EFT below the electroweak scale and constraints from EDMs

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and with V. Cirigliano and E. Mereghetti

work in progress

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Outline

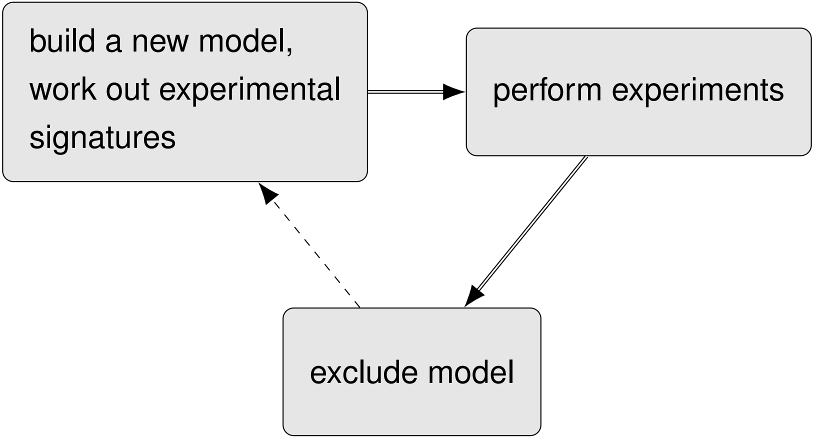
Particle physics in a crisis?

- Standard Model very successful
- only a few discrepancies around $2 \dots 4\sigma$:
  - muon $g-2$
  - B-physics observables: $R(D^{(*)})$, $R(K^{(*)})$, $\dots$
- clear signals of New Physics:
  - neutrino masses
  - dark matter
  - baryon asymmetry
- naturalness so far a rather bad guide in the search for New Physics...

How to search for and describe New Physics?

- UV-complete models, mainly motivated by naturalness
- simplified models, often designed to explain a particular experimental result
- model-independent approaches using effective field theories

Model building



Advantages of using EFTs

- based on a very small set of assumptions
- generic framework, can be used ‘stand-alone’ or in connection with a broad range of specific models
- work with the relevant degrees of freedom at a particular energy $\Rightarrow$ simplify calculations
- connect different energy regimes, avoid large logs

Disadvantages

- limited range of validity
- large number of free parameters

Going beyond tree-level

- mixing and running can be important
- obtain correlations between different observables
- high-precision observables at low energies
- precision of LHC searches constantly improving

SMEFT assumptions

- New Physics at scale $\Lambda \gg v \approx 246$ GeV
- underlying theory respects $G_{\text{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- spontaneous breaking $SU(2)_L \times U(1)_Y \to U(1)_Q$
- Higgs particle and Goldstone bosons form an electroweak doublet

Degrees of freedom and power counting

- field content: all the fields of the SM
- expansion in powers of v/Λ and p/Λ
- Lagrangian:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \cdots \,,$$

where

$$\mathcal{L}_n = \sum_i C_i^{(n)} \mathcal{Q}_i^{(n)} \,, \qquad C_i^{(n)} \propto \frac{1}{\Lambda^{n-4}}$$

→ Buchmüller, Wyler (1986), Grzadkowski et al. (2010)
→ Lehman (2014), Lehman, Martin (2015, 2016), Henning et al. (2016, 2017)

HEFT assumptions

- New Physics at scale $\Lambda \geq 4\pi v \gg v \approx 246$ GeV
- underlying theory respects $G_{\mathrm{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- spontaneous breaking $SU(2)_L \times U(1)_Y \to U(1)_Q$ as in the SM
- Higgs particle treated independently of Goldstone bosons

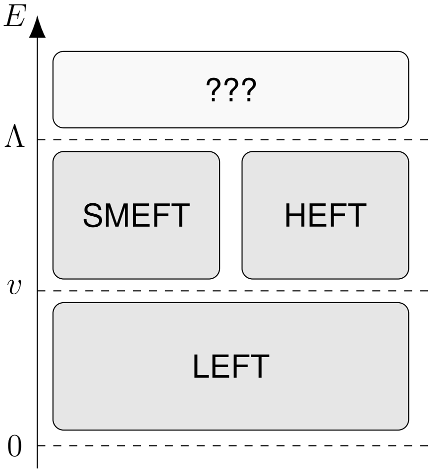
$\to$ Feruglio (1993), Grinstein, Trott (2007)

Degrees of freedom and power counting

- field content: all the fields of the SM
- nonlinear realisation leads to a fusion with ChPT
- appropriate description e.g. for strongly-coupled New Physics scenarios
- power counting controversial in the literature (naive dimensional analysis vs. pure chiral counting)

→ Alonso et al. (2013), Buchalla et al. (2016)

EFTs at different energies



- use appropriate EFT at each energy scale in order to resum logarithms
- below electroweak scale: use low-energy EFT (LEFT), where heavy SM particles are integrated out

Low-energy EFT

- basically the old Fermi theory of weak interaction, or ‘weak Hamiltonian’ of flavour physics
- well-known and studied in detail for particular processes
- however, a complete and systematic treatment was missing in the literature

