The Impact of Resonances in the Electroweak Effective Lagrangian

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OUTLINE

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4) Summary

1. Motivation

i) The Standard Model (SM) provides an extremely succesful description of the electroweak and strong interactions.

ii) A key feature is the particular mechanism adopted to break the electroweak gauge symmetry to the electroweak subgroup, $SU(2)_L \times U(1)_Y \to U(1)_{QED}$, so that the W and Z bosons become massive. The LHC discovered a new particle around 125 GeV*. → **Higgs Physics**

iii) What if this new particle is not a standard Higgs boson? Or a scalar resonance? We should look for alternative mechanisms of mass generation. → **Strongly Coupled Scenarios**

iv) Strongly-coupled models: usually they do contain resonances. Similar to Chiral Symmetry Breaking in QCD. → **Resonance Theory**

v) They should fulfilled the existing phenomenological tests. → **Oblique Electroweak Observables****

vi) They can be used to estimate the Low Energy Couplings (LECs) of the Electroweak Effective Theory → **Estimation of the LECs**

* CMS and ATLAS Collaborations.

** Peskin and Takeuchi '92.

Similarities to Chiral Symmetry Breaking in QCD

i) Neglecting the g' coupling, the Lagrangian is invariant under global $SU(2)_L$ x $SU(2)_R$ transformations. The Electroweak Symmetry Breaking (EWSB) turns out to be $SU(2)_L$ x $SU(2)_R$ ➔ $SU(2)_{L+R}$ (custodial symmetry).

ii) Absolutely similar to the Chiral Symmetry Breaking (ChSB) occuring in QCD. So the same pion Lagrangian describes the Goldstone boson dynamics associated with the EWSB, being replaced f_π by $v=1/\sqrt{(2G_F)}=246$ GeV. Similar to Chiral Perturbation Theory (ChPT)*^.

$$\Delta\mathcal{L}^{(2)}_{\rm ChPT} = \frac{f_\pi^2}{4}\langle u_\mu u^\mu\rangle \quad \rightarrow \quad \Delta\mathcal{L}^{(2)}_{\rm EW} = \frac{v^2}{4}\langle u_\mu u^\mu\rangle$$

iii) We can introduce the resonance fields needed in strongly-coupled models in a similar way as in ChPT: Resonance Chiral Theory (RChT)**.

✓ Note the implications of a naïve rescaling from QCD to EW:

$$\begin{cases} f_\pi = 0.090\,\text{GeV} & \longrightarrow \quad v = 0.246\,\text{TeV} \\ M_\rho = 0.770\,\text{GeV} & \longrightarrow \quad M_V = 2.1\,\text{TeV} \\ M_{a1} = 1.260\,\text{GeV} & \longrightarrow \quad M_A = 3.4\,\text{TeV} \end{cases}$$

iv) The estimations of the S and T parameters in strongly-coupled EW models are similar to the determination of L_{10} and $f_{\pi+}^2$ - $f_{\pi0}^2$ in ChPT***.

v) The determination of the Electroweak LECs is similar to the ChPT case**.

* Weinberg '79
* Gasser and Leutwyler '84 '85
* Bijnens et al. '99 '00

^Dobado, Espriu and Herrero '91
^Espriu and Herrero '92
^Herrero and Ruiz-Morales '94

**Ecker et al. '89
** Cirigliano et al. '06

*** Pich, IR and Sanz-Cillero '08.

2. First Step:

Constraining the Resonance Theory
from the Phenomenology

2.1. Oblique Electroweak Observables

✓ Universal oblique corrections via the EW boson self-energies (transverse in the Landau gauge)

$$\mathcal{L}_{\rm v.p.} \doteq -\frac{1}{2} W^3_\mu \, \Pi^{\mu\nu}_{33}(q^2) W^3_\nu - \frac{1}{2} B_\mu \, \Pi^{\mu\nu}_{00}(q^2) B_\nu - W^3_\mu \, \Pi^{\mu\nu}_{30}(q^2) B_\nu - W^+_\mu \, \Pi^{\mu\nu}_{WW}(q^2) W^-_\nu$$

