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Resonances in the electroweak chiral Lagrangian

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Work in progress
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OUTLINE

1) Motivation

2) Constructing the Lagrangian with resonances

3) Estimation of the LECs

4) Short-distance constraints

5) Phenomenology

    1) Oblique electroweak obsevables (S and T)
    2) Contributions to $Z \to \bar{b}b$

6) Conclusions

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Preliminary

1. Motivation: framework

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, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{QED}$, 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.

→ Resonance Theory

* CMS and ATLAS Collaborations.

1. Motivation: what do we want to do?

Estimation of the LECs → Resonance Lagrangians can be used to estimate the Low Energy Couplings (LECs) of the Electroweak Chiral Lagrangian

Short-distance constraints → Short-distance contraints are fundamental in order to reduce the number of resonance parameters.

Phenomenology → Which values for the resonance masses are required from phenomenology?

Why at Chiral Dynamics?: similarities to Chiral Symmetry Breaking in QCD

i) Custodial symmetry: The Lagrangian is approximately invariant under global $SU(2)_L \times SU(2)_R$ transformations. Electroweak Symmetry Breaking (EWSB) turns to be $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$.

ii) 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)*^.

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

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:

$$\left\{\begin{array}{lcl} f_\pi = 0.090\,\mathrm{GeV} & \longrightarrow & v = 0.246\,\mathrm{TeV} \\ M_\rho = 0.770\,\mathrm{GeV} & \longrightarrow & M_V = 2.1\,\mathrm{TeV} \\ M_{a1} = 1.260\,\mathrm{GeV} & \longrightarrow & M_A = 3.4\,\mathrm{TeV} \end{array}\right.$$

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

As in QCD, the assumed high-energy constraints are fundamental.

* 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

2. Constructing the Lagrangian with resonances

- ✓ Two strongly coupled Lagrangians for two energy regions:
  - ✓ Electroweak Chiral Lagrangian (ECLh) at low energies (without resonances).
  - ✓ Resonance Theory at high energies* (with resonances).

- ✓ The aim of this work is threefold:
  1. Estimation of the Low-Energy Constants (LECs) in terms of resonance parameters.
  2. High-energy constraints as a keypoint.
  3. Phenomenological applications.

- ✓ Steps:
  1. Building the resonance Lagrangian
  2. Matching the two effective theories
  3. Requiring a good short-distance behaviour
  4. Phenomenology

- ✓ This program works pretty well in QCD: estimation of the LECs (Chiral Perturbation Theory) by using Resonance Chiral Theory** and importance of short-distance constraints***.

* Pich, IR, Santos and Sanz-Cillero [in progress]
** Cirigliano et al. ’06
*** Ecker et al. ‘89

How do we construct the Lagrangian?

- ✓ Custodial symmetry
- ✓ Degrees of freedom:
  - ✓ At low energies: bosons χ (EW goldstones, gauge bosons, h), fermions ψ
  - ✓ At high energies: previous dof + resonances (V,A,S,P triplets and singlets)
- ✓ *Chiral* counting*

$$\frac{\chi}{v} \sim \mathcal{O}\left(p^0\right) \qquad \frac{\psi}{v} \sim \mathcal{O}\left(\sqrt{p}\right) \qquad \partial_\mu,\, m_\chi,\, m_\psi \sim \mathcal{O}(p)$$

- ✓ So
  - ✓ At low energies: $\mathcal{L}_{\rm ECLh} = \mathcal{L}_2 + \mathcal{L}_4 + \ldots$
  - ✓ At high energies: $\mathcal{L}_R = c_R\, R\, \mathcal{O}_{p^2}[\chi,\psi] + \ldots$
- ✓ Short-distance constraints

* Weinberg '79
* Appelquist and Bernand '80
* Longhitano '80, '81
* Manohar, and Georgi '84
* Gasser and Leutwyler '84 '85
* Hirn and Stern '05
* Alonso et al. '12
* Buchalla, Catá and Krause '13
* Brivio et al. '13
* Delgado et al. '14
* Pich, IR, Santos and Sanz-Cillero [in progress]

