Electroweak chiral perturbation theory with fermions

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Joaquín Santos Blasco

IFIC, Instituto de Física Corpuscular
UV, Universitat de València

In collaboration with:
A. **Pich** (IFIC, Valencia, Spain)
I. **Rosell** (CEU, Valencia, Spain)
J.J. **Sanz-Cillero** (UAM, Madrid, Spain)

Motivation

- The SM provides an extremely successful description of strong and weak interactions.
- $SU(2)_L \otimes U(1)_Y \to U(1)_{QED} \Rightarrow W$ and Z bosons become massive $\Rightarrow$ Higgs physics.
- What if this new particle is not the Standard Higgs boson? Scalar resonance?
  $\Rightarrow$ We should look alterative mechanisms for mass generation.
- Strongly coupled models $\Rightarrow$ Similar to Chiral Symmetry breaking in QCD
  $\Rightarrow$ Resonance theory.

Constraining the theory

Let's consider a low-energy effective theory containing the SM gauge bosons coupled to the EW Goldstones, one light scalar state S_1 (the Higgs) and the lightest axial and vector resonances.

$$
\begin{aligned}
\mathcal{L} &= \frac{v^2}{4}\langle u^\mu u_\nu \rangle \left(1 + \frac{2\kappa_W}{v} S_1\right) \\
&+ \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu} \rangle \quad + \quad \frac{i G_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu] \rangle \\
&+ \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu} \rangle \quad + \quad \sqrt{2}\lambda_1^{SA}\,\partial_\mu S_1 \langle A^{\mu\nu} u_\nu \rangle \,.
\end{aligned}
$$

- We have 7 resonance parameters $\Rightarrow$ Importance of short-distance information.
- In contrast to QCD, the underlying theory is ignored.
- Weimberg sum-rules $\Rightarrow$ High energy constrains.
- Oblique EW observables $\Rightarrow$ Phenomenological constrains.

Matching with EW effective theory

2 strongly coupled Lagrangians for 2 energy regions.

- Resonance theory at high energies (with resonances)
- EW effective theory at low energies (without resonances)

Matching these 2 theories ⇒ Determination of the Low Energy Constants (LECs)

LECs contain information of the heavier states.

This program works in QCD ⇒ Estimation of the LECs (Chiral Perturbation Theory) by using Resonance Chiral Theory.

As preliminary example, the purely bosonic Lagrangian

The purely bosonic Lagrangian

At high energies:

$$\begin{aligned}
\mathcal{L}_S &= \frac{c_{d_1}}{\sqrt{2}} S_1 \langle\, u_\mu u^\mu \,\rangle\,, \\
\mathcal{L}_P &= 0\,, \\
\mathcal{L}_V &= \frac{F_V}{2\sqrt{2}} \langle\, V_{\mu\nu} f_+^{\mu\nu} \,\rangle \quad + \quad \frac{iG_V}{2\sqrt{2}} \langle\, V_{\mu\nu} [u^\mu, u^\nu] \,\rangle \quad + \quad \frac{\widetilde{F}_V}{2\sqrt{2}} \langle\, V_{\mu\nu} f_-^{\mu\nu} \,\rangle\,, \\
\mathcal{L}_A &= \frac{F_A}{2\sqrt{2}} \langle\, A_{\mu\nu} f_-^{\mu\nu} \,\rangle \quad + \quad \frac{\widetilde{F}_A}{2\sqrt{2}} \langle\, A_{\mu\nu} f_+^{\mu\nu} \,\rangle \quad - \quad \frac{i\widetilde{G}_V}{2\sqrt{2}} \langle\, A_{\mu\nu} [u^\mu, u^\nu] \,\rangle\,,
\end{aligned}$$

At low energies:

$$\begin{aligned}
\mathcal{L}_4 \supset\; & \frac{1}{4} a_1 \langle\, f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu} \,\rangle \\
&+ \frac{i}{2}(a_2 - a_3) \langle\, f_+^{\mu\nu} [u_\mu, u_\nu] \,\rangle \quad + \quad \frac{i}{2}(a_2 + a_3) \langle\, f_-^{\mu\nu} [u_\mu, u_\nu] \,\rangle \\
&+ a_4 \langle\, u_\mu u_\nu \,\rangle \langle\, u^\mu u^\nu \,\rangle \quad + \quad a_5 \langle\, u_\mu u^\mu \,\rangle^2 \\
&+ \frac{1}{2} H_1 \langle\, f_+^{\mu\nu} f_{+\,\mu\nu} \quad + \quad f_-^{\mu\nu} f_{-\,\mu\nu} \,\rangle \quad + \quad \widetilde{H}_1 \langle\, f_+^{\mu\nu} f_{-\,\mu\nu} \,\rangle\,.
\end{aligned}$$

Matching

$$
\begin{aligned}
a_1 &= -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2} + \frac{\widetilde{F}_V^2}{4M_V^2} - \frac{\widetilde{F}_A^2}{4M_A^2}, \\
a_2 &= -\frac{F_V G_V}{4M_V^2} - \frac{\widetilde{F}_V G_V}{4M_V^2} - \frac{F_A \widetilde{G}_A}{4M_A^2} - \frac{\widetilde{F}_A \widetilde{G}_A}{4M_A^2}, \\
a_3 &= \frac{F_V G_V}{4M_V^2} - \frac{\widetilde{F}_V G_V}{4M_V^2} - \frac{F_A \widetilde{G}_A}{4M_A^2} + \frac{\widetilde{F}_A \widetilde{G}_A}{4M_A^2}, \\
a_4 &= \frac{G_V^2}{4M_V^2} + \frac{\widetilde{G}_A^2}{4M_A^2}, \\
a_5 &= \frac{c_{d1}^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} - \frac{\widetilde{G}_A^2}{4M_A^2}, \\
H_1 &= -\frac{F_V^2}{8M_V^2} - \frac{F_A^2}{8M_A^2} - \frac{\widetilde{F}_V^2}{8M_V^2} - \frac{\widetilde{F}_A^2}{8M_A^2}, \\
\widetilde{H}_1 &= -\frac{F_V \widetilde{F}_V}{4M_V^2} - \frac{F_A \widetilde{F}_A}{4M_A^2}.
\end{aligned}
$$

Next step: short distance constrains + fermionic operators