✓ S parameter*: new physics in the difference between the Z self-energies at $Q^2=M_Z^2$ and $Q^2=0$.

$$e_3 \;=\; \frac{g}{g'}\, \widetilde{\Pi}_{30}(0)\,, \qquad \Pi_{30}(q^2) \;=\; q^2\, \widetilde{\Pi}_{30}(q^2) \,+\, \frac{g^2 \tan\theta_W}{4}\, v^2\,, \qquad S = \frac{16\pi}{g^2}\, \left(e_3 - e_3^{\rm SM}\right).$$

✓ T parameter*: custodial symmetry breaking

$$e_1 \;=\; \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{M_W^2} \;\stackrel{**}{=}\; \frac{Z^{(+)}}{Z^{(-)}} - 1 \qquad\qquad T \;=\; \frac{4\pi}{g'^2 \cos^2\theta_W}\, \left(e_1 - e_1^{\rm SM}\right)$$

✓ We follow the useful dispersive representation introduced by Peskin and Takeuchi* for S and a dispersion relation for T (checked for the lowest cuts):

$$S \;=\; \frac{16\pi}{g^2 \tan\theta_W} \int_0^\infty \frac{{\rm d}t}{t} \left(\rho_S(t) - \rho_S(t)^{\rm SM} \right)$$

$$T \;=\; \frac{16\pi}{g'^2 \cos^2\theta_W} \int_0^\infty \frac{{\rm d}t}{t^2} \left(\rho_T(t) - \rho_T(t)^{\rm SM} \right)$$

- ✓ $\rho_S(t)$ and $\rho_T(t)$ are the sectral functions of the W^3B and of the difference of the neutral and charged Goldstone boson self-energies, respectively.
- ✓ They need to be well-behaved at short-distances to get the convergence of the integral.
- ✓ S and T parameters are defined for a reference value for the SM Higgs mass.

* Peskin and Takeuchi '92.
** Barbieri et al. '93

2.2. The Calculation

i) The Lagrangian

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

$\kappa_W=\kappa_Z=a=\omega=1$ recovers the SM vertex

$$\mathcal{L} = \frac{v^2}{4}\langle u_\mu u^\mu\rangle \left(1+\frac{2\,\kappa_W}{v}\,S_1\right)$$

← π and S_1 sector

$$+\frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{i\,G_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu,u^\nu]\rangle$$

← π and V sector

$$+\frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle + \sqrt{2}\,\lambda_1^{SA}\,\partial_\mu S_1\,\langle A^{\mu\nu} u_\nu\rangle$$

← π, S_1 and A sector

Seven resonance parameters: κ_W, F_V, G_V, F_A, λ_1^{SA}, M_V and M_A. → The high-energy constraints are fundamental.

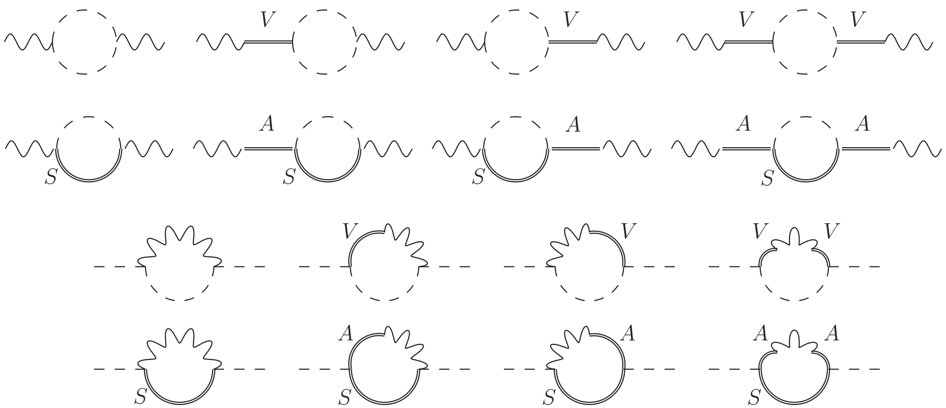
ii) At leading-order (LO)*

→ $$S_{\rm LO} = 4\pi\left(\frac{F_V^2}{M_V^2}-\frac{F_A^2}{M_A^2}\right)$$

→ $$T_{\rm LO} = 0$$

* Peskin and Takeuchi '92.

