Model independent constraints on four-leptons operators

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EFT hypothesis

New physics can be described by effective operators added to the Standard Model if:

- the new theory reduces at low energy to the Standard Model
- the energy scale of new physics Λ is high compared to the electroweak scale v (there are no undiscovered light particles)

If we assume baryon and lepton number conservation, the leading corrections come from dimension-six operators :

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) \tag{1}$$

EFT hypothesis

$\mathcal{L}_6$ operators depend only on Standard Model fields and assumed symmetries. In this work, we assume:

- the baryon and lepton number are conserved
- no flavor symmetry is imposed

This makes 2499 independent (real) operators O_i ; we use a set of operators called the *Warsaw basis* .

We use the notation :

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{v^2} \sum_i c_i O_i \tag{2}$$

$$c_i = 0.01 \Leftrightarrow \frac{\Lambda}{\sqrt{g_i}} = \frac{v}{\sqrt{c_i}} = 2.5\,\mathrm{TeV} \tag{3}$$

Four-leptons operators

We focus on the four-leptons operators ; in the Warsaw basis, they fall into three classes :

$$\begin{aligned} O_{\ell\ell} &= (\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell) \\ O_{ee} &= (\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e) \\ O_{\ell e} &= (\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e) \end{aligned} \tag{4}$$

All other structures (scalar, tensor) can be expressed with these operators via Fiertz transformations.
Counting the flavour indices, there are in total **27 flavour-conserving operators** and more flavour-violating operators.

Four-leptons operators

More explicitly, the operators conserving flavour can be rearranged into the following table :

One flavor ($i = 1 \ldots 3$)	Two flavors ($i < j = 1 \ldots 3$)
$[O_{\ell\ell}]_{iiii} = \frac{1}{2}(\bar{\ell}_i\gamma_\mu\ell_i)(\bar{\ell}_i\gamma^\mu\ell_i)$	$[O_{\ell\ell}]_{iijj} = (\bar{\ell}_i\gamma_\mu\ell_i)(\bar{\ell}_j\gamma^\mu\ell_j)$
	$[O_{\ell\ell}]_{ijji} = (\bar{\ell}_i\gamma_\mu\ell_j)(\bar{\ell}_j\gamma^\mu\ell_i)$
$[O_{\ell e}]_{iiii} = (\bar{\ell}_i\gamma_\mu\ell_i)(\bar{e}_i\gamma^\mu e_i)$	$[O_{\ell e}]_{iijj} = (\bar{\ell}_i\gamma_\mu\ell_i)(\bar{e}_j\gamma^\mu e_j)$
	$[O_{\ell e}]_{jjii} = (\bar{\ell}_j\gamma_\mu\ell_j)(\bar{e}_i\gamma^\mu e_i)$
	$[O_{\ell e}]_{ijji} = (\bar{\ell}_i\gamma_\mu\ell_j)(\bar{e}_j\gamma^\mu e_i)$
$[O_{ee}]_{iiii} = \frac{1}{2}(\bar{e}_i\gamma_\mu e_i)(\bar{e}_i\gamma^\mu e_i)$	$[O_{ee}]_{iijj} = (\bar{e}_i\gamma_\mu e_i)(\bar{e}_j\gamma^\mu e_j)$

Table: The full set of lepton flavor conserving 4-lepton operators in the D=6 EFT Lagrangian.

Objective

Our objective is to constrain as many four-leptons operator as possible using experimental results without assuming any flavour structure.

We will use data from:

- LEP-2 lepton pair production : ALEPH, DELPHI, L3, OPAL, SLD collaborations 1302.3415
- Neutrino scattering on electrons : CHARM-II collaboration, Phys. Lett. B335 (1994) 246-252
- Moller scattering : SLAC E158 collaboration hep-ex/0504049
- Muon and Tau decays

Vertex corrections

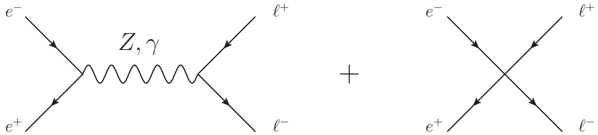
These experiments are sensitive not only to four-leptons operators but also to *vertex corrections* which correct the couplings of the Z and W boson to leptons.

These vertex corrections can be very precisely probed by LEP-1 experimental data taken at the Z-pole, see Efrati, Falkowski, Soreq, 1503.07872.

In the final fit, we include the chi-square function of the above mentionned work.

Method

Assuming that the dimension-six operators are small, the leading correction is given by the interference term between the tree-level SM diagram and the four-leptons interaction:



We look at the difference between experimental data and precision SM computations and fit it to the correction induced by dimension-six operators leaving all Wilson coefficients free.

LEP-2 Data

LEP-2 data include, at energies above the Z-pole:

$e^+e^- \to e^+e^-$

- Differential cross-section
- Corrections depend on the Wilson coefficients $[c_{\ell\ell}]_{1111}$, $[c_{\ell e}]_{1111}$ and $[c_{ee}]_{1111}$.