Bosonic Lagrangians at low and high energies

i) At low energies*

$$\begin{aligned}\mathcal{L}_4 \;=\;& \frac{1}{4}c_1\langle f_+^{\mu\nu}f_{+\,\mu\nu} - f_-^{\mu\nu}f_{-\,\mu\nu}\rangle + \frac{i}{2}(c_2-c_3)\langle f_+^{\mu\nu}[u_\mu,u_\nu]\rangle + \frac{i}{2}(c_2+c_3)\langle f_-^{\mu\nu}[u_\mu,u_\nu]\rangle \\ &+c_4\langle u_\mu u_\nu\rangle\,\langle u^\mu u^\nu\rangle + c_5\langle u_\mu u^\mu\rangle^2 + c_6\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle + c_7\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle \\ &+c_8\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4} + c_9\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu}u_\nu\rangle + \widetilde{c}_9\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu}u_\nu\rangle \\ &+\frac{1}{2}c_{10}\langle f_+^{\mu\nu}f_{+\,\mu\nu} + f_-^{\mu\nu}f_{-\,\mu\nu}\rangle + \widetilde{c}_{10}\langle f_+^{\mu\nu}f_{-\,\mu\nu}\rangle + c_{11}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}\end{aligned}$$

ii) At high energies**

$$\mathcal{L}_S = \frac{c_d}{\sqrt{2}}S_1\langle u_\mu u^\mu\rangle$$

$$\mathcal{L}_P = d_P\frac{(\partial_\mu h)}{v}\langle P u^\mu\rangle$$

$$\mathcal{L}_V = \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu}f_+^{\mu\nu}\rangle + \frac{iG_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu,u^\nu]\rangle + F_{V_1}X^{\mu\nu}V_{1\,\mu\nu} + \frac{\widetilde{F}_V}{2\sqrt{2}}\langle V_{\mu\nu}f_-^{\mu\nu}\rangle + \sqrt{2}\widetilde{\lambda}_1^{hV}(\partial^\mu h)\langle u^\nu V_{\mu\nu}\rangle$$

$$\mathcal{L}_A = \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu}f_-^{\mu\nu}\rangle + \sqrt{2}\lambda_1^{hA}(\partial^\mu h)\langle u^\nu A_{\mu\nu}\rangle + \frac{\widetilde{F}_A}{2\sqrt{2}}\langle A_{\mu\nu}f_+^{\mu\nu}\rangle + \frac{i\widetilde{G}_A}{2\sqrt{2}}\langle A_{\mu\nu}[u^\mu,u^\nu]\rangle + \widetilde{F}_{A_1}X^{\mu\nu}A_{1\,\mu\nu}$$

P-odd terms

* Longhitano '80 '81
* Guo, Ruiz-Femenia and Sanz-Cillero '15
** Pich, IR, Santos and Sanz-Cillero [in progress]

3. Estimation of the LECs

- ✓ Integration of the heavy modes
- ✓ Similar to the ChPT case*

$$e^{iS_{\text{eff}}[\chi,\psi]} = \int [\mathrm{d}R]\, e^{iS[\chi,\psi,R]}$$

- ✓ Results**

$$c_1 = -\frac{F_V^2}{4M_V^2} + \frac{\widetilde{F}_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2} - \frac{\widetilde{F}_A^2}{4M_A^2}$$

$$c_2 - c_3 = -\frac{F_V G_V}{2M_V^2} - \frac{\widetilde{F}_A \widetilde{G}_A}{2M_A^2}$$

$$c_2 + c_3 = -\frac{\widetilde{F}_V G_V}{2M_V^2} - \frac{F_A \widetilde{G}_A}{2M_A^2}$$

