EFT below the electroweak scale: running, matching, and hadronic effects

Peter Stoffer

Faculty of Physics, University of Vienna

in collaboration with E. Jenkins and A. Manohar: JHEP **03** (2018) 016, JHEP **01** (2018) 084,

with W. Dekens, E. Jenkins, and A. Manohar: JHEP **01** (2019) 088,

with W. Dekens: JHEP **10** (2019) 197

April 12, 2021

LHC EFT WG Meeting “Heavy flavour aspects in EFT fits”

universität wien

1 Introduction

2 EFT below the electroweak scale

3 Matching SMEFT to LEFT

4 Non-perturbative effects in $\mu \to e\gamma$

5 Summary

1 Introduction

2 EFT below the electroweak scale

3 Matching SMEFT to LEFT

4 Non-perturbative effects in $\mu \to e\gamma$

5 Summary

Effective field theories (EFTs)

- based on a **small set of assumptions**
- generic and systematic **quantum field theories**, can be used “stand-alone” for fits to experiments or in connection with a broad range of specific models
- work only with the **relevant particles** at a particular energy $\Rightarrow$ simplify calculations
- EFT parameters depend on energy scale
  $\Rightarrow$ **running & mixing**
- connect **different energy regimes** (renormalization group, avoid large logarithms)

1 Introduction

2 EFT below the electroweak scale

3 Matching SMEFT to LEFT

4 Non-perturbative effects in $\mu \to e\gamma$

5 Summary

EFT for new physics above the weak scale

"**Standard Model EFT**" (SMEFT) assumptions:

$\rightarrow$ Buchmüller, Wyler (1986)

- new physics **at high energies** $\Lambda \gg v \approx 246$ GeV
- underlying theory respects the **same symmetry principles** as the SM
- Higgs particle part of electroweak doublet (as in SM)
- dimensional power counting, expansion in v/Λ, p/Λ

EFT below the electroweak scale

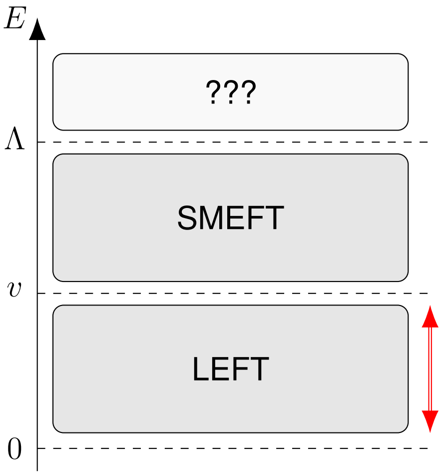
"**Low-energy EFT**" (LEFT):

- only **light SM particles** (no Higgs, weak bosons, or top quark)
- basically the old Fermi theory of weak interaction
- complete and systematic treatment up to dimension 6 recently worked out

  $\rightarrow$ Jenkins, Manohar, Stoffer, JHEP **01** (2018) 084, JHEP **03** (2018) 016
- operator basis now known up to dimension 9

  $\rightarrow$ Li et al. (2020), C. W. Murphy (2020)
- dimensional power counting, expansion in m/v, p/v

EFTs for new physics



- partial LEFT operator basis and running previously studied in detail
- first complete treatment up to dimension six:

  $\rightarrow$ Jenkins, Manohar, Stoffer (2018)

EFT below the electroweak scale

LEFT Lagrangian:

$$\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QED+QCD}} + \sum_i L_i \mathcal{O}_i + \ldots$$

Additional effective operators:

- dimension 3: Majorana-neutrino masses ($\Delta L = \pm 2$)
- dimension 5: $\Delta B = \Delta L = 0$ **dipole** operators for $\psi = u, d, e$ and $\Delta L = \pm 2$ neutrino-dipole operators
- dimension 6: CP-even and CP-odd **three-gluon** operators, as well as **four-fermion** operators