$e^+e^- \to \mu^+\mu^-$

- Total cross-section and forward backward asymmetry
- Corrections depend on the combinations $[c_{\ell\ell}]_{1122} + [c_{\ell\ell}]_{1221}$, $[c_{\ell e}]_{1122} + [c_{\ell e}]_{2211}$ and $[c_{ee}]_{1122}$.

$e^+e^- \to \tau^+\tau^-$ similar to the muon case.

Correction induced by four-leptons operators

In the muon case, the correction induced by four-leptons operators in the cross-section is:

$$
\begin{aligned}
\delta\sigma &= \frac{1}{24\pi v^2}\left\{e^2\left([c_{\ell\ell}]+[c_{ee}]+[c_{\ell e}]\right)\right. \\
&+ \left.\frac{s}{s-m_Z^2}\left[g_L^2[c_{\ell\ell}]+g_R^2[c_{ee}]+g_L g_R[c_{\ell e}]\right]\right\} \\
\delta\sigma_{FB} &= \frac{1}{32\pi v^2}\left\{e^2\left([c_{\ell\ell}]+[c_{ee}]-[c_{\ell e}]\right)\right. \\
&+ \left.\frac{s}{s-m_Z^2}\left[(g_L^2[c_{\ell\ell}]+g_R^2[c_{ee}]-g_L g_R[c_{\ell e}]\right]\right\}
\end{aligned}
$$

Fit to LEP-2 data

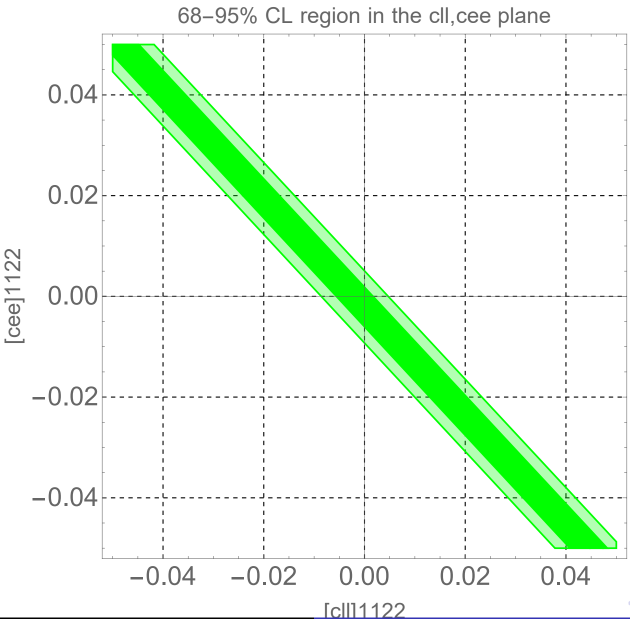
If we fit the three Wilson coefficients to LEP-2 data only, here are the results:

Best fit and errors

	Electron	Muon	Tau
$c_{\ell\ell}$	-0.71 ± 0.79	1.06 ± 1.26	1.4 ± 1.7
$c_{\ell e}$	$(-3.7 \pm 2.7) \cdot 10^{-3}$	$(1.5 \pm 5) \cdot 10^{-3}$	$(-5.6 \pm 6.4) \cdot 10^{-3}$
c_{ee}	0.74 ± 0.80	-1.14 ± 1.36	1.55 ± 1.82

In each column there is a **strong correlation** between $c_{\ell\ell}$ and c_{ee}, there are **two** constraints per sector.

Fit to LEP-2 data



How to lift the degeneracy in the muon sector ?

We need more experiments to lift the degeneracy of LEP-2 data.

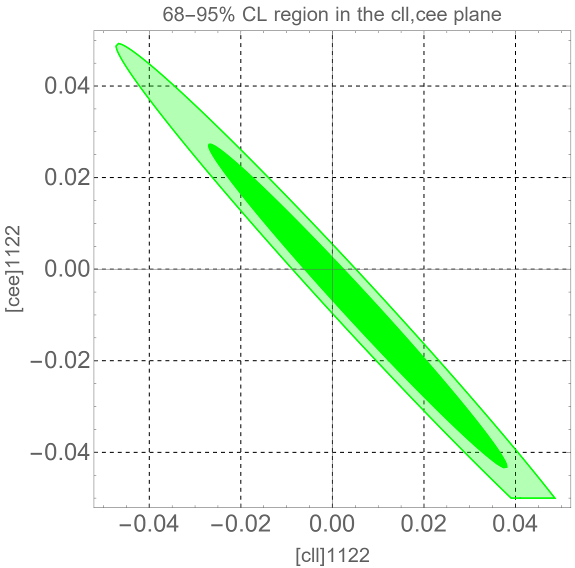
In the muon sector we use:

- Muon neutrino scattering on electrons from CHARM : $\nu_\mu e^- \to \nu_\mu e^-$ and $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ which is affected by $c_{\ell\ell}$ and $c_{\ell e}$ only.
- LEP-1 pole measurements which constrains $[c_{\ell\ell}]_{1221}$.

