CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

The order parameters of CP violation in the SMEFT

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06/07/2021

Work in progress
with E. Gendy, C. Grojean and J. Ruderman

Motivation

What is the (basis-independent) parameter space of CPV observables in the SM(EFT) ?

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In this talk : **when does the SMEFT conserve CP ?**

CP breaking in the SM

When does the SM break CP ?

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$$\mathcal{L} \supset \frac{i}{\sqrt{2}} \overline{u_L} \gamma^\mu W_\mu^+ V_{\rm CKM} d_L - \overline{u_L} {\rm diag}(m_{u_i}) u_R + (d) + h.c.$$

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complex matrix !

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$$=$$

$$\begin{pmatrix} \frac{3}{5} - \frac{4i}{5} & 0 & 0 \\ 0 & \frac{5}{13} - \frac{12i}{13} & 0 \\ 0 & 0 & \frac{3}{5} - \frac{4i}{5} \end{pmatrix} \begin{pmatrix} \frac{3}{13} & \frac{4}{13} & \frac{12}{13} \\ -\frac{692}{845} & -\frac{381}{845} & \frac{60}{169} \\ \frac{444}{845} & -\frac{708}{845} & \frac{25}{169} \end{pmatrix} \begin{pmatrix} \frac{4}{5} + \frac{3i}{5} & 0 & 0 \\ 0 & \frac{3}{5} + \frac{4i}{5} & 0 \\ 0 & 0 & \frac{5}{13} + \frac{12i}{13} \end{pmatrix}$$

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$$\mathcal{J} = \mathrm{Im}(V_{{\rm CKM},us} V_{{\rm CKM},cb} V^*_{{\rm CKM},ub} V^*_{{\rm CKM},cs}) = 0$$

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If $m_u = m_c$ (or $m_u = m_t$ or …) **CP** ✓

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$$(y_t^2 - y_c^2)(y_t^2 - y_u^2)(y_c^2 - y_u^2)(y_b^2 - y_s^2)(y_b^2 - y_d^2)(y_s^2 - y_d^2)\mathcal{J}$$

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

$$\mathcal{L} \supset -\overline{Q_L} Y_u u_R \tilde{H} + (d) + h.c.$$

$$Y_u = \mathrm{diag}(y_u, y_c, y_t) \ , \ Y_d = V_{\rm CKM} \mathrm{diag}(y_d, y_s, y_b)$$

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$$J_4 = \mathrm{Im}\,\mathrm{Tr}\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]^3$$

Flavour invariant

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

$$Y_u = \begin{pmatrix} Y_{u,11} & Y_{u,12} & Y_{u,13} \\ Y_{u,21} & Y_{u,22} & Y_{u,23} \\ Y_{u,31} & Y_{u,32} & Y_{u,33} \end{pmatrix}$$

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CP is conserved in the SM
iff
J4=0

[Jarlskog '85]

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$\Longrightarrow$ No CP breaking in the SM with Nf=2 **[Cabibbo '63, Kobayashi/Maskawa '73]**

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$\Longrightarrow$ CP breaking is a **collective effect**

Explains suppressions

$$d_e^{\mathrm{Fig.1a}} \sim e\mathcal{J} \frac{m_e m_c^2 m_s^2}{m_W^6} \frac{\alpha_W^3 \alpha_s}{(4\pi)^4}$$

[Pospelov/ Ritz '13]

CP is conserved in the SM iff J4=0

[Jarlskog '85]

CP breaking BSM ?

CP breaking in the SMEFT

No new particle at the LHC, no clear deviation from SM couplings : renewed interest in **effective field theories** (EFTs)

$$\mathcal{L} = \mathcal{L}_{d\leq 4} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} \mathcal{O}_i$$

If no light BSM d.o.f. : generic framework to interpret experimental results

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The SMEFT

$$A_\mu^{a,i,Y} \quad \psi_{i,L/R} \quad H$$

$$SU(3)\times SU(2)\times U(1)$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{d_i-4}}\mathcal{O}_i$$

$$\mathcal{O}_i = C^{(1)}_{H\psi_L,ij}\bar{\psi}^i_L\gamma^\mu\psi^j_L\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$

[Buchmüller/Wyler '85, Grzadkowski et al '10]

CP breaking in the SMEFT

When does the SMEFT break CP
at dimension-six ?

CP breaking in the SMEFT

When does the SMEFT break CP
at dimension-six ?