Field content and symmetries

- all SM particles apart from $W^\pm$, Z, h, t
- EW symmetry spontaneously broken: in LEFT, only $SU(3)_c \times U(1)_Q$ is left

Power counting

- dimensional counting
- expansion parameter m/v, p/v
- depending on the high-scale EFT, a second expansion scheme is inherited (e.g. v/Λ from SMEFT)
- note that in DR, loops never generate factors of v in the numerator

Lagrangian

- LEFT Lagrangian: $\mathcal{L}_{\mathrm{LEFT}} = \mathcal{L}_{\mathrm{QCD+QED}} + \sum_i L_i \mathcal{O}_i$
- leading-order Lagrangian is just QCD + QED:

$$\begin{aligned}
\mathcal{L}_{\mathrm{QCD+QED}} &= -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&\quad + \theta_{\mathrm{QCD}} \frac{g^2}{32\pi^2} G^A_{\mu\nu} \widetilde{G}^{A\mu\nu} + \theta_{\mathrm{QED}} \frac{e^2}{32\pi^2} F_{\mu\nu} \widetilde{F}^{\mu\nu} \\
&\quad + \sum_{\psi = u,d,e,\nu_L} \overline{\psi} i \not{D} \psi \\
&\quad - \left[\sum_{\psi = u,d,e} \overline{\psi}_{Rr} [M_\psi]_{rs} \psi_{Ls} + \mathrm{h.c.} \right]
\end{aligned}$$

Additional LEFT operators: $d = 3$

- $\Delta L = \pm 2$ Majorana mass terms for the neutrinos:

$$\mathcal{L}_{\not{L}}^{(3)} = -\frac{1}{2}[M_\nu]_{rs}(\nu_{Lr}^T C \nu_{Ls}) + \text{h.c.}$$

- for three neutrino generations, there are 12 operators (including h.c. and before diagonalisation)

Additional LEFT operators: $d = 5$

- $\Delta B = \Delta L = 0$ dipole operators for $\psi = u, d, e$:

$$\mathcal{L}^{(5)} = \sum_{\psi=e,u,d} \left(L_{\underset{rs}{\psi\gamma}} \mathcal{O}_{\underset{rs}{\psi\gamma}} + \text{h.c.} \right) + \sum_{\psi=u,d} \left(L_{\underset{rs}{\psi G}} \mathcal{O}_{\underset{rs}{\psi G}} + \text{h.c.} \right) ,$$

where

$$\mathcal{O}_{\underset{rs}{\psi\gamma}} = \bar{\psi}_{Lr} \sigma^{\mu\nu} \psi_{Rs} F_{\mu\nu} , \quad \mathcal{O}_{\underset{rs}{\psi G}} = \bar{\psi}_{Lr} \sigma^{\mu\nu} T^A \psi_{Rs} G^A_{\mu\nu}$$

- 70 Hermitian operators for $n_u = 2$, $n_d = n_e = 3$

Additional LEFT operators: $d = 5$

- $\Delta L = \pm 2$ neutrino dipole operators:

$$\mathcal{L}^{(5)}_{\not{L}} = \underset{rs}{L_{\nu\gamma}} \, \underset{rs}{\mathcal{O}_{\nu\gamma}} + \mathrm{h.c.}\,,$$

where

$$\underset{rs}{\mathcal{O}_{\nu\gamma}} = \nu^T_{Lr} C \sigma^{\mu\nu} \nu_{Ls} F_{\mu\nu}$$

- antisymmetric in flavour indices $\Rightarrow$ 6 Hermitian operators for $n_\nu = 3$

Additional LEFT operators: $d = 6$

- two gluonic operators:

$$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu} \,,$$
$$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$$

Additional LEFT operators: $d = 6$

- $\Delta B = \Delta L = 0$ four-fermion operators of the following classes: $(\bar{L}L)(\bar{L}L)$, $(\bar{R}R)(\bar{R}R)$, $(\bar{L}L)(\bar{R}R)$, $(\bar{L}R)(\bar{L}R) + \mathrm{h.c.}$, $(\bar{L}R)(\bar{R}L) + \mathrm{h.c.}$.
- 78 structures, in total 3631 Hermitian operators for $n_u = 2$, $n_d = n_e = n_\nu = 3$
- our choice: use Fierz identities to remove tensorial operators if possible; no lepto-quark bilinears

Additional LEFT operators: $d = 6$

- 12 $\Delta L = \pm 4$ four-fermion operators:

$$\mathcal{O}^{S,LL}_{\substack{\nu\nu \\ prst}} = (\nu^T_{Lp} C \nu_{Lr})(\nu^T_{Ls} C \nu_{Lt})$$

- 1200 $\Delta L = \pm 2$ four-fermion operators, e.g.

$$\mathcal{O}^{S,LL}_{\substack{\nu e \\ prst}} = (\nu^T_{Lp} C \nu_{Lr})(\bar{e}_{Rs} e_{Lt})$$