In the tau sector:

- Tau decay to electron

Fit to all muon data



Numerical results

In the muon sector, all operators can be separately constrained, but only at the percent level.

$$\begin{pmatrix} [c_{\ell\ell}]_{1122} \\ [c_{\ell\ell}]_{1221} \\ [c_{\ell e}]_{1122} \\ [c_{\ell e}]_{2211} \\ [c_{ee}]_{1122} \end{pmatrix} = \begin{pmatrix} 0.6 \pm 2.2 \\ -4.9 \pm 1.6 \\ -0.4 \pm 2.2 \\ 0.5 \pm 2.2 \\ 4.3 \pm 2.9 \end{pmatrix} \times 10^{-2} \tag{5}$$

E158 measurements

SLAC E158 measures $\sin^2\theta_W^{eff}$ from parity violating Moller scattering.

$$\sin^2\theta_W^{exp} = 0.2397 \pm 0.0013 \tag{6}$$

Whereas SM calculations predict

$$\sin^2\theta_W^{th} = 0.2381 \pm 0.0006 \tag{7}$$

The presence of four-leptons operators can be interpreted as a shift in $\sin^2\theta_W^{eff}$ given by:

$$\delta\sin^2\theta_W^{eff} = -\frac{1}{4}([c_{ee}]_{1111} - [c_{\ell\ell}]_{1111}) \tag{8}$$

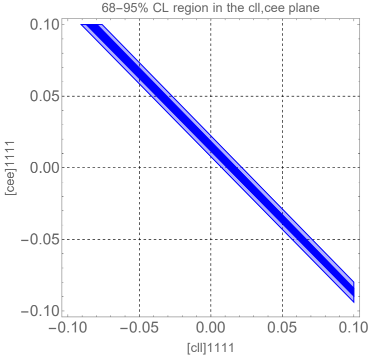
This translates to:

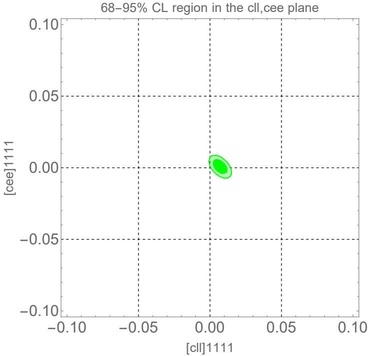
$$[c_{ee}]_{1111} - [c_{\ell\ell}]_{1111} = -0.0064 \pm 0.0053 \tag{9}$$

Numerical results

In the electron sector, all operators are constrained at a few per-mille level:

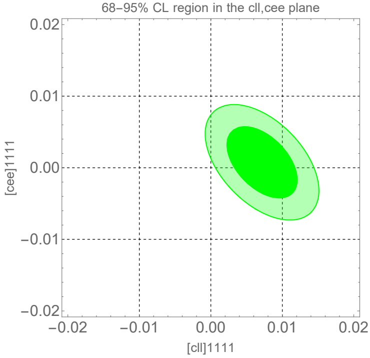
$$\begin{pmatrix} [c_{\ell\ell}]_{1111} \\ [c_{\ell e}]_{1111} \\ [c_{ee}]_{1111} \end{pmatrix} = \begin{pmatrix} 9.3 \pm 3.8 \\ -2.3 \pm 2.2 \\ 2.9 \pm 3.9 \end{pmatrix} \times 10^{-3} \tag{10}$$

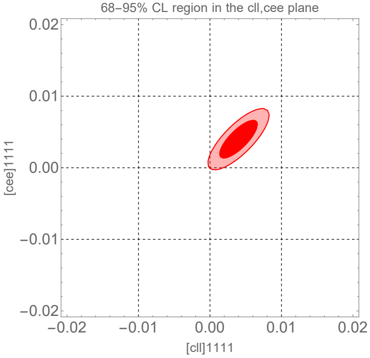




Assuming precision measurement of $\sin^2\theta_W$ at MOLLER with a precision of 0.1% and SM prediction equally precise:

$$\begin{pmatrix} [c_{\ell\ell}]_{1111} \\ [c_{\ell e}]_{1111} \\ [c_{ee}]_{1111} \end{pmatrix} = \begin{pmatrix} 6 \pm 2.7 \\ -2.3 \pm 2.2 \\ 6 \pm 2.7 \end{pmatrix} \times 10^{-3} \tag{11}$$





Conclusion 1

- EFT is a model-independent approach to study BSM physics, however the number of dimension-six operators is huge
- We derive bounds on 16 four-leptons operators
- There is an important complementarity between collider data and parity-violating measurements
- Most operators involving e are well constrained but we have nothing on 4μ, 4τ, $2\mu 2\tau$ operators

Conclusion 2

- We are working on a similar analysis for two-quarks two-leptons operators
- Collider data includes $ee \to \bar{q}q$ at LEP and Drell Yan $pp \to \ell\ell$ at LHC
- We expect parity-violating measurements of Qweak, PVDIS to play the same role
- We hope to update our analysis with new precision measurements of parity-violating processes.