EFT below the electroweak scale and constraints from EDMs

Peter Stoffer

Physics Department, UC San Diego

in collaboration with E. Jenkins and A. Manohar


and with V. Cirigliano and E. Mereghetti

work in progress

19th March 2018

High Energy Seminar, UC Davis
Outline

1. Introduction
2. EFTs for New Physics
3. EFT below the electroweak scale
4. Neutron EDM
5. Conclusions and outlook
Overview

1 Introduction

2 EFTs for New Physics

3 EFT below the electroweak scale

4 Neutron EDM

5 Conclusions and outlook
Particle physics in a crisis?

- Standard Model very successful
- only a few discrepancies around $2 \ldots 4\sigma$:
  - muon $g - 2$
  - $B$-physics observables: $R(D^{(*)})$, $R(K^{(*)})$, ...
- 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

build a new model, work out experimental signatures

perform experiments

exclude model
Introduction

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
Overview

1 Introduction

2 EFTs for New Physics
   SMEFT
   HEFT

3 EFT below the electroweak scale

4 Neutron EDM

5 Conclusions and outlook
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 $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$
- 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 $v/\Lambda$ and $p/\Lambda$
- Lagrangian:

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

where

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

→ Buchmüller, Wyler (1986), Grzadkowski et al. (2010)
HEFT assumptions

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

→ 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)
Overview

1 Introduction
2 EFTs for New Physics
3 EFT below the electroweak scale
   Field content and symmetries
   Power counting
   Operator basis
   Tree-level matching with SMEFT
   Anomalous dimensions
   Equations of motion
4 Neutron EDM
5 Conclusions and outlook
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. $v/\Lambda$ from SMEFT)
- note that in DR, loops never generate factors of $v$ in the numerator
Lagrangian

- **LEFT Lagrangian:** \( \mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QCD+QED}} + \sum_i L_i \mathcal{O}_i \)

- leading-order Lagrangian is just QCD + QED:

\[
\mathcal{L}_{\text{QCD+QED}} = -\frac{1}{4} G_{\mu\nu}^A G^{A\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
+ \theta_{\text{QCD}} \frac{g^2}{32\pi^2} G_{\mu\nu}^A \tilde{G}^{A\mu\nu} + \theta_{\text{QED}} \frac{e^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \\
+ \sum_{\psi=u,d,e,\nu_L} \bar{\psi} i \not{D} \psi \\
- \left[ \sum_{\psi=u,d,e} \bar{\psi}_{Rr} [M_\psi]_{rs} \psi_{Ls} + \text{h.c.} \right]
\]
Additional LEFT operators: $d = 3$

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

$$\mathcal{L}^{(3)}_L = -\frac{1}{2} [M_\nu]_{rs} (\nu^T_{Lr} C \nu_{Ls}) + \text{h.c.}$$

- 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 $\psi = u, d, e$:

\[
\mathcal{L}^{(5)} = \sum_{\psi = e, u, d} \left( L_{\psi \gamma} O_{\psi \gamma} + \text{h.c.} \right) + \sum_{\psi = u, d} \left( L_{\psi G} O_{\psi G} + \text{h.c.} \right),
\]

where

\[
O_{\psi \gamma} = \bar{\psi}_{Lr} \sigma_{\mu\nu} \psi_{Rs} F_{\mu\nu}, \quad O_{\psi G} = \bar{\psi}_{Lr} \sigma_{\mu\nu} T^A \psi_{Rs} G^A_{\mu\nu}.
\]

- 70 Hermitian operators for $n_u = 2, n_d = n_e = 3$
Additional LEFT operators: $d = 5$

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

$$\mathcal{L}_{L}^{(5)} = L_{\nu_{r}L}^{\gamma} O_{\nu_{\gamma}r_{s}} + h.c.,$$

where

$$O_{\nu_{\gamma}r_{s}} = \nu_{L_{r}}^{T} C\sigma^{\mu\nu} \nu_{L_{s}} F_{\mu\nu}$$

- antisymmetric in flavour indices $\Rightarrow$ 6 Hermitian operators for $n_{\nu} = 3$
Additional LEFT operators: $d = 6$

- two gluonic operators:

\[
\mathcal{O}_G = f^{ABC} G^{A \nu}_\mu G^{B \lambda}_\nu G^{C \mu}_\lambda, \\
\mathcal{O}_{\tilde{G}} = f^{ABC} \tilde{G}^{A \nu}_\mu G^{B \lambda}_\nu G^{C \mu}_\lambda
\]
Additional LEFT operators: $d = 6$