Additional LEFT operators: $d = 6$

- 576 $\Delta B = \Delta L = \pm 1$ four-fermion operators, e.g.

$$\mathcal{O}^{S,LL}_{\substack{udd\\prst}} = \epsilon_{\alpha\beta\gamma}(u^{\alpha T}_{Lp} C d^{\beta}_{Lr})(d^{\gamma T}_{Ls} C \nu_{Lt})$$

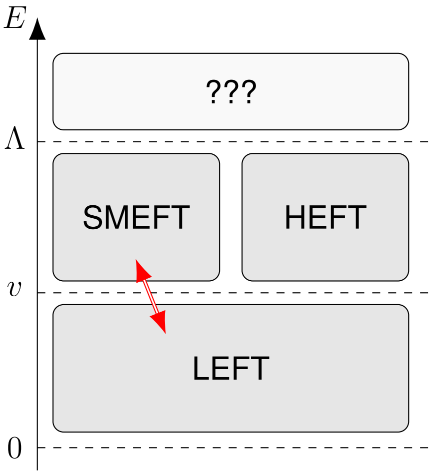
- 456 $\Delta B = -\Delta L = \pm 1$ four-fermion operators, e.g.

$$\mathcal{O}^{S,LR}_{\substack{udd\\prst}} = \epsilon_{\alpha\beta\gamma}(u^{\alpha T}_{Lp} C d^{\beta}_{Lr})(\bar{\nu}_{Ls} d^{\gamma}_{Rt})$$

LEFT operators

- in total 5963 operators at dimensions three, five, and six: 3099 CP-even and 2864 CP-odd
- basis free of redundancies (EOM, Fierz, etc.)
- cross-checked with Hilbert series

Matching between the EFTs



- complete matching from SMEFT to LEFT at tree level performed
- leads to relations between the LEFT operator coefficients

SMEFT in the broken phase

- Higgs in unitary gauge:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ [1 + c_{H,\mathrm{kin}}]\, h + v_T \end{pmatrix} ,$$

where

$$c_{H,\mathrm{kin}} := \left(C_{H\Box} - \frac{1}{4} C_{HD} \right) v^2 , \quad v_T := \left(1 + \frac{3 C_H v^2}{8\lambda} \right) v$$

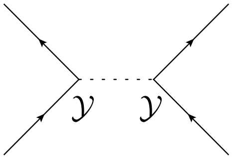
- modifications from SM due to dimension-six Higgs operators in SMEFT

SMEFT in the broken phase

- dimension-six modifications of fermion masses and Yukawa couplings $\Rightarrow$ no longer proportional
- modifications of gauge-boson mass terms
- weak charged and neutral currents modified as well, e.g. coupling of $\mathcal{W}^+$ to right-handed current $\bar{u}_R \gamma^\mu d_R$
- after rotation to mass eigenstates, modified weak currents lead to non-unitary effective CKM quark-mixing matrix

Integrating out weak-scale SM particles

consider Higgs-exchange diagram:



$$[\mathcal{Y}_\psi]_{rs} = \frac{1}{v_T}[M_\psi]_{rs}\left[1 + c_{H,\mathrm{kin}}\right] - \frac{v^2}{\sqrt{2}} C^*_{\substack{\psi H\\ sr}}$$

$\mathcal{Y}^2$ has terms of order $(m/v)^2$, mv/Λ^2, v^4/Λ^4
$\Rightarrow$ diagram $\mathcal{Y}^2/m_h^2$ is of same order as dimension-7 or 8 contributions in LEFT or dimension-8 in SMEFT

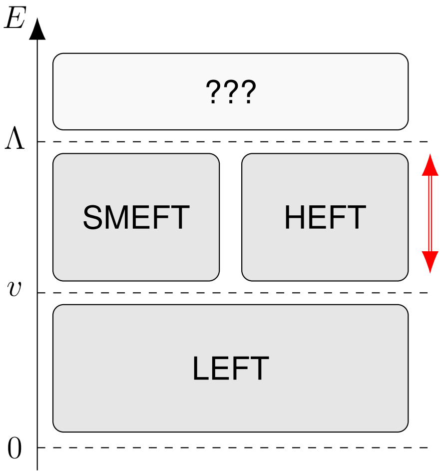
Integrating out weak-scale SM particles

- for SMEFT ⇒ LEFT matching: rewrite terms

$$\ldots \frac{1}{\Lambda^n} = \underbrace{\ldots \frac{1}{v^n}}_{\text{LEFT counting}} \times \underbrace{\frac{v^n}{\Lambda^n}}_{\text{SMEFT counting}}$$

- tree-level matching simple: fix Higgs field to vev and compute $\mathcal{W}/\mathcal{Z}$-exchange diagrams