Type of op.	# of ops	# of real coeffs	# of imaginary coeffs
Yukawa	3	27	27
Dipoles	8	72	72
current-current	8	51	30
all bilinears	19	150	129
LLLL	5	171	54
RRRR	7	255	195
LLRR	8	360	288
LRRL	1	81	81
LRLR	4	324	324
all 4-Fermi	25	1191	1014
all		1341	1143

**[Grzadkowski/Iskrzynski/Misiak/Rosiek '10,
Alonso/Manohar/Jenkins '13]**

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Collective aspects, basis-independence: use **flavour-invariants**

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iff
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Observation 1: CP conservation follows the EFT power counting

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$\Longrightarrow$ CP should be conserved order by order

CP breaking in the SMEFT

When does the SMEFT break CP at dimension-six ?

CP is conserved in the SMEFT iff J4 =0 & ? = 0

Observation 1: CP conservation follows the EFT power counting

$\Longrightarrow$ CP should be conserved order by order

$\Longrightarrow$ Some imaginary parts are unphysical at first order

$$|\mathcal{A}|^2 = |\mathcal{A}_{\mathrm{SM}}|^2 + \frac{2}{\Lambda^2}\mathrm{Re}\left(\mathcal{A}_{\mathrm{SM}}\mathcal{A}^*_{\mathrm{BSM}}\right)$$

CP breaking in the SMEFT

When does the SMEFT break CP at dimension-six ?

CP is conserved in the SMEFT
iff
J4 =0 & ? = 0

Observation 1: CP conservation follows the EFT power counting

$\Longrightarrow$ CP should be conserved order by order

$\Longrightarrow$ Some imaginary parts are unphysical at first order

Type of op.	# of ops	# real	# im.	# CP-odd inv.
Yukawa	3	27	27	21
Dipoles	8	72	72	60
current-current	8	51	30	21
all bilinears	19	150	129	102
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
all		1341	1143	699

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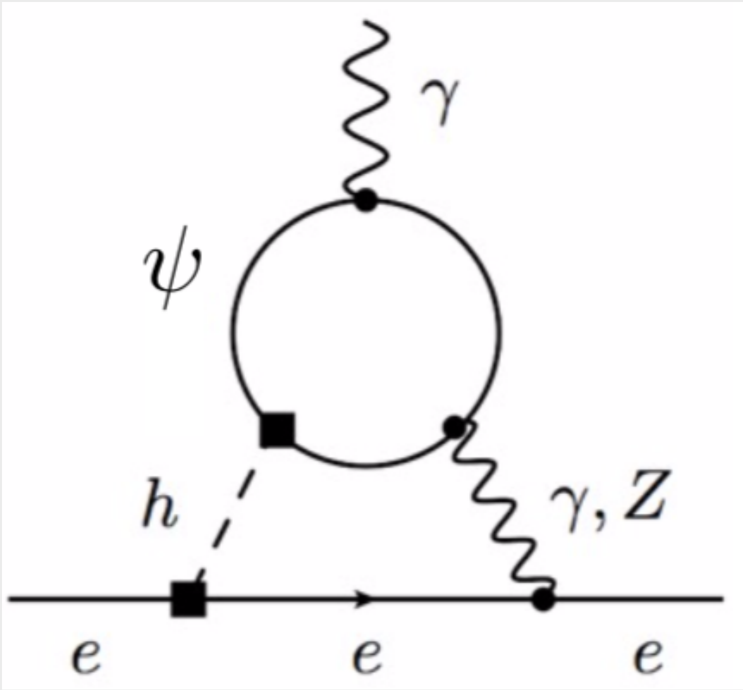
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C_{uH}}{\Lambda^2} |H|^2 \overline{Q_L} u_R \tilde{H} + h.c.$$

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

[Barr/Zee '90, Brod/Haisch/Zupan '13]