- $\Delta B = \Delta L = 0$ four-fermion operators of the following classes: $(\bar{L}L)(\bar{L}L)$, $(\bar{R}R)(\bar{R}R)$, $(\bar{L}L)(\bar{R}R)$, $(\bar{L}R)(\bar{L}R) + \text{h.c.}$, $(\bar{L}R)(\bar{R}L) + \text{h.c.}$

- 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:

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

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

$$\mathcal{O}^{S,LL}_{\nu e}^{prst} = (\nu^T_{Lp} C \nu_{Lr})(\bar{e}_{Rs} e_{Lt})$$
Additional LEFT operators: $d = 6$

- $576 \Delta B = \Delta L = \pm 1$ four-fermion operators, e.g.
  \[
  O_{u dd}^{S,LL} \epsilon_{\alpha \beta \gamma} (u_{Lp}^\alpha C d_{Lr}^\beta) (d_{Ls}^\gamma C \nu_{Lt})
  \]

- $456 \Delta B = -\Delta L = \pm 1$ four-fermion operators, e.g.
  \[
  O_{u dd}^{S,LR} \epsilon_{\alpha \beta \gamma} (u_{Lp}^\alpha C d_{Lr}^\beta) (\bar{\nu}_{Ls} d_{Rt}^\gamma)
  \]
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:

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

where

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

- 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 \( W^+ \) 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:

\[ [\mathcal{Y}_\psi]_{rs} = \frac{1}{v_T} [M_\psi]_{rs} [1 + c_{H,\text{kin}}] - \frac{v^2}{\sqrt{2}} C_{\psi H}^{sr} \]

\( \mathcal{Y}^2 \) has terms of order \( (m/v)^2, mv/\Lambda^2, v^4/\Lambda^4 \)

\( \Rightarrow \) 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 $\Rightarrow$ LEFT matching: rewrite terms

$$\cdots \frac{1}{\Lambda^n} = \cdots \frac{1}{v^n} \times \frac{v^n}{\Lambda^n}$$

LEFT counting \hspace{2cm} SMEFT counting

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

\[ \frac{v}{\Lambda^2} = \frac{1}{v} \times \frac{v^2}{\Lambda^2} \]

⇒ 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
EFT below the electroweak scale

Anomalous dimensions

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 $\bar{\psi}(i\slashed{D})^3\psi$
Overview

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4. Neutron EDM
   Electric dipole moments
   Experimental status
   EDMs in the LEFT
   Matching to lattice
   Renormalisation scheme
   BRST construction

5. Conclusions and outlook
Electric dipole moments

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

Electric dipole moments

Definition

- three-point function with off-shell photon:
  \[ \langle N(p', s')|\gamma^*(q, \lambda)N(p, s)\rangle = ie(2\pi)^4\delta^{(4)}(q + p - p')\epsilon^\lambda_\mu(q) \]
  \[ \times \bar{u}(p', s')\Gamma^\mu(p, p', q)u(p, s), \]

- decomposition of vertex function into form factors:
  \[ \Gamma^\mu(p, p', q) = \gamma^\mu F_E(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_N}F_M(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_N}\gamma_5 F_D(q^2) \]
  \[ + \left( \gamma^\mu - \frac{2m_Nq^\mu}{q^2} \right)\gamma_5 F_A(q^2) \]

- EDM:
  \[ d_N = -\frac{F_D(0)}{2m_N} \]
Neutron EDM

• current limit (ILL Grenoble):
  \[ d_n < 3.0 \cdot 10^{-26} \text{ e cm} \quad (90\% \text{ CL}) \rightarrow \text{Pendlebury et al. (2015)} \]

• EW contribution: \( d_{n}^{\text{SM}} \sim 10^{-32} \text{ e cm} \)
  \rightarrow \text{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 $\theta$-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

\[ d_N \sim \sum_i L_i \langle N | O_i | N \rangle \]

- \( L_i \): LEFT operator coefficients
- \( \langle N | O_i | N \rangle \): 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: Regularisation-Independent (Symmetric) Momentum-subtraction scheme
  → 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 $R_\xi$ gauge
Matching $\overline{\text{MS}}$ and RI-SMOM

- one-loop matching calculation between $\overline{\text{MS}}$ and RI/SMOM has been carried out for the dimension-five (C)EDM operators $→$ Bhattacharya et al. (2016)

- work in progress: extending this to the dimension-six Weinberg three-gluon operator $\widetilde{G}GG$

- translation between different schemes:

$$O_i^{\overline{\text{MS}}} = C_{ij}O_j^{\text{RI}}, \quad C_{ij} = (Z_{ij}^{\overline{\text{MS}}})^{-1} Z_{kj}^{\text{RI}}$$

at one loop:

$$Z_{ij} = 1_{ij} + \Delta_{ij}, \quad C_{ij} = 1_{ij} - \Delta_{ij}^{\overline{\text{MS}}} + \Delta_{ij}^{\text{RI}}$$
Constructing the operator basis