$$c_4 = \frac{G_V^2}{4M_V^2} + \frac{\widetilde{G}_A^2}{4M_A^2}$$

$$c_5 = \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} - \frac{\widetilde{G}_A^2}{4M_A^2}$$

$$c_6 = -\frac{\widetilde{\lambda}_1^{hV\,2} v^2}{M_V^2} - \frac{\lambda_1^{hA\,2} v^2}{M_A^2}$$

$$c_7 = \frac{d_P^2}{2M_P^2} + \frac{\widetilde{\lambda}_1^{hV\,2} v^2}{M_V^2} + \frac{\lambda_1^{hA\,2} v^2}{M_A^2}$$

$$c_8 = 0$$

$$c_9 = -\frac{\widetilde{F}_V \widetilde{\lambda}_1^{hV} v}{M_V^2} - \frac{F_A \lambda_1^{hA} v}{M_A^2}$$

$$\widetilde{c}_9 = -\frac{F_V \widetilde{\lambda}_1^{hV} v}{M_V^2} - \frac{\widetilde{F}_A \lambda_1^{hA} v}{M_A^2}$$

$$c_{10} = -\frac{F_V^2}{8M_V^2} - \frac{\widetilde{F}_V^2}{8M_V^2} - \frac{F_A^2}{8M_A^2} - \frac{\widetilde{F}_A^2}{8M_A^2}$$

$$\widetilde{c}_{10} = -\frac{F_V \widetilde{F}_V}{4M_V^2} - \frac{F_A \widetilde{F}_A}{4M_A^2}$$

$$c_{11} = -\frac{F_{V_1}^2}{M_{V_1}^2} - \frac{\widetilde{F}_{A_1}^2}{M_{A_1}^2}$$

- ✓ Next step: short-distance constraints

* Ecker et al. '89

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

4. Short-distance constraints*

- ✓ From QCD we've learnt the importance of sum-rules and form factos at large energies:
  - ✓ Operators with a large number of derivatives tend to violate the asymptotic behaviour.
  - ✓ The constraints are required to reduce the number of unknown resonance parameters.
- ✓ In strongly-coupled approaches to the EWSB:
  - ✓ The underlying theory is less known.
  - ✓ We consider form factors into two EW Goldstones and into fermion-antifermion.

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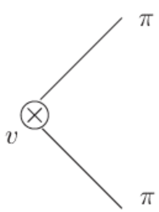
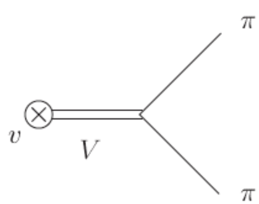
Vector form factors and considering only P-even terms





$$\Delta\mathcal{L}_4 = \frac{i}{2}(c_2 - c_3)\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle + c_{10}^{\psi^2 h^0}\langle f_{+\mu\nu}\nabla^\mu J_V^\nu\rangle$$

$$\Delta\mathcal{L}_R = \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{iG_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu]\rangle + c_{V1}\langle \nabla^\mu J_V^\nu V_{\mu\nu}\rangle$$

$$\mathcal{F}^v_{\pi\pi}(q^2) = 1 + \frac{F_V G_V}{v^2}\frac{q^2}{M_V^2 - q^2}$$

$$\mathcal{F}^v_{\psi\overline{\psi}}(q^2) = 1 - \sqrt{2}F_V c_{V1}\frac{q^2}{M_V^2 - q^2}$$

$$\Rightarrow \quad F_V G_V = v^2, \qquad \sqrt{2}F_V c_{V1} = -1$$

$$\Rightarrow \quad c_2 - c_3 = -\frac{F_V G_V}{2M_V^2} = -\frac{v^2}{2M_V^2}, \qquad c_{10}^{\psi^2 h^0} = -\frac{F_V c_{V1}}{\sqrt{2}M_V^2} = \frac{1}{2M_V^2}$$