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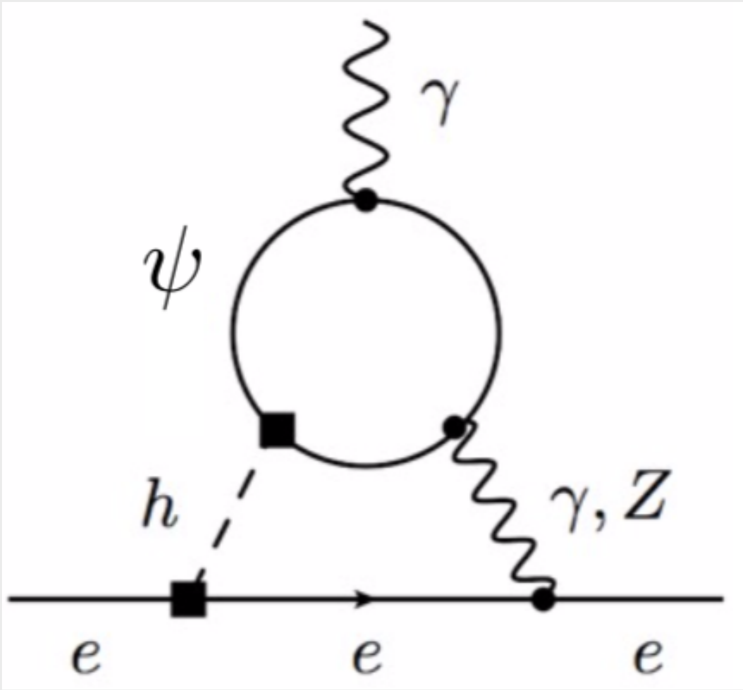

one-to-one correspondance with invariants

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$$Y_u = \mathrm{diag}(a_u\lambda^8, y_c\lambda^4, y_t)$$

$$Y_d = V_{\mathrm{CKM}}\mathrm{diag}(y_d\lambda^7, y_s\lambda^5, y_b\lambda^3)$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$L_1 = \mathrm{ImTr}\left(Y_u Y_u^\dagger Y_d Y_d^\dagger Y_u C_{Hu} Y_u^\dagger\right) \sim \lambda^{12}$$
$$L_2 = \mathrm{ImTr}\left((Y_u Y_u^\dagger)^2 (Y_d Y_d^\dagger)^2 Y_u C_{Hu} Y_u^\dagger\right) \sim \lambda^{18}$$
$$L_3 = \mathrm{ImTr}\left(Y_u Y_u^\dagger Y_d Y_d^\dagger (Y_u Y_u^\dagger)^2 (Y_d Y_d^\dagger)^2 Y_u C_{Hu} Y_u^\dagger\right) \sim \lambda^{24}$$

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Ex : $C_{Hu,ij}\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)\overline{u_i}\gamma^\mu u_j$

Froggatt-Nielsen models

$$Y_u \sim \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^7 & \lambda^4 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix} \quad C_{HQ} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$L_1 = \mathrm{ImTr}\left(Y_u Y_u^\dagger Y_d Y_d^\dagger Y_u C_{Hu} Y_u^\dagger\right) \sim \lambda^{14}$$
$$L_2 = \mathrm{ImTr}\left((Y_u Y_u^\dagger)^2 (Y_d Y_d^\dagger)^2 Y_u C_{Hu} Y_u^\dagger\right) \sim \lambda^{20}$$
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Ex : 2HDM in the decoupling limit, most invariants prop. to J4

Outlook

We found **necessary and sufficient conditions for CP conservation at dimension-six in the SMEFT**. They define the new sources of CPV in a basis-independent way, and connect easily to UV models insensitive to preferred IR bases.

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Other topics :

- CPV with J4 != 0 and parameter space of CPV observables
- preferred invariants given a UV model
- …

THANK YOU

CP-odd flavour invariants for 4-Fermi ops

For 4-Fermi operators : « A-type » $\mathrm{Im}\left(M^{uH}_{ij} M^{dH}_{kl} C^{QuQd}_{ijkl}\right)$