iii) At next-to-leading order (NLO)*



✓ Dispersive relations

✓ Only lightest two-particles cuts have been considered, since higher cuts are supposed to be suppressed**.

iv) High-energy constraints

- ✓ We have seven resonance parameters: importance of short-distance information.
- ✓ In contrast to QCD, the underlying theory is ignored
- ✓ Weinberg Sum-Rules (WSR)***:

$$\Pi_{30}(s) = \frac{g^2 \tan\theta_W}{4}\, s\, [\Pi_{VV}(s) - \Pi_{AA}(s)] \left\{ \begin{array}{lcl} \displaystyle\frac{1}{\pi}\int_0^\infty \mathrm{d}t\, [\mathrm{Im}\Pi_{VV}(t) - \mathrm{Im}\Pi_{AA}(t)] & = & v^2 \\ \displaystyle\frac{1}{\pi}\int_0^\infty \mathrm{d}t\, t\, [\mathrm{Im}\Pi_{VV}(t) - \mathrm{Im}\Pi_{AA}(t)] & = & 0 \end{array} \right.$$

- ✓ We have 7 resonance parameters and up to 5 constraints:
  - ✓ With both, the 1st and the 2nd WSR: κ_W and M_V as free parameters
  - ✓ With only the 1st WSR: κ_W, M_V and M_A as free parameters

* Barbieri et al.'08
* Cata and Kamenik '08
* Orgogozo and Rynchov '11 '12

** Pich, IR and Sanz-Cillero '12

*** Weinberg '67
*** Bernard et al. '75.

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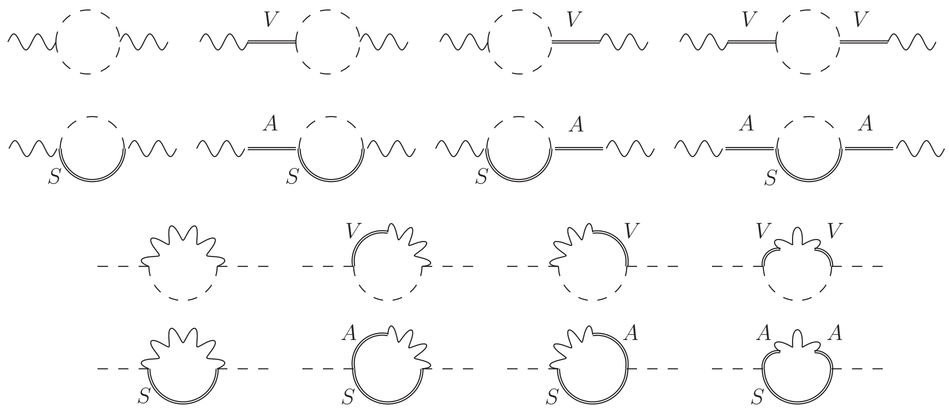

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iv) High-energy constraints

- ✓ We have seven resonance parameters: importance of short-distance information.
- ✓ In contrast to QCD, the underlying theory is ignored
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1st WSR at LO: $F_V^2\, M_V^2 \;-\; F_A^2\, M_A^2 \;=\; 0$

1st WSR at NLO (= VFF^ and AFF^^): $F_V G_V = v^2$, $F_A \lambda_1^{SA} = \kappa_W v$

2nd WSR at LO: $F_V^2 \;-\; F_A^2 \;=\; v^2$

2nd WSR at NLO: $\kappa_W \;=\; \frac{M_V^2}{M_A^2}$

- ✓ We have 7 resonance parameters and up to 5 constraints:
  - ✓ With both, the 1st and the 2nd WSR: κ_W and M_V as free parameters
  - ✓ With only the 1st WSR: κ_W, M_V and M_A as free parameters

* Barbieri et al.'08
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* Orgogozo and Rynchov '11 '12