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

5. Phenomenology: oblique electroweak observables (S and T)

- ✓ Universal oblique corrections via the EW boson self-energies:
  - ✓ S*: new physics in the difference between the Z self-energies at $Q^2=M_Z^2$ and $Q^2=0$.
  - ✓ T*: custodial symmetry breaking
- ✓ We follow the useful dispersive representation introduced by Peskin and Takeuchi* for S and a dispersion relation for T (checked for the lowest cuts)**:

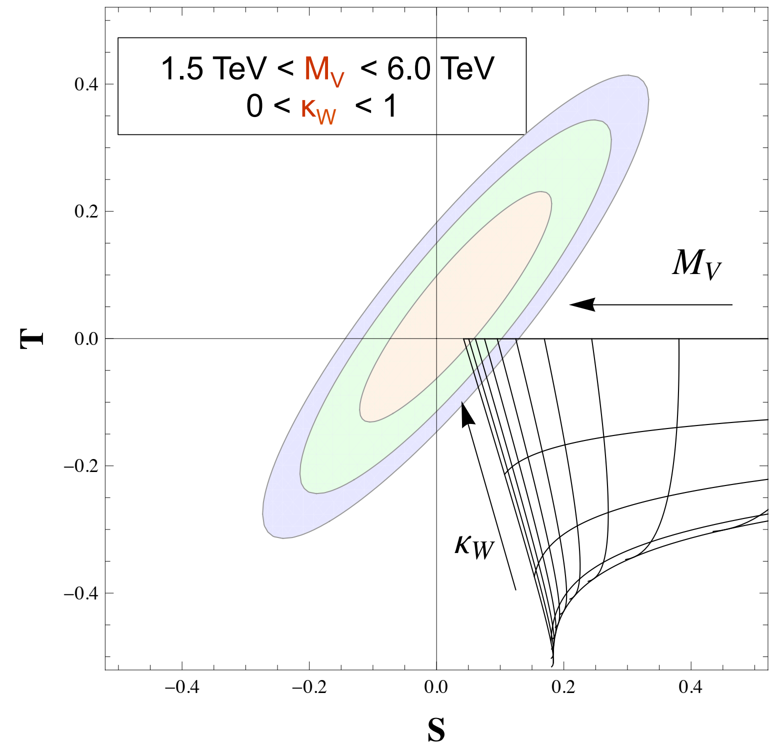
$$
\begin{aligned}
S &= \frac{16\pi}{g^2 \tan\theta_W} \int_0^\infty \frac{\mathrm{d}t}{t} \left(\rho_S(t) - \rho_S(t)^{\rm SM} \right) \\
T &= \frac{16\pi}{g'^2 \cos^2\theta_W} \int_0^\infty \frac{\mathrm{d}t}{t^2} \left(\rho_T(t) - \rho_T(t)^{\rm SM} \right)
\end{aligned}
$$

  - ✓ $\rho_S(t)$ and $\rho_T(t)$ are the spectral 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.
  - ✓ We considered only P even terms***.

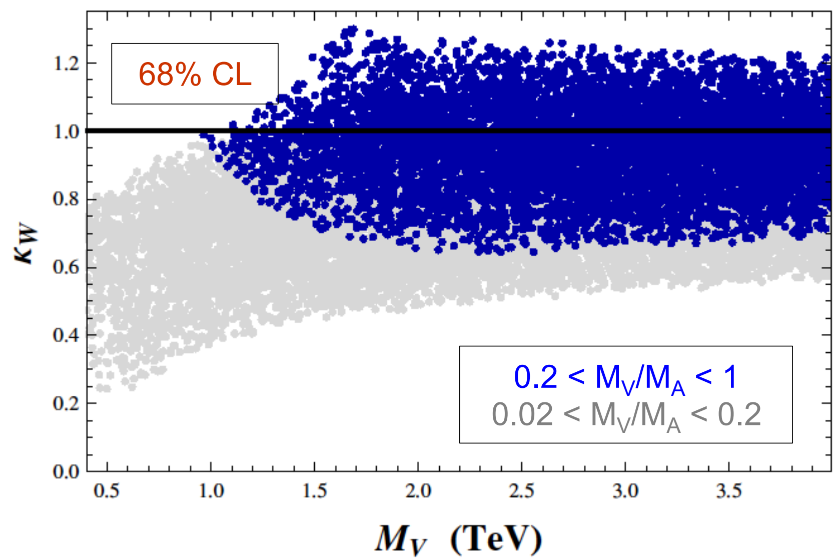
* Peskin and Takeuchi '92
** Pich, IR and Sanz-Cillero '13 '14
*** Barbieri et al. '93

