Compilation of low-energy constraints on 4-fermion operators in the SMEFT

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Introduction
Goal: put bounds on $D = 6$ SMEFT with arbitrary flavor structure (2499 operators).

Continuation of the work in:

- **Eifrati, Falkowski, Soreq 1503.07872** (LEP-1 $Z$-pole observables, constrain vertex corrections)
- **Falkowski, KM 1511.07434** (4-leptons operators)
- **González-Alonso, Martin Camalich 1605.07114** ($d/s \rightarrow u\ell\nu$ transitions)

Our focus is 2-leptons 2-quarks operators: $\ell\ell qq$ and $\nu\nu qq$ processes.
We consider the SMEFT Lagrangian:

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{v^2} O_i^{D=6} \quad (1) \]

where \( v = 246 \) GeV is extracted from \( G_F \).

We look at low-energy observables (non-LHC) from LEP (\( \sqrt{s} \sim 200 \) GeV) and other experiments, so we are well in the validity range of the EFT expansion where the linear term dominates.
Approximations

- We consider the terms linear in the $c_i$'s (interference term $\text{SM} \times O_i^{D=6}$): the likelihood is Gaussian.
- We consider only QCD running of the Wilson coefficients (for chirality-breaking operators).
- We work in the limit $V_{\text{CKM}} = 1$.
- We work in the massless fermions limit for collider data.
Experimental data and fit
LEP-I: Z-pole measurements, see 1503.07872.

LEP-2: \( e^+ e^- \rightarrow \ell^+ \ell^- \) total cross section and forward-backward asymmetry for muons and taus.
\( e^+ e^- \rightarrow e^+ e^- \) differential cross-section, see 1511.07434.

\( e^+ e^- \rightarrow q\bar{q} \): total cross-section only
\( e^+ e^- \rightarrow c\bar{c} \) or \( b\bar{b} \): total cross section and forward-backward asymmetry.

\( \sqrt{s} = 130 \) to 209 GeV.
Neutrino scattering experiments usually measure the ratio of neutral current to charged current events:

$$R_{\nu_i} = \frac{\sigma(\nu_i N \rightarrow \nu_i X)}{\sigma(\nu_i N \rightarrow \ell_i^- X)}$$

$$R_{\bar{\nu}_i} = \frac{\sigma(\bar{\nu}_i N \rightarrow \bar{\nu}_i X)}{\sigma(\bar{\nu}_i N \rightarrow \ell_i^+ X)}$$

constraining two combinations of neutrino to $u, d$ quark interaction term.

We use data from experiments with $\nu_\mu$ beams: CHARM (Z. Phys. C36 (1987) 611), CCFR (hep-ex/9701010) and CDHS (Z. Phys. C45 (1990) 361).
Atomic Parity Violation in the Cesium atom: measure of the weak charge of the $^{133}\text{Cs}$ atom. Large number of quarks and very precise measurement: most stringent 1-operator bounds.

The proton weak charge: QWEAK (1307.5275) with $e^- p \rightarrow e^- p$ polarization asymmetry.

Deep inelastic scattering $e^- D \rightarrow e^- D$: PVDIS (Nature 506 (2014) 7486) and SAMPLE (nucl-ex/0412054).

All together constrain 4 combinations of $eeqq$ operators.
Analysis of pion and kaon leptonic and semi-leptonic decays, hyperon decays and superallowed nuclear $\beta$ transitions in González-Alonso, Martin Camalich 1605.07114.

Very strong constraints on chirality-violating operators which are not probed by collider experiments

\[
[O_{lequ}]_{IIJJ} = (\overline{\ell}_i \overline{e}_j^c) \epsilon_{jk} (\overline{q}_j^k \overline{u}_j^c)
\]

\[
[O_{lequ}^{(3)}]_{IIJJ} = (\overline{\ell}_i \overline{\sigma}_{\mu\nu} \overline{e}_j^c) \epsilon_{jk} (\overline{q}_j^k \overline{\sigma}_{\mu\nu} \overline{u}_j^c)
\]

\[
[O_{ledq}]_{IIJJ} = (\overline{\ell}_i \overline{e}_j^c) \epsilon_{jk} (d_j^c q_j^k)
\]
Other measurements

- $\nu_e N$ scattering
- $\mu p$ scattering (polarization asymmetry)
- $\nu_\mu e$ scattering
- $\tau$ leptonic decay
- $\tau$ polarization at VENUS
- Neutrino trident production at CHARM
- $J/\psi$ and $\Upsilon$ leptonic decays
Fit and results

We get simulatenous constraints on 61 combinations of Wilson coefficients (21 vertex corrections, 15 LLLL and 25 LLQQ operators). Long way to go before 2499.