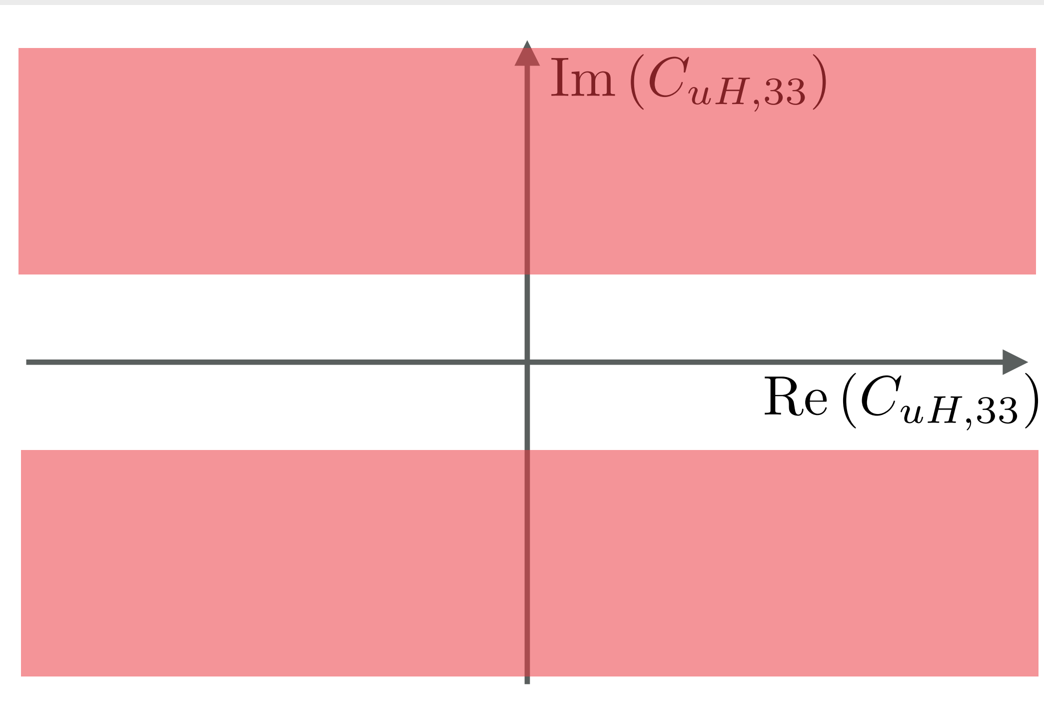
« B-type » $\mathrm{Im}\left(M^{uH}_{kj} M^{dH}_{il} C^{QuQd}_{ijkl}\right)$

$M^{uH}_{kj} \rightarrow Y_u^\dagger\ ,\ Y_u^\dagger Y_d Y_d{}^\dagger\ ,\ ...$

How many « CP-odd directions » are there ?

How many parameters enter CP-odd observables ?