Running in the EFTs



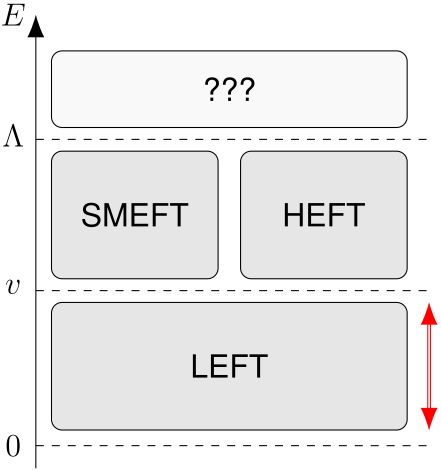
- one-loop RGE for SMEFT known

  → Jenkins et al. (2013, 2014)
  → Alonso et al. (2014)

- one-loop RGE for HEFT recently calculated

  → Buchalla et al. (2017)
  → Alonso et al. (2017)

Running in the EFTs



- RGE for LEFT previously only partly known

  → many references...

  e.g. for B-physics:

  → Aebischer et al. (2017)

Power counting and RGE

- calculation of complete one-loop RGE up to dimension-six effects in the LEFT
- graph with insertions of higher-dimensional operators $(d_i \geq 5)$:

$$d = 4 + \sum_i (d_i - 4)$$

- up to dimension six:
  - single-operator insertions of dimension five and six
  - double-operator insertions of dimension five

Double-dipole insertions

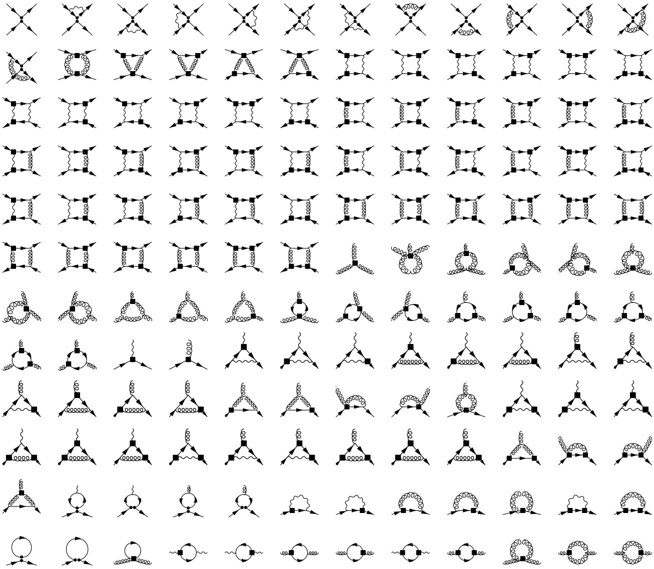
- if the LEFT derives from SMEFT as the high-scale EFT: dipole coefficients are of order

$$\frac{v}{\Lambda^2} = \frac{1}{v} \times \frac{v^2}{\Lambda^2}$$

$\Rightarrow$ double insertions are SMEFT dimension-8

- however, in HEFT dipoles are only $1/\Lambda$-suppressed
- keep double-dipole insertions as well as dimension-five corrections to EOM in single-dipole insertions

Full set of one-loop diagrams



Equations of motion vs. field redefinitions

- when calculating the one-loop diagrams, counterterms are generated that are not explicitly in the LEFT basis, but related to LEFT operators by field redefinitions
- performing these field redefinitions is often referred to as using the EOM
- blind application of the EOM, however, can lead to incorrect results if the operators are not manifestly Hermitian, e.g. terms of the form $\bar{\psi}(i\not{D})^3\psi$

Electric dipole moments

- permanent electric dipole moments (EDM) are P/CP-odd observables
- in the SM due to CP-violation in the CKM matrix (or due to QCD θ-term), loop suppressed and tiny
- $\Rightarrow$ EDMs are attractive observables to search for new sources of CP-violation beyond the SM

Definition

- three-point function with off-shell photon:

$$\langle N(p',s')|\gamma^*(q,\lambda)N(p,s)\rangle = ie(2\pi)^4\delta^{(4)}(q+p-p')\epsilon_\mu^\lambda(q) \\ \times \bar{u}(p',s')\Gamma^\mu(p,p',q)u(p,s),$$

- decomposition of vertex function into form factors:

$$\Gamma^\mu(p,p',q) = \gamma^\mu F_E(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_N}F_M(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_N}\gamma_5 F_D(q^2) \\ + \left(\gamma^\mu - \frac{2m_N q^\mu}{q^2}\right)\gamma_5 F_A(q^2)$$

- EDM:

$$d_N = -\frac{F_D(0)}{2m_N}$$

Neutron EDM

- current limit (ILL Grenoble):
  $d_n < 3.0 \cdot 10^{-26}\,\mathrm{e\,cm}$ (90% CL) $\rightarrow$ Pendlebury et al. (2015)
- EW contribution: $d_n^{\mathrm{SM}} \sim 10^{-32}\,\mathrm{e\,cm}$
  $\rightarrow$ He et al. (1989), Dar (2000)
- ongoing and future experiments:
  ILL, PSI, TUM, TRIUMF, Jülich, LANL, ...
- limits expected to improve by two orders of magnitude