Important correlations, some directions are constrained at $10^{-4}$ level, others at 10% level. The full likelihood is given in the paper.

In flavor symmetric limit, all vertex corrections, LLLL and LLQQ operators are constrained (18 operators) at percent level.
Electron-quark four-fermion operators
### Table of operators

| Operator | Expression |
|----------|------------|
| $[O_{\ell q}]_{1II}$ | $\left(\bar{\ell}_1 \sigma_\mu \ell_1\right)\left(\bar{q}_I \sigma_\mu q_I\right)$ |
| $[O^{(3)}_{\ell q}]_{1II}$ | $\left(\bar{\ell}_1 \sigma_\mu \sigma_i \ell_1\right)\left(\bar{q}_I \sigma_\mu \sigma_i q_I\right)$ |
| $[O_{\ell u}]_{1II}$ | $\left(\bar{\ell}_1 \sigma_\mu \ell_1\right)\left(u^c_I \sigma_\mu \bar{u}^c_I\right)$ |
| $[O_{\ell d}]_{1II}$ | $\left(\bar{\ell}_1 \sigma_\mu \ell_1\right)\left(d^c_I \sigma_\mu \bar{d}^c_I\right)$ |
| $[O_{eq}]_{1II}$ | $\left(e^c_1 \sigma_\mu \bar{e}^c_1\right)\left(\bar{q}_I \sigma_\mu q_I\right)$ |
| $[O_{eu}]_{1II}$ | $\left(e^c_1 \sigma_\mu \bar{e}^c_1\right)\left(u^c_I \sigma_\mu \bar{u}^c_I\right)$ |
| $[O_{ed}]_{1II}$ | $\left(e^c_1 \sigma_\mu \bar{e}^c_1\right)\left(d^c_I \sigma_\mu \bar{d}^c_I\right)$ |

**Table**: The full set of flavor and chirality conserving 2-electrons 2-quarks operators in the $D=6$ EFT Lagrangian: 21 operators.
Number of constraints

We have 21 operators and 16 experimental constraints:

- 2 from $ee \rightarrow q\bar{q}$ from LEP
- 8 from $ee \rightarrow c\bar{c}$ and $ee \rightarrow b\bar{b}$ cross-section and FB asymmetry
- 4 from parity-violating $eeqq$ measurements
- 1 from $d \rightarrow u\ell\nu$ decays
- 1 from $\nu_e\nu_eqq$ scattering (very bad precision)

so 5 flat directions.

In practise 2 almost flat directions.
We have 5 flat directions which can be parametrized as follows:

- (F1) $[c_{\ell u}]_{1133}$, (F2) $[c_{eu}]_{1133}$, (F3) $[c_{\ell q}]_{1133} + [c^{(3)}_{\ell q}]_{1133}$: absence of $ee \to t\bar{t}$ process.
- (F4) One combination of 1122 coefficients: no $ee \to s\bar{s}$ measurement.
- (F5) One combination of 1111 coefficients: Parity-violating $eeqq$ measurements are insensitive to the vector-vector coupling of electron to quarks.

The situation is much worse for muon-quark operators!
Conclusion

We put together bounds from a wide range of 4-fermions experiments.

We get constraints on 61 combinations of Wilson coefficients: lots of unconstrained directions, especially involving second and third generations.

What can we add?

- Hadronic tau decays (see Cirigliano et al. 1809.01161).
- $c$ and $b$ mesons (semi-)leptonic decays: need to include the CKM matrix (see Descotes-Genon et al. 1812.08163).