LEFT operators

→ Jenkins, Manohar, Stoffer, JHEP **03** (2018) 016

- 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

Power counting and RGE

→ Jenkins, Manohar, Stoffer, JHEP **01** (2018) 084

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

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

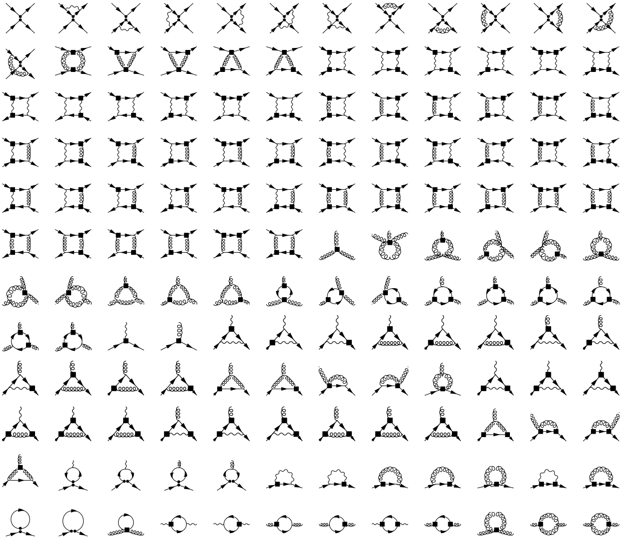
- up to dimension six:
  - single-operator insertions of dimension five and six
  - double-operator insertions of dimension five
- results have later been implemented in public code:

`wilson` → Aebischer et al. (2018)

`DsixTools` → Celis et al. (2017), Fuentes-Martin et al. (2020)

Full set of one-loop diagrams for LEFT running

→ Jenkins, Manohar, Stoffer, JHEP **01** (2018) 084



1 Introduction

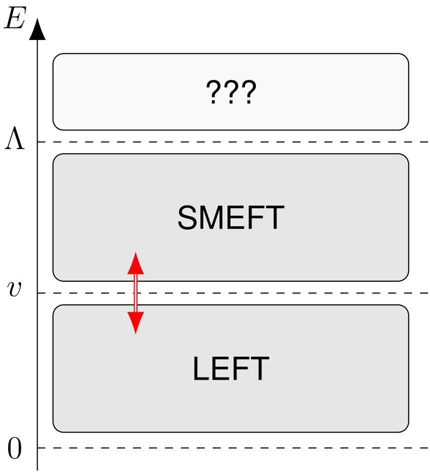
2 EFT below the electroweak scale

3 Matching SMEFT to LEFT

4 Non-perturbative effects in $\mu \to e\gamma$

5 Summary

Matching between the EFTs



- tree-level matching from SMEFT to LEFT

  → Jenkins, Manohar, Stoffer
  JHEP **03** (2018) 016

- complete one-loop matching

  → Dekens, Stoffer
  JHEP **10** (2019) 197

- leads to relations between LEFT operator coefficients

SMEFT in the broken phase

- Higgs in unitary gauge:

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

where

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

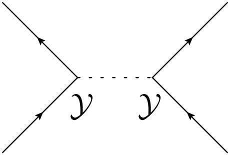
- **modifications from SM** due to dimension-six Higgs operators in SMEFT

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:



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

$\mathcal{Y}^2$ 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

One-loop matching

→ Dekens, Stoffer, JHEP **10** (2019) 197

- simplify matching calculation:

$$\text{tree}_{\text{LEFT}} + \text{loop}_{\text{LEFT}}\Big|_{\mu_W} = \text{tree}_{\text{SMEFT}} + \text{loop}_{\text{SMEFT}}\Big|_{\mu_W}$$