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

$1 > \kappa_W > 0.94$
$M_A \approx M_V > 5$ TeV
(68%CL)



ii) 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.

iii) Preliminary results: inclusion of fermion cut doesn't change appreciably the results**.

* Pich, IR and Sanz-Cillero '13 '14
** Pich, IR, Santos and Sanz-Cillero [in progress]

5. Phenomenology: contributions to $Z \to \bar{b}b$ *

- ✓ Tipically it is complicated to keep a small BSM contribution to $Z \to \bar{b}b$ **, as experiments require***.

- ✓ The low-energy Lagrangian:

$$\Delta\mathcal{L}_4 \;=\; c_{10}^{\psi^2 h^0}\langle f_{+\mu\nu}\nabla^\mu J_V^\nu\rangle + c_{11}^{\psi^2 h^0}\langle f_{-\mu\nu}\nabla^\mu J_A^\nu\rangle$$

- ✓ By using the estimations of the LECs in terms of resonance parameters and the short-distance constraints (fermion-antifermion vector and axial vector form factors), we get:

$$c_{10}^{\psi^2 h^0} v^2 \;=\; -\frac{F_V c_{V1} v^2}{\sqrt{2}M_V^2} = \frac{v^2}{2M_V^2}$$

$$c_{11}^{\psi^2 h^0} v^2 \;=\; -\frac{F_A c_{A1} v^2}{\sqrt{2}M_A^2} = -\frac{v^2}{2M_A^2}$$

- ✓ From phenomenology we get the upper bounds:

$$|c_{10}^{\psi^2 h^0} v^2| \;<\; 1.4\times 10^{-2}$$

$$|c_{11}^{\psi^2 h^0} v^2| \;<\; 7\times 10^{-3}$$

- ✓ So $M_V \gtrsim 1.5\,\mathrm{TeV}$ and $M_A \gtrsim 2\,\mathrm{TeV}$. Similar to bounds from S and T.

* Pich, IR, Santos and Sanz-Cillero [in progress]
** Agashe et al. '06
** Efrati, Falkowski and Soreq '15
*** LEP

6. Conclusions

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 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) Chiral counting and short-distance constraints.

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

c) *Chiral* counting and short-distance constraints.

Estimation of the LECs

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

Phenomenology: natural suppression in low-energy observables

1. S and T: $M_V > 5$ TeV ($M_V > 1$ TeV) for 1st and 2nd WSR (only 1st WSR)
2. Contributions to $Z \to b\bar{b}$: $M_V \gtrsim 1.5\,\mathrm{TeV}$

Backup slides: calculation of S and T

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 h (the Higgs) and the lightest vector and axial-vector resonances:

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

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

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

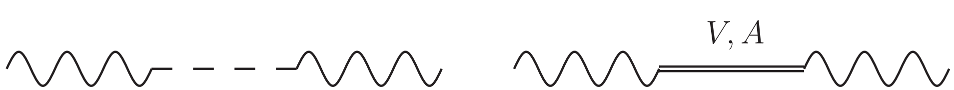
$$+\frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu}f_-^{\mu\nu}\rangle+\sqrt{2}\,\lambda_1^{hA}\,\partial_\mu h\,\langle A^{\mu\nu}u_\nu\rangle$$

- π and h sector
- π and V sector
- π, h and A sector

Seven resonance parameters: κ_W, F_V, G_V, F_A, λ_1^{hA}, M_V and M_A.