EDMs in the LEFT

- leading contribution to leptonic EDMs given directly in terms of the LEFT dipole operators
- hadronic EDMs (nEDM) more complicated: QCD is non-perturbative
- any P-odd, CP-odd flavour-conserving operator can contribute non-perturbatively to EDM:
  - QCD θ-term
  - dimension-five (C)EDM operators
  - Weinberg's dimension-six three-gluon operator
  - dimension-six P/CP-odd four-fermion operators

EDMs in the LEFT

- contribution at low energies schematically given as

$$d_N \sim \sum_i L_i \langle N|\mathcal{O}_i|N\rangle$$

L_i: LEFT operator coefficients

$\langle N|\mathcal{O}_i|N\rangle$: hadronic matrix element

- estimating and calculating the matrix elements:
    - chiral perturbation theory and NDA
    - non-perturbative lattice QCD calculations
    - at present, uncertainties are very large

Lattice QCD for matrix elements

- a priori the best way to compute the matrix elements
- problem with lattice and LEFT:

$$d_N \sim \sum_i L_i(\mu) \langle N | \mathcal{O}_i^{\overline{\text{MS}}} | N \rangle$$

  $\overline{\text{MS}}$ cannot be implemented on the lattice!

- need for a matching calculation between $\overline{\text{MS}}$ continuum calculation and lattice QCD

RI schemes

- widely used scheme amenable to lattice calculations: RI-(S)MOM: **R**egularisation-**I**ndependent (**S**ymmetric) **MOM**entum-subtraction scheme

  $\rightarrow$ Martinelli et al. (1995), Sturm et al. (2010)

- impose renormalisation conditions on truncated off-shell Green's functions for Euclidean momenta
- RI-SMOM: insert momentum into operator to avoid unwanted IR effects in lattice calculations (pion poles)
- calculation in a fixed R_ξ gauge

Matching $\overline{\mathrm{MS}}$ and RI-SMOM

- one-loop matching calculation between $\overline{\mathrm{MS}}$ and RI/SMOM has been carried out for the dimension-five (C)EDM operators $\rightarrow$ Bhattacharya et al. (2016)
- work in progress: extending this to the dimension-six Weinberg three-gluon operator $\widetilde{G}GG$
- translation between different schemes:

$$\mathcal{O}_i^{\overline{\mathrm{MS}}} = C_{ij}\mathcal{O}_j^{\mathrm{RI}}\,, \quad C_{ij} = \left(Z^{\overline{\mathrm{MS}}}\right)^{-1}_{ik} Z^{\mathrm{RI}}_{kj}$$

at one loop:

$$Z_{ij} = \mathbb{1}_{ij} + \Delta_{ij}\,, \quad C_{ij} = \mathbb{1}_{ij} - \Delta_{ij}^{\overline{\mathrm{MS}}} + \Delta_{ij}^{\mathrm{RI}}$$

Constructing the operator basis

Several complications compared to $\overline{\mathrm{MS}}$ calculations:

- gauge fixing explicitly breaks gauge symmetry to BRST symmetry
- off-shell Green's function in fixed gauge
  $\Rightarrow$ EOM operators and gauge-variant operators contribute
- momentum insertion in operators
  $\Rightarrow$ total-derivative operators contribute

Physical operators

Leading-order Lagrangian:

$$\mathcal{L}_{\mathrm{QED+QCD}} = \bar{q}(i\not{D} - \mathcal{M})q - \frac{1}{4} G_A^{\mu\nu} G_{\mu\nu}^A - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \theta_{\mathrm{QCD}} \frac{g^2}{32\pi^2} G_A^{\mu\nu} \widetilde{G}_{\mu\nu}^A$$

with the light quarks only:

$q = (u, d, s)$, $\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s)$

Chiral symmetry

- approximate chiral symmetry:

$$q_{L,R} \overset{\chi}{\mapsto} U_{L,R} q_{L,R} \,, \quad \bar{q}_{L,R} \overset{\chi}{\mapsto} \bar{q}_{L,R} U^{\dagger}_{L,R}$$

- symmetry restored if $\mathcal{M}$ (and charge matrix Q) are promoted to spurion field with transformation

$$\mathcal{M} \overset{\chi}{\mapsto} U_L \mathcal{M} U_R^{\dagger} \,, \quad \mathcal{M}^{\dagger} \overset{\chi}{\mapsto} U_R \mathcal{M}^{\dagger} U_L^{\dagger}$$

Gauge-invariant operators

- building blocks:

$$q_{L,R}, \bar{q}_{L,R}, G^A_{\mu\nu}, F_{\mu\nu}, \mathcal{M}, \mathcal{M}^\dagger, Q_{L,R}, \partial_\mu, D_\mu$$

- symmetries required for mixing with Weinberg operator:
  - Lorentz scalars
  - $SU(3)_c \times U(1)_Q$
  - chirally invariant (in spurion sense)
  - P-odd, CP-odd
  - mass dimension ≤ 6
- cross-checked with Hilbert series