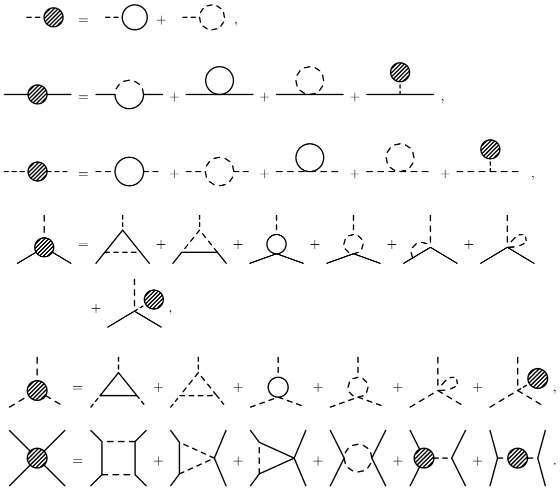
- **expand loops** in all low scales

$$\text{tree}_{\text{LEFT}} + \cancel{\text{loop}_{\text{LEFT}}^{\text{exp}}}\Big|_{\mu_W} = \text{tree}_{\text{SMEFT}} + \text{loop}_{\text{SMEFT}}^{\text{exp}}\Big|_{\mu_W}$$

- 754 SMEFT diagrams including finite parts

One-loop matching

→ Dekens, Stoffer, JHEP **10** (2019) 197



Gauge fixing

- using background-field gauge for SMEFT

  $\to$ Helset, Paraskevas, Trott (2018)

$$F \mapsto F + \hat{F}$$

- external fields and tree-level propagators: classical fields $\hat{F}$, unitary gauge
- loops: quantum fields F, R_ξ **gauge**
- no $\gamma - Z$ **mixing** at tree level or at one loop on shell
- no $\gamma - h$ **mixing**

The old γ_5 problem

- use **anticommuting** γ_5 whenever possible

  $\rightarrow$ Trueman (1996), Jegerlehner (2001)

- γ_5 in closed fermion loops problematic
- $\epsilon^{\mu\nu\lambda\sigma}$ in SMEFT vertices
- in general, **'t Hooft–Veltman** scheme generates spurious anomalies $\Rightarrow$ requires symmetry-restoring counterterms
- use **chiral vertices** and **check Ward identities** in critical cases

1 Introduction

2 EFT below the electroweak scale

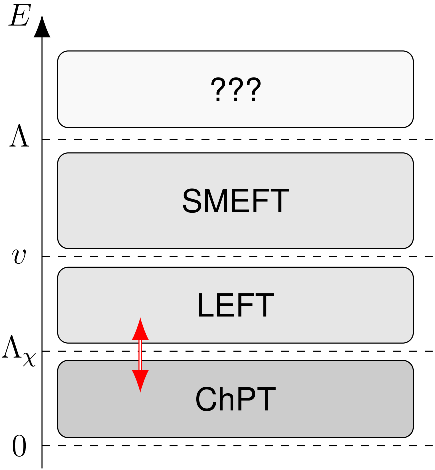
3 Matching SMEFT to LEFT

4 Non-perturbative effects in $\mu \to e\gamma$

5 Summary

Matching to Chiral Perturbation Theory (ChPT)

→ Dekens, Jenkins, Manohar, Stoffer, JHEP **01** (2019) 088



- at the hadronic scale, QCD is **non-perturbative**
- **ChPT** can be formulated including LEFT effects
- non-perturbative matching required, e.g. using lattice QCD simulations

Lepton-flavor violation: $\mu \to e\gamma$

$\to$ Dekens, Jenkins, Manohar, Stoffer, JHEP **01** (2019) 088

- **hadronic effects** can show up in a purely leptonic process
- LF violation due to many operators, e.g.

$$\mathcal{O}_{eq}^{S,RR} = (\bar{e}_{Lp} e_{Rr})(\bar{q}_{Ls} q_{Rt})$$
$$\mathcal{O}_{eq}^{V,LL} = (\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{q}_{Ls} \gamma_\mu q_{Lt})$$
$$\mathcal{O}_{eq}^{T,RR} = (\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{q}_{Ls} \sigma_{\mu\nu} q_{Rt})$$