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

\[ \mathcal{L}_{\text{QED+QCD}} = \bar{q}(i \slashed{D} - \mathcal{M})q - \frac{1}{4} G^A \tilde{G}^A_{\mu \nu} - \frac{1}{4} F^\mu \nu F_{\mu \nu} \]

\[ + \theta_{\text{QCD}} \frac{g^2}{32 \pi^2} G^A_{\mu \nu} \tilde{G}^A_{\mu \nu} \]

with the light quarks only:

\[ q = (u, d, s), \quad \mathcal{M} = \text{diag}(m_u, m_d, m_s) \]
Chiral symmetry

- approximate chiral symmetry:

  \[ q_{L,R} \xrightarrow{\chi} U_{L,R}q_{L,R} , \quad \bar{q}_{L,R} \xrightarrow{\chi} \bar{q}_{L,R}U_{L,R}^\dagger \]

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

  \[ \mathcal{M} \xrightarrow{\chi} U_L\mathcal{M}U_R^\dagger , \quad \mathcal{M}^\dagger \xrightarrow{\chi} U_R\mathcal{M}^\dagger U_L^\dagger \]
Gauge-invariant operators

- building blocks:

\[ q_{L,R}, \bar{q}_{L,R}, G_A^{\mu \nu}, F_{\mu \nu}, M, M^\dagger, Q_{L,R}, \partial_\mu, D_\mu \]

- 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 \( \leq 6 \)

- cross-checked with Hilbert series
BRST symmetry

- add ghosts and gauge fixing to Lagrangian:

\[
\mathcal{L} = \mathcal{L}_{\text{QCD+QED}} + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{gh}},
\]

\[
\mathcal{L}_{\text{gh}} = \partial_\mu \bar{c}^A (D_\mu A^C c^C) + \partial_\mu \bar{c}_\gamma \partial_\mu c_\gamma,
\]

\[
\mathcal{L}_{\text{GF}} = \frac{\xi}{2} G^A G^A + (\partial_\mu G^A) G^A_\mu + \frac{\xi_\gamma}{2} A^2 + (\partial_\mu A) A_\mu
\]

- no longer gauge invariant, but still BRST invariant
BRST symmetry

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

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

• BRST operator:

\[ \hat{W} = \frac{\delta S}{\delta G^A_\mu} \frac{\delta}{\delta J_A^\mu} + \frac{\delta S}{\delta J_A^\mu} \frac{\delta}{\delta G^A_\mu} + \ldots \]

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 \(-1\):

\[ \mathcal{N} = \hat{W} \cdot \mathcal{F} \]

→ Joglekar, Lee (1976)

⇒ most general solution of Slavnov-Taylor identities
Nuisance operators

- building blocks for seed operators:
  \[ q_{L,R}, \bar{q}_{L,R}, G^A_{\mu}, A_\mu, \mathcal{M}, \mathcal{M}^\dagger, Q_{L,R}, \partial_\mu, \text{ghosts, BRST sources} \]

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

- cross-checked with Hilbert series
Operator basis

- mixing structure for \((O, N)\):

\[
Z = \begin{pmatrix}
Z_{OO} & Z_{ON} \\
0 & Z_{NN}
\end{pmatrix}
\]

- 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: $\theta$-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 $\alpha_{\text{QED}}$):
  - 12 gauge-invariant EOM operators, e.g.
    \[ \mathcal{N} = i(\bar{q}_E M^2 \gamma_5 q + \bar{q} M^2 \gamma_5 q_E), \quad q_E := (i\not{D} - M)q \]
  - 19 gauge-variant operators, e.g.
    \[ \mathcal{N} = i(\bar{q}_E \gamma_5 q + \bar{q} \gamma_5 q_E) G^\mu_a G^{\mu}_a \]
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Conclusions and outlook

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 $(\text{dim-5})^2$ 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
Conclusions and outlook

nEDM

- use constraining power of precision (n)EDM measurements
- problem at low energies are (huge) hadronic uncertainties
- use lattice QCD for matrix elements
  ⇒ 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**