BRST symmetry

- add ghosts and gauge fixing to Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD+QED}} + \mathcal{L}_{\mathrm{GF}} + \mathcal{L}_{\mathrm{gh}} ,$$
$$\mathcal{L}_{\mathrm{gh}} = \partial^\mu \bar{c}^A (D_\mu^{AC} c^C) + \partial^\mu \bar{c}_\gamma \partial_\mu c_\gamma ,$$
$$\mathcal{L}_{\mathrm{GF}} = \frac{\xi}{2} G^A G^A + (\partial^\mu G^A) G_\mu^A + \frac{\xi_\gamma}{2} A^2 + (\partial^\mu A) A_\mu$$

- no longer gauge invariant, but still BRST invariant

BRST symmetry

- add source terms for BRST variations of all the fields:

$$\mathcal{L}[J] = \mathcal{L} + J^{\mu}_{A} \frac{\delta G^{A}_{\mu}}{\delta \lambda} + \ldots = \mathcal{L} - J^{\mu,A}(D^{AC}_{\mu} c^{C}) + \ldots$$

- BRST operator:

$$\hat{W} = \frac{\delta S}{\delta G^{A}_{\mu}} \frac{\delta}{\delta J^{\mu}_{A}} + \frac{\delta S}{\delta J^{A}_{\mu}} \frac{\delta}{\delta G^{\mu}_{A}} + \ldots$$

is nil-potent ($\hat{W}^2 = 0$) and has ghost number $+1$

- all gauge-variant operators can be written as a BRST variation of 'seed operators' $\mathcal{F}$ with ghost number -1:

$$\mathcal{N} = \hat{W} \cdot \mathcal{F}$$ $\rightarrow$ Joglekar, Lee (1976)

$\Rightarrow$ most general solution of Slavnov-Taylor identities

Nuisance operators

- building blocks for seed operators:

  $q_{L,R}, \bar{q}_{L,R}, G^A_\mu, A_\mu, \mathcal{M}, \mathcal{M}^\dagger, Q_{L,R}, \partial_\mu,$ ghosts, BRST sources

- required symmetries/properties:
  - Lorentz scalars
  - (global) $SU(3)_c \times U(1)_Q$
  - chirally invariant (in spurion sense)
  - P-odd, CP-odd
  - mass dimension ≤ 6
  - ghost number -1
- cross-checked with Hilbert series

Operator basis

- mixing structure for $(\mathcal{O}, \mathcal{N})$:

$$Z = \left(\begin{array}{c|c} Z_{\mathcal{O}\mathcal{O}} & Z_{\mathcal{O}\mathcal{N}} \\ \hline 0 & Z_{\mathcal{N}\mathcal{N}} \end{array} \right)$$

- nuisance operators do not contribute to physical matrix elements (nEDM), but needed to define (non-perturbatively) renormalised finite RI-SMOM operators
- BRST construction gives all (gauge-invariant) EOM operators + gauge-variant operators
- cross-checked with Hilbert series

Operator basis

- $\mathcal{O}$ operators: θ-term, EDM, chromo-EDM, Weinberg operator + total derivative operators
- $\mathcal{N}$ operators: 1 at dimension four, but 31 at dimension six (at leading order in $\alpha_{\rm QED}$):
  - 12 gauge-invariant EOM operators, e.g.

$$\mathcal{N} = i(\bar{q}_E \mathcal{M}^2 \gamma_5 q + \bar{q} \mathcal{M}^2 \gamma_5 q_E)\,, \quad q_E := (i\not{D} - \mathcal{M})q$$

  - 19 gauge-variant operators, e.g.

$$\mathcal{N} = i(\bar{q}_E \gamma_5 q + \bar{q} \gamma_5 q_E) G^a_\mu G^\mu_a$$

LEFT

- we constructed the full LEFT operator basis up to dimension six
- tree-level matching to SMEFT at the weak scale
- complete one-loop RGE, including (dim-5)^2 effects and ‘down’-mixing
- completes a unified SMEFT framework to compute all leading-log effects from the scale of New Physics down to low energies
- also valid for HEFT as the high-scale EFT
- future work: phenomenology, global fits

nEDM

- use constraining power of precision (n)EDM measurements
- problem at low energies are (huge) hadronic uncertainties
- use lattice QCD for matrix elements
  $\Rightarrow$ matching calculation to appropriate scheme

nEDM

- for Weinberg three-gluon operator: popular RI-SMOM scheme leads to a plethora of nuisance operators
- ongoing work: formulate renormalisation conditions
- lattice expert have to decide about feasibility
- perhaps need to consider alternative schemes (e.g. position-space Green's functions)

Backup

LEFT basis

$\nu\nu + \text{h.c.}$	
$\mathcal{O}_\nu$	$(\nu_{Lp}^T C \nu_{Lr})$

$(\nu\nu)X + \text{h.c.}$	
$\mathcal{O}_{\nu\gamma}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr}) F_{\mu\nu}$