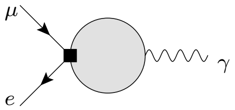
Lepton-flavor violation: $\mu \to e\gamma$

- matching of semileptonic operators to ChPT is standard: external scalar, vector, and tensor sources

  $\to$ Gasser, Leutwyler (1984), Catà, Mateu (2007)

- at lowest order in $\alpha_{\rm QED}$: $\langle\gamma(p,\epsilon)|S|0\rangle$ and $\langle\gamma(p,\epsilon)|V^\mu|0\rangle$ vanish due to Lorentz and gauge invariance

- **semileptonic tensor operators** contribute to $\mu \to e\gamma$:



- non-perturbative effects **not suppressed** by light quark masses

Lepton-flavor violation: $\mu \to e\gamma$

- constraints on SMEFT operators at the weak scale through matching SMEFT $\Rightarrow$ LEFT
- two competing effects:
  - **perturbative RGE** mixing of tensor operators into dipoles when running from $\mu = M_W$ to $\mu = 2\,\mathrm{GeV}$
  - **non-perturbative matching** effect
- $\mu \to e\gamma$ (MEG) gives **best limit** for strange-quark operator at the electroweak scale ($c_T = \mathcal{O}(1)$):

$$(c_T - 3.1) L^{T,RR}_{\substack{ed \\ e\mu ss}} < 2.8 \times 10^{-5}\,\mathrm{TeV}^{-2}$$

- $\mu \to e$ conversion in nuclei (SINDRUM II) gives stronger limits for up- and down-quark operators

1 Introduction

2 EFT below the electroweak scale

3 Matching SMEFT to LEFT

4 Non-perturbative effects in $\mu \to e\gamma$

5 Summary

LEFT

- we constructed the full LEFT **operator basis** up to dimension six
- complete **one-loop RGE**, including (dim-5)^2 effects
- **one-loop matching** to SMEFT at the weak scale
- unified framework to compute **leading-log** effects from the scale of New Physics down to low energies
- first step towards next-to-leading-log accuracy
- many interesting applications: LF violation, CP-violation (EDMs), flavor physics, connection with collider physics

$\mu \to e\gamma$

- contributions of semileptonic tensor operators: RGE effect and non-perturbative matching effect
- **non-perturbative effects** can lead to interesting enhancements and new constraints
- non-perturbative effect dominates for up- and down-quarks
- $\mu \to e\gamma$ gives strongest constraints on strange-quark operator (better than $\mu \to e$ conversion): $\Lambda_{\text{BSM}} \gtrsim 450\,\text{TeV}$
- analogous effect also present in $(g-2)_\mu$

$\to$ Aebischer, Dekens, Jenkins, Manohar, Sengupta, Stoffer: 2102.08954 [hep-ph]

Backup

LEFT basis

$\nu\nu + \text{h.c.}$		$(\nu\nu)X + \text{h.c.}$		$(\bar{L}R)X + \text{h.c.}$		X^3	
$\mathcal{O}_\nu$	$(\nu_{Lp}^T C \nu_{Lr})$	$\mathcal{O}_{\nu\gamma}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr}) F_{\mu\nu}$	$\mathcal{O}_{e\gamma}$	$\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr} F_{\mu\nu}$	$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
				$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp} \sigma^{\mu\nu} u_{Rr} F_{\mu\nu}$	$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
				$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp} \sigma^{\mu\nu} d_{Rr} F_{\mu\nu}$		
				$\mathcal{O}_{uG}$	$\bar{u}_{Lp} \sigma^{\mu\nu} T^A u_{Rr} G_{\mu\nu}^A$		
				$\mathcal{O}_{dG}$	$\bar{d}_{Lp} \sigma^{\mu\nu} T^A d_{Rr} G_{\mu\nu}^A$		

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

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

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

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

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