** Pich, IR and Sanz-Cillero '12

*** Weinberg '67
*** Bernard et al. '75.

^ Ecker et al. '89

^^Pich, IR and Sanz-Cillero '08

2.3. Phenomenology

S = 0.03 ± 0.10 * (M_H=0.126 TeV)
T = 0.05 ± 0.12 * (M_H=0.126 TeV)

i) LO results

i.i) 1st and 2nd WSRs**

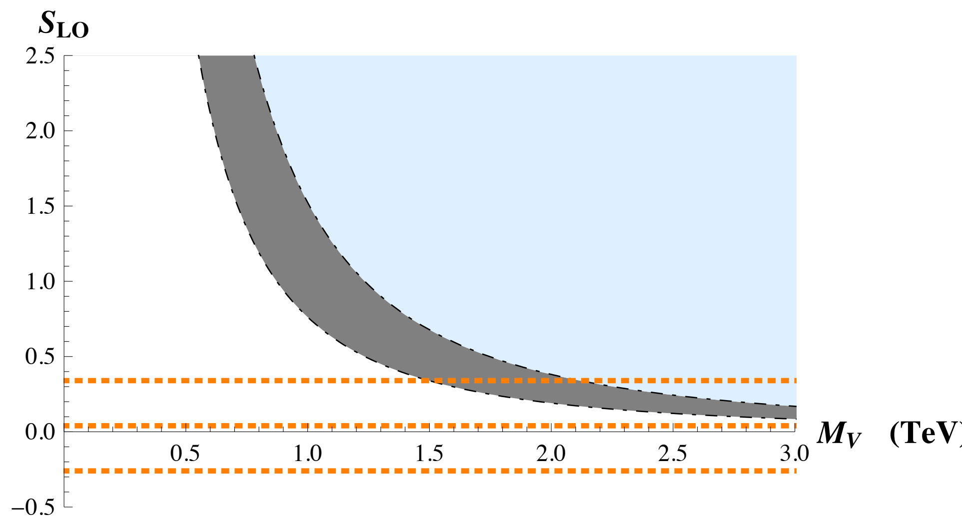
$$S_{\rm LO} = \frac{4\pi v^2}{M_V^2}\left(1+\frac{M_V^2}{M_A^2}\right)$$

$$\frac{4\pi v^2}{M_V^2} < S_{\rm LO} < \frac{8\pi v^2}{M_V^2}$$

i.ii) Only 1st WSR***

$$S_{\rm LO} = 4\pi\left\{\frac{v^2}{M_V^2} + F_A^2\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)\right\}$$