<table>
<thead>
<tr>
<th>$\nu\nu + \text{h.c.}$</th>
<th>$(\nu\nu)X + \text{h.c.}$</th>
<th>$(\bar{LR})X + \text{h.c.}$</th>
<th>$X^3$</th>
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</thead>
<tbody>
<tr>
<td>$\mathcal{O}<em>\nu \left( \nu_L^T C \nu</em>{LR} \right)$</td>
<td>$\mathcal{O}<em>{\nu\gamma} \left( \nu_L^T C \sigma^{\mu\nu} \nu</em>{LR} \right) F_{\mu\nu}$</td>
<td>$\mathcal{O}<em>{\epsilon\gamma} \bar{\epsilon}</em>{Lp} \sigma^{\mu\nu} e_{Rr} F_{\mu\nu}$</td>
<td>$\mathcal{O}<em>G f^{ABC}</em>{\mu} G^A_{\nu} G^B_{\rho} G^C_{\mu}$</td>
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<tr>
<td>$\mathcal{O}_{\mu\gamma}$</td>
<td>$\bar{u}<em>{Lp} \sigma^{\mu\nu} u</em>{Rr} F_{\mu\nu}$</td>
<td>$\mathcal{O}<em>d \bar{d}</em>{Lp} \sigma^{\mu\nu} d_{Rr} F_{\mu\nu}$</td>
<td>$\mathcal{O}<em>G f^{ABC}</em>{\mu} \tilde{G}^A_{\nu} G^B_{\rho} G^C_{\mu}$</td>
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<tr>
<td>$\mathcal{O}_{\nu\gamma}$</td>
<td>$\bar{d}<em>{Lp} \sigma^{\mu\nu} d</em>{Rr} F_{\mu\nu}$</td>
<td>$\mathcal{O}<em>{dG} \bar{d}</em>{Lp} \sigma^{\mu\nu} T^A d_{Rr} G^A_{\mu\nu}$</td>
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<tr>
<td>$\mathcal{O}<em>{uG} \bar{u}</em>{Lp} \sigma^{\mu\nu} T^A u_{Rr} G^A_{\mu\nu}$</td>
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## LEFT basis

\[ \Delta L = 4 + \text{h.c.} \]

\[ \mathcal{O}_{\nu
\nu}^{S,LL} \mid (\nu_{L_p}^T C \nu_{L_r})(\nu_{L_s}^T C \nu_{L_t}) \]

<table>
<thead>
<tr>
<th>\Delta L = 2 + \text{h.c.}</th>
<th>\Delta B = \Delta L = 1 + \text{h.c.}</th>
<th>\Delta B = -\Delta L = 1 + \text{h.c.}</th>
</tr>
</thead>
</table>
| \( \mathcal{O}_{\nu
\nu}^{S,LL} \mid (\nu_{L_p}^T C \nu_{L_r})(\bar{e}_{Rs} e_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(u_{L_p}^{\alpha T} C d_{L_r}^\beta)(d_{L_s}^T C \nu_{L_t}) \) | \( \epsilon_{\alpha \beta \gamma}(d_{L_p}^{\alpha T} C u_{L_r}^\beta)(\bar{e}_{Rs} d_{Lt}) \) |
| \( \mathcal{O}_{\nu
\nu}^{T,LL} \mid (\nu_{L_p}^T C \sigma_{\mu \nu} \nu_{L_r})(\bar{e}_{Rs} \sigma_{\mu \nu} e_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(d_{L_p}^{\alpha T} C u_{L_r}^\beta)(u_{L_s}^T C e_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(u_{L_p}^{\alpha T} C d_{L_r}^\beta)(\bar{e}_{Rs} d_{Lt}) \) |
| \( \mathcal{O}_{\nu
\nu}^{S,LR} \mid (\nu_{L_p}^T C \nu_{L_r})(\bar{e}_{Rs} e_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(u_{L_p}^{\alpha T} C u_{L_r}^\beta)(d_{R_s}^T C e_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(d_{L_p}^{\alpha T} C d_{L_r}^\beta)(\bar{e}_{Rs} d_{Lt}) \) |
| \( \mathcal{O}_{\nu
\nu}^{S,RL} \mid (\nu_{L_p}^T C \nu_{L_r})(\bar{u}_{Rs} \sigma_{\mu \nu} u_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(u_{L_p}^{\alpha T} C u_{L_r}^\beta)(u_{L_t}^T C e_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(d_{L_p}^{\alpha T} C d_{L_r}^\beta)(\bar{e}_{Rs} d_{Lt}) \) |
| \( \mathcal{O}_{\nu
\nu}^{T,LL} \mid (\nu_{L_p}^T C \nu_{L_r})(\bar{u}_{Rs} \mu_{\nu} u_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(d_{L_p}^{\alpha T} C u_{L_r}^\beta)(u_{L_t}^T C e_{Lt}) \) | \( \epsilon_{\alpha \beta \gamma}(d_{L_p}^{\alpha T} C d_{L_r}^\beta)(\bar{e}_{Rs} d_{Lt}) \) |