With non-zero J4, real and imaginary parts violate CP



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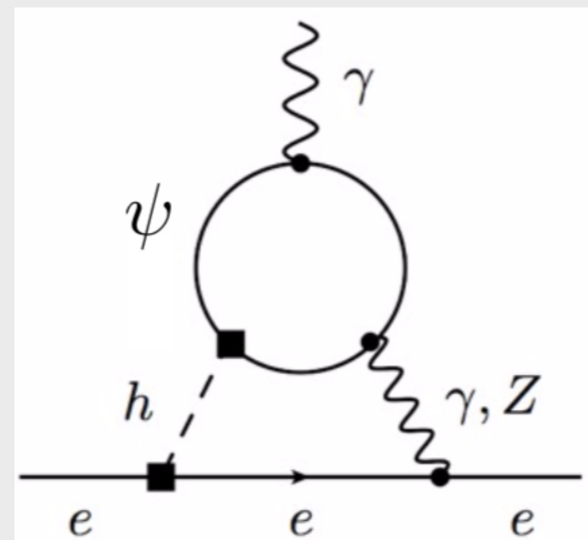
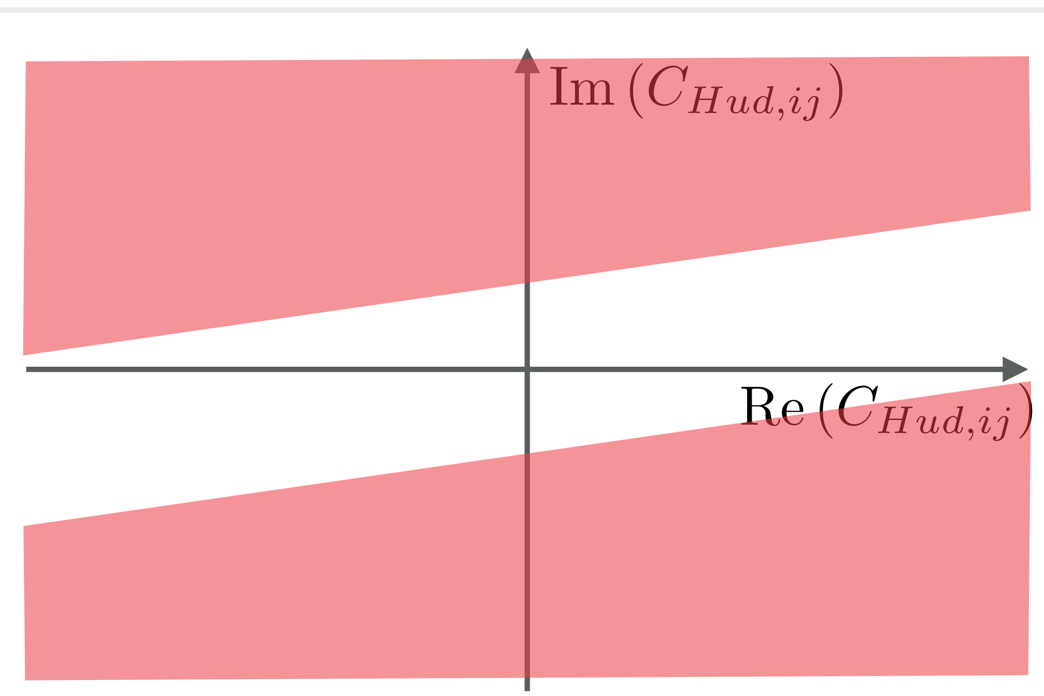
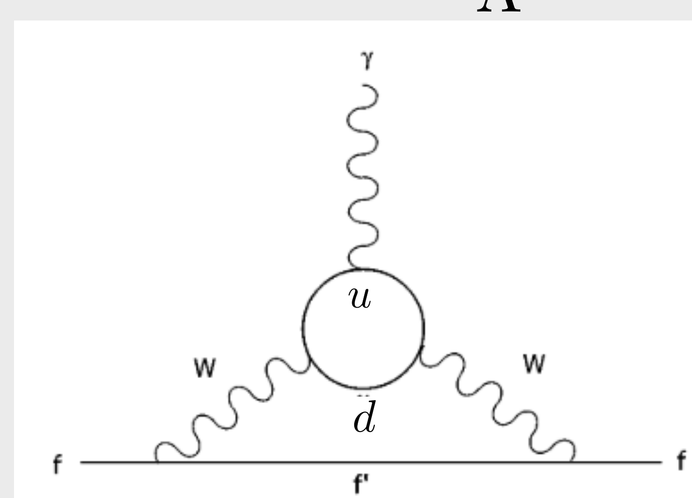


[Brod/Haisch /Zupan ‘13]



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{C_{Hud,mn}}{\Lambda^2} i\tilde{H}^\dagger D_\mu H \overline{u}_{R,m}\gamma^\mu d_{R,n}$$



[Kadoyoshi/ Oshimo ’97]

Theta QCD

$$\mathcal{L}_{\rm QCD} \supset -\theta_{QCD}\frac{g_s^2}{16\pi^2}{\rm Tr}(G\tilde{G})$$

	$SU(3)_{Q_L}$	$U(1)_{Q_L}$	$SU(3)_{u_R}$	$U(1)_{u_R}$	$SU(3)_{d_R}$	$U(1)_{d_R}$
Q_L	$\mathbf{3}$	1	$\mathbf{1}$	0	$\mathbf{1}$	0
u_R	$\mathbf{1}$	0	$\mathbf{3}$	1	$\mathbf{1}$	0
d_R	$\mathbf{1}$	0	$\mathbf{1}$	0	$\mathbf{3}$	1
Y_u	$\mathbf{3}$	1	$\bar{\mathbf{3}}$	-1	$\mathbf{1}$	0
Y_d	$\mathbf{3}$	1	$\mathbf{1}$	0	$\bar{\mathbf{3}}$	-1
$e^{i\theta_{QCD}}$	$\mathbf{1}$	6	$\mathbf{1}$	-3	$\mathbf{1}$	-3

$$\bar{\theta} \equiv \theta_{QCD} - \arg\det\left(Y_u Y_d\right)$$

$${\rm Im}\left(e^{-i\theta_{QCD}}\epsilon^{ABC}\epsilon^{abc}\epsilon^{DEF}\epsilon^{def}Y_{u,Aa}Y_{u,Bb}C_{QuQd,CcDd}Y_{d,Ee}Y_{d,Ff}\right)$$

In the UV, suppressed by $e^{-\frac{8\pi^2}{g_s^2}} \approx \lambda^{37-38}$. Relevant in the IR ?