$$S_{\rm LO} > \frac{4\pi v^2}{M_V^2}$$



At LO $M_A > M_V > 1.5$ TeV at 95% CL

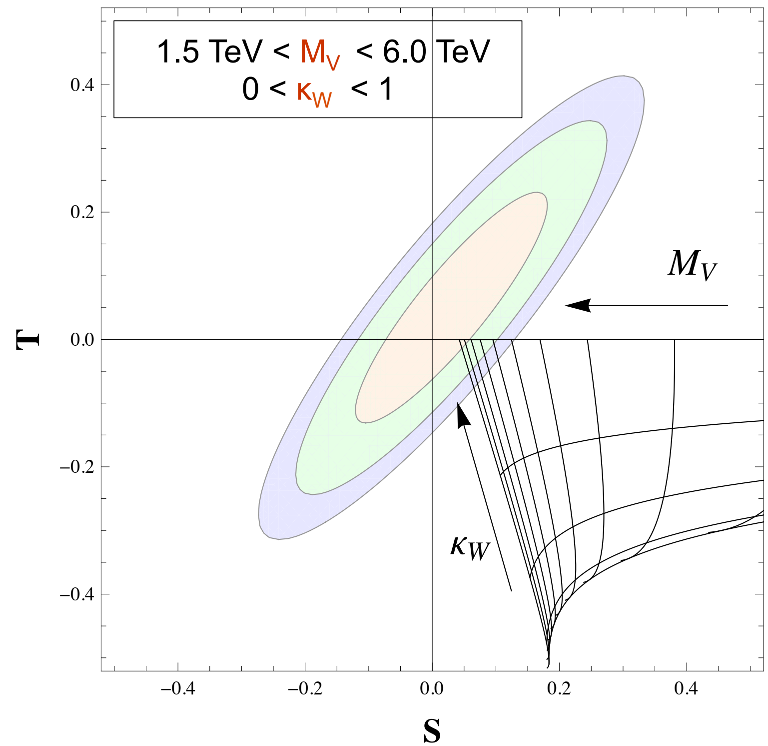
* Gfitter
* LEP EWWG
* Zfitter

** Peskin and Takeuchi ’92

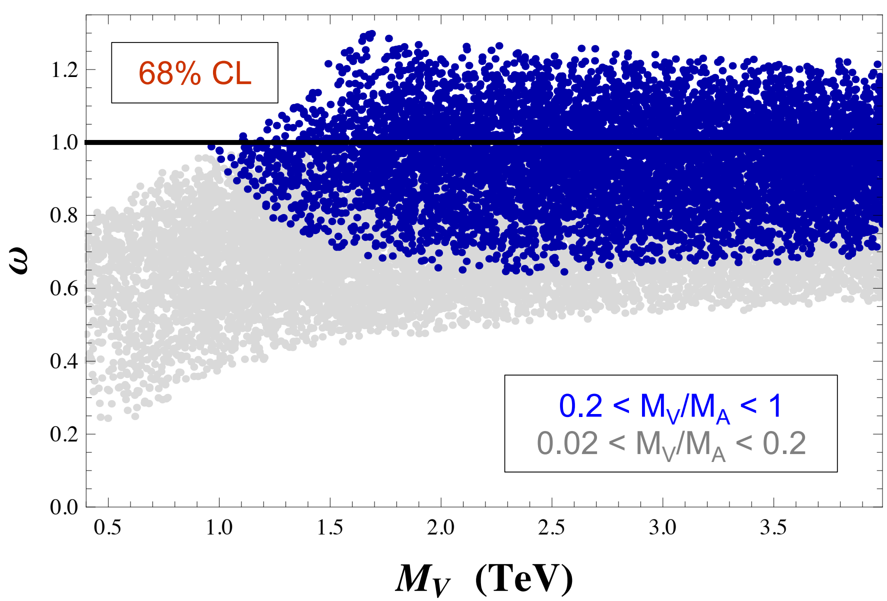
*** Pich, IR and Sanz-Cillero ’12

ii) NLO results: 1st and 2nd WSRs*

$1 > \kappa_W > 0.94$
$M_A \approx M_V > 4$ TeV
(95%CL)



iii) NLO results: 1st WSR and $M_V < M_A$*



Similar conclusions, but softened

- ✓ A moderate resonance-mass splitting implies $\kappa_W \approx 1$.
- ✓ $M_V < 1$ TeV implies large resonance-mass splitting.
- ✓ In any scenario $M_A > 1.5$ TeV at 68% CL.

* Pich, IR and Sanz-Cillero '13 '14

3. Second Step:

Constraining the Electroweak Effective Theory from the Resonance Theory

3.1. Matching the theories*

- ✓ Once we have constrained the Resonance Theory by using short-distance constraints and the Phenomenology, we want to use it to determine the Low-Energy Constants (LECs).

- ✓ Two strongly coupled Lagrangians for two energy regions:

  - ✓ Electroweak Effective Theory at low energies* (without resonances)
  - ✓ Resonance Theory at high energies** (with resonances)

- ✓ The LECs contain information from heavier states.

