C_{Qu}^{1,8}$ $C_{Qd}^{1,8}$ | $C_{LedQ}$ $C_{LeQu}^{1,3}$ | $C_{QuQd}^{1,8}$ |
| ⋮ $U(2)\times U(1)\times U(2)_{u_R}\times U(2)_{d_R}$ ⋮ | 3 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 1 |
| | | $\times 6$ | | | | | | | | $\times 3$ | |

To be compared with
(arxix:1802.07237)

| | |
|---|---|
| four heavy quarks | $11 + 2$ CPV |
| two light and two heavy quarks | 14 |
| two heavy quarks and bosons | $9 + 6$ CPV ← |
| two heavy quarks and two leptons | $(8 + 3$ CPV$) \times 3$ lepton flavours ← |

# For example, zooming on $U(2)^5$

| | Bilinears | | | | 4-Fermi | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Flavour symmetries of the quark sector of the SM | $C_{eH}$ $C_{eW}$ $C_{eB}$ | $C_{uH}$ $C_{uG}$ $C_{uW}$ $C_{uB}$ $C_{dH}$ $C_{dG}$ $C_{dW}$ $C_{dB}$ $C_{Hud}$ | $C_{HL}^{1,3}$ $C_{He}$ | $C_{HQ}^{1,3}$ $C_{Hu}$ $C_{Hd}$ | $C_{LL}$ $C_{ee}$ | $C_{Le}$ | $C_{QQ}^{1,3}$ $C_{uu}$ $C_{dd}$ | $C_{LQ}^{1,3}$ $C_{Qe}$ $C_{Lu}$ $C_{eu}$ $C_{Ld}$ $C_{ed}$ | $C_{ud}^{1,8}$ $C_{Qu}^{1,8}$ $C_{Qd}^{1,8}$ | $C_{LedQ}$ $C_{LeQu}^{1,3}$ | $C_{QuQd}^{1,8}$ |
| ⋮ $U(2)\times U(1)\times U(2)_{u_R}\times U(2)_{d_R}$ ⋮ | 3 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 1 |
| | | $\times 6$ | | | | | | | | $\times 3$ | $\times 2$ |

## To be compared with

(arxix:1802.07237)

| | |
|---|---|
| four heavy quarks | 11 + 2 CPV ← |
| two light and two heavy quarks | 14 |
| two heavy quarks and bosons | 9 + 6 CPV ← |
| two heavy quarks and two leptons | (8 + 3 CPV) × 3 lepton flavours ← |

# Thank you!