$(\overline{L}R)X + \text{h.c.}$	
$\mathcal{O}_{e\gamma}$	$\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr}\, F_{\mu\nu}$
$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp}\sigma^{\mu\nu} u_{Rr}\, F_{\mu\nu}$
$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp}\sigma^{\mu\nu} d_{Rr}\, F_{\mu\nu}$
$\mathcal{O}_{uG}$	$\bar{u}_{Lp}\sigma^{\mu\nu} T^A u_{Rr}\, G_{\mu\nu}^A$
$\mathcal{O}_{dG}$	$\bar{d}_{Lp}\sigma^{\mu\nu} T^A d_{Rr}\, G_{\mu\nu}^A$

X^3	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$

LEFT basis

$(\overline{L}L)(\overline{L}L)$

$\mathcal{O}_{\nu\nu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{\nu}_{Ls}\gamma_\mu \nu_{Lt})$
$\mathcal{O}_{ee}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu e}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu u}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{\nu d}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{eu}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{ed}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{\nu edu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu u_{Lt}) + \text{h.c.}$
$\mathcal{O}_{uu}^{V,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{dd}^{V,LL}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V1,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V8,LL}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Ls}\gamma_\mu T^A d_{Lt})$

$(\overline{R}R)(\overline{R}R)$

$\mathcal{O}_{ee}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{eu}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{uu}^{V,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{dd}^{V,RR}$	$(\bar{d}_{Rp}\gamma^\mu d_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V1,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V8,RR}$	$(\bar{u}_{Rp}\gamma^\mu T^A u_{Rr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$

$(\overline{L}L)(\overline{R}R)$

$\mathcal{O}_{\nu e}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{ee}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{\nu u}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{\nu d}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{eu}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ue}^{V,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{de}^{V,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{\nu edu}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{h.c.}$
$\mathcal{O}_{uu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{uu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$
$\mathcal{O}_{ud}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{du}^{V1,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{du}^{V8,LR}$	$(\bar{d}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$
$\mathcal{O}_{dd}^{V1,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{dd}^{V8,LR}$	$(\bar{d}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{uddu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{h.c.}$
$\mathcal{O}_{uddu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A u_{Rt}) + \text{h.c.}$

$(\overline{L}R)(\overline{L}R) + \text{h.c.}$

$\mathcal{O}_{ee}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{e}_{Ls} e_{Rt})$
$\mathcal{O}_{eu}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{eu}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{u}_{Ls}\sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{ed}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{ed}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu} d_{Rt})$
$\mathcal{O}_{\nu edu}^{S,RR}$	$(\bar{\nu}_{Lp} e_{Rr})(\bar{d}_{Ls} u_{Rt})$
$\mathcal{O}_{\nu edu}^{T,RR}$	$(\bar{\nu}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{uu}^{S1,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{uu}^{S8,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{u}_{Ls} T^A u_{Rt})$
$\mathcal{O}_{ud}^{S1,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{ud}^{S8,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
$\mathcal{O}_{dd}^{S1,RR}$	$(\bar{d}_{Lp} d_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{dd}^{S8,RR}$	$(\bar{d}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
$\mathcal{O}_{uddu}^{S1,RR}$	$(\bar{u}_{Lp} d_{Rr})(\bar{d}_{Ls} u_{Rt})$
$\mathcal{O}_{uddu}^{S8,RR}$	$(\bar{u}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A u_{Rt})$

$(\overline{L}R)(\overline{R}L) + \text{h.c.}$

$\mathcal{O}_{eu}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Rs} u_{Lt})$
$\mathcal{O}_{ed}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Rs} d_{Lt})$
$\mathcal{O}_{\nu edu}^{S,RL}$	$(\bar{\nu}_{Lp} e_{Rr})(\bar{d}_{Rs} u_{Lt})$

LEFT basis

$\mathbf{\Delta L = 4 + h.c.}$	
$\mathcal{O}^{S,LL}_{\nu\nu}$	$(\nu^T_{Lp} C \nu_{Lr})(\nu^T_{Ls} C \nu_{Lt})$