- ✓ Steps:

  1. Building the resonance Lagrangian
  2. Matching the two effective theories
  3. Requiring a good short-distance behaviour

- ✓ This program works in QCD: estimation of the LECs (Chiral Perturbation Theory) by using Resonance Chiral Theory

- ✓ As a preliminary example we show this game in the purely bosonic Lagrangian

* Pich, IR, Santos and Sanz-Cillero '14 [in progress]

3.2. The purely bosonic Lagrangians

i) At low energies*

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

ii) At high energies**

$$
\begin{aligned}
\mathcal{L}_S &= \frac{c_{d\,1}}{\sqrt{2}} S_1 \langle u_\mu u^\mu \rangle \\
\mathcal{L}_P &= 0 \\
\mathcal{L}_V &= \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{i G_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu]\rangle + \frac{\widetilde{F}_V}{2\sqrt{2}}\langle V_{\mu\nu} f_-^{\mu\nu}\rangle \\
\mathcal{L}_A &= \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle + \frac{\widetilde{F}_A}{2\sqrt{2}}\langle A_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{i\widetilde{G}_A}{2\sqrt{2}}\langle A_{\mu\nu}[u^\mu, u^\nu]\rangle
\end{aligned}
$$

Terms not appearing in QCD

* Longhitano '80 '81

** Pich, IR, Santos and Sanz-Cillero '14 [in progress]

3.3. Determination of the Low-Energy Constants

i) Matching*

$$
\begin{aligned}
a_1 &= -\frac{F_V^2}{4M_V^2} + \frac{\widetilde{F}_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2} - \frac{\widetilde{F}_A^2}{4M_A^2} \\
a_2 - a_3 &= -\frac{F_V G_V}{2M_V^2} - \frac{\widetilde{F}_A \widetilde{G}_A}{2M_A^2} \\
a_2 + a_3 &= -\frac{\widetilde{F}_V G_V}{2M_V^2} - \frac{F_A \widetilde{G}_A}{2M_A^2} \\
a_4 &= \frac{G_V^2}{4M_V^2} + \frac{\widetilde{G}_A^2}{4M_A^2} \\
a_5 &= \frac{c_{d\,1}^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} - \frac{\widetilde{G}_A^2}{4M_A^2} \\
H_1 &= -\frac{F_V^2}{8M_V^2} - \frac{\widetilde{F}_V^2}{8M_V^2} - \frac{F_A^2}{8M_A^2} - \frac{\widetilde{F}_A^2}{8M_A^2} \\
\widetilde{H}_1 &= -\frac{F_V \widetilde{F}_V}{4M_V^2} - \frac{F_A \widetilde{F}_A}{4M_A^2}
\end{aligned}
$$

ii) Next step: short-distance constraints + fermionic operators*

* Pich, IR, Santos and Sanz-Cillero ’14 [in progress]

4. Summary

1. What? **Electroweak Strongly Coupled Models**

2. Why? **What if this new particle around 125 GeV is not a SM Higgs bosson?**

- ✓ We should look for alternative ways of mass generation: strongly-coupled models.
- ✓ They should fulfilled the existing phenomenological tests.
- ✓ They can be used to determine the LECs

3. Where? **Effective approach**

a) EWSB: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$: similar to ChSB in QCD: ChPT.

b) Strongly-coupled models: similar to resonances in QCD: RChT.

c) General Lagrangian with at most two derivatives and short-distance information.

4. How?

Determination of S and T at NLO

1. Dispersive representation for S and T
2. Short-distance constraints

Determination of the LECs

1. Integrating out the resonances
2. Short-distance constraints

Constraining strongly-coupled models by considering S and T

- ✓ Strongly coupled scenarios are allowed by the current experimental data.
- ✓ The Higgs-like boson must have a WW coupling close to the SM one (κ_W=1):
  - ✓ With the 2nd WSR κ_W in [0.94, 1] at 95% CL
  - ✓ For larger departures from κ_W=1 the 2nd WSR must be dropped.
  - ✓ A moderate resonance-mass splitting implies $\kappa_W \approx 1$
- ✓ Resonance masses above the TeV scale:
  - ✓ At LO $M_A > M_V > 1.5$ TeV at 95% CL.
  - ✓ With the 2nd WSR $M_V > 4$ TeV at 95% CL.
  - ✓ With only the 1st WSR $M_V < 1$ TeV implies large resonance-mass splitting.

Determining the LECs in terms of resonance couplings

- ✓ Matching the Resonance Theory and the Electroweak Effective Theory.
- ✓ Similar to the QCD case.
- ✓ Short-distance constraints are fundamental.