$\mathbf{\Delta L = 2 + h.c.}$	
$\mathcal{O}^{S,LL}_{\nu e}$	$(\nu^T_{Lp} C \nu_{Lr})(\bar{e}_{Rs} e_{Lt})$
$\mathcal{O}^{T,LL}_{\nu e}$	$(\nu^T_{Lp} C \sigma^{\mu\nu} \nu_{Lr})(\bar{e}_{Rs} \sigma_{\mu\nu} e_{Lt})$
$\mathcal{O}^{S,LR}_{\nu e}$	$(\nu^T_{Lp} C \nu_{Lr})(\bar{e}_{Ls} e_{Rt})$
$\mathcal{O}^{S,LL}_{\nu u}$	$(\nu^T_{Lp} C \nu_{Lr})(\bar{u}_{Rs} u_{Lt})$
$\mathcal{O}^{T,LL}_{\nu u}$	$(\nu^T_{Lp} C \sigma^{\mu\nu} \nu_{Lr})(\bar{u}_{Rs} \sigma_{\mu\nu} u_{Lt})$
$\mathcal{O}^{S,LR}_{\nu u}$	$(\nu^T_{Lp} C \nu_{Lr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}^{S,LL}_{\nu d}$	$(\nu^T_{Lp} C \nu_{Lr})(\bar{d}_{Rs} d_{Lt})$
$\mathcal{O}^{T,LL}_{\nu d}$	$(\nu^T_{Lp} C \sigma^{\mu\nu} \nu_{Lr})(\bar{d}_{Rs} \sigma_{\mu\nu} d_{Lt})$
$\mathcal{O}^{S,LR}_{\nu d}$	$(\nu^T_{Lp} C \nu_{Lr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}^{S,LL}_{\nu edu}$	$(\nu^T_{Lp} C e_{Lr})(\bar{d}_{Rs} u_{Lt})$
$\mathcal{O}^{T,LL}_{\nu edu}$	$(\nu^T_{Lp} C \sigma^{\mu\nu} e_{Lr})(\bar{d}_{Rs} \sigma_{\mu\nu} u_{Lt})$
$\mathcal{O}^{S,LR}_{\nu edu}$	$(\nu^T_{Lp} C e_{Lr})(\bar{d}_{Ls} u_{Rt})$
$\mathcal{O}^{V,RL}_{\nu edu}$	$(\nu^T_{Lp} C \gamma^{\mu} e_{Rr})(\bar{d}_{Ls} \gamma_{\mu} u_{Lt})$
$\mathcal{O}^{V,RR}_{\nu edu}$	$(\nu^T_{Lp} C \gamma^{\mu} e_{Rr})(\bar{d}_{Rs} \gamma_{\mu} u_{Rt})$

$\mathbf{\Delta B = \Delta L = 1 + h.c.}$	
$\mathcal{O}^{S,LL}_{udd}$	$\epsilon_{\alpha\beta\gamma}(u^{\alpha T}_{Lp} C d^{\beta}_{Lr})(d^{\gamma T}_{Ls} C \nu_{Lt})$
$\mathcal{O}^{S,LL}_{duu}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Lp} C u^{\beta}_{Lr})(u^{\gamma T}_{Ls} C e_{Lt})$
$\mathcal{O}^{S,LR}_{uud}$	$\epsilon_{\alpha\beta\gamma}(u^{\alpha T}_{Lp} C u^{\beta}_{Lr})(d^{\gamma T}_{Rs} C e_{Rt})$
$\mathcal{O}^{S,LR}_{duu}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Lp} C u^{\beta}_{Lr})(u^{\gamma T}_{Rs} C e_{Rt})$
$\mathcal{O}^{S,RL}_{uud}$	$\epsilon_{\alpha\beta\gamma}(u^{\alpha T}_{Rp} C u^{\beta}_{Rr})(d^{\gamma T}_{Ls} C e_{Lt})$
$\mathcal{O}^{S,RL}_{duu}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Rp} C u^{\beta}_{Rr})(u^{\gamma T}_{Ls} C e_{Lt})$
$\mathcal{O}^{S,RL}_{dud}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Rp} C u^{\beta}_{Rr})(d^{\gamma T}_{Ls} C \nu_{Lt})$
$\mathcal{O}^{S,RL}_{ddu}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Rp} C d^{\beta}_{Rr})(u^{\gamma T}_{Ls} C \nu_{Lt})$
$\mathcal{O}^{S,RR}_{duu}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Rp} C u^{\beta}_{Rr})(u^{\gamma T}_{Rs} C e_{Rt})$

$\mathbf{\Delta B = -\Delta L = 1 + h.c.}$	
$\mathcal{O}^{S,LL}_{ddd}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Lp} C d^{\beta}_{Lr})(\bar{e}_{Rs} d^{\gamma}_{Lt})$
$\mathcal{O}^{S,LR}_{udd}$	$\epsilon_{\alpha\beta\gamma}(u^{\alpha T}_{Lp} C d^{\beta}_{Lr})(\bar{\nu}_{Ls} d^{\gamma}_{Rt})$
$\mathcal{O}^{S,LR}_{ddu}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Lp} C d^{\beta}_{Lr})(\bar{\nu}_{Ls} u^{\gamma}_{Rt})$
$\mathcal{O}^{S,LR}_{ddd}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Lp} C d^{\beta}_{Lr})(\bar{e}_{Ls} d^{\gamma}_{Rt})$
$\mathcal{O}^{S,RL}_{ddd}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Rp} C d^{\beta}_{Rr})(\bar{e}_{Rs} d^{\gamma}_{Lt})$
$\mathcal{O}^{S,RR}_{udd}$	$\epsilon_{\alpha\beta\gamma}(u^{\alpha T}_{Rp} C d^{\beta}_{Rr})(\bar{\nu}_{Ls} d^{\gamma}_{Rt})$
$\mathcal{O}^{S,RR}_{ddd}$	$\epsilon_{\alpha\beta\gamma}(d^{\alpha T}_{Rp} C d^{\beta}_{Rr})(\bar{e}_{Ls} d^{\gamma}_{Rt})$