The high-energy constraints are fundamental.

ii) At leading-order (LO)*

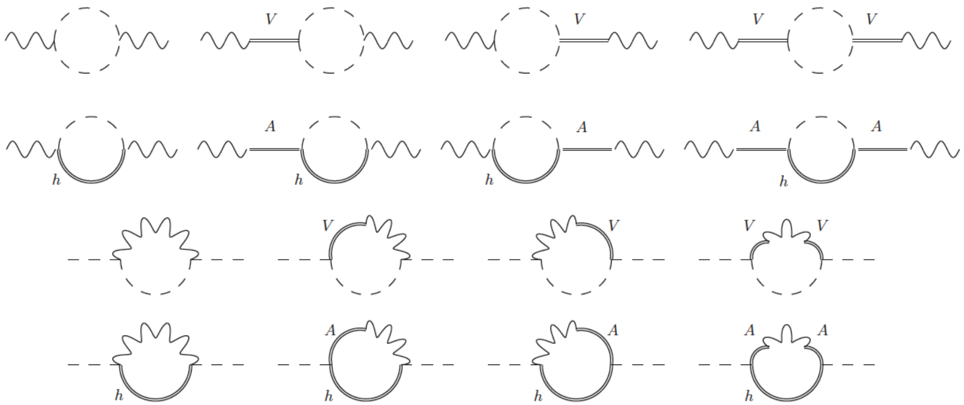


$$S_{\rm LO}=4\pi\left(\frac{F_V^2}{M_V^2}-\frac{F_A^2}{M_A^2}\right)$$

$$T_{\rm LO}=0$$

* 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)***:

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

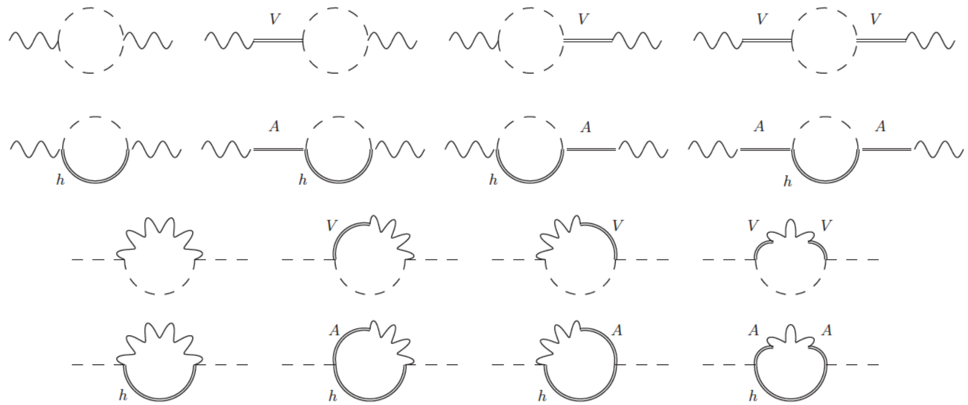
- ✓ We have 7 resonance parameters and up to 5 constraints:
  - ✓ With both, the 1st and the 2nd WSR: κ_W and M_V as free parameters
  - ✓ With only the 1st WSR: κ_W, M_V and M_A as free parameters

* 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.

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



- ✓ Dispersive relations
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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
- ✓ Weinberg Sum-Rules (WSR)***:

1st WSR at LO: $F_V^2\, M_V^2 \; - \; F_A^2\, M_A^2 \; = \; 0$

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

1st WSR at NLO (= VFF^ and AFF^^):

$$F_V G_V = v^2$$

$$F_A \lambda_1^{hA} = \kappa_W v$$

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

- ✓ 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

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^ Ecker et al. '89

^^Pich, IR and Sanz-Cillero '08

Backup slides: S and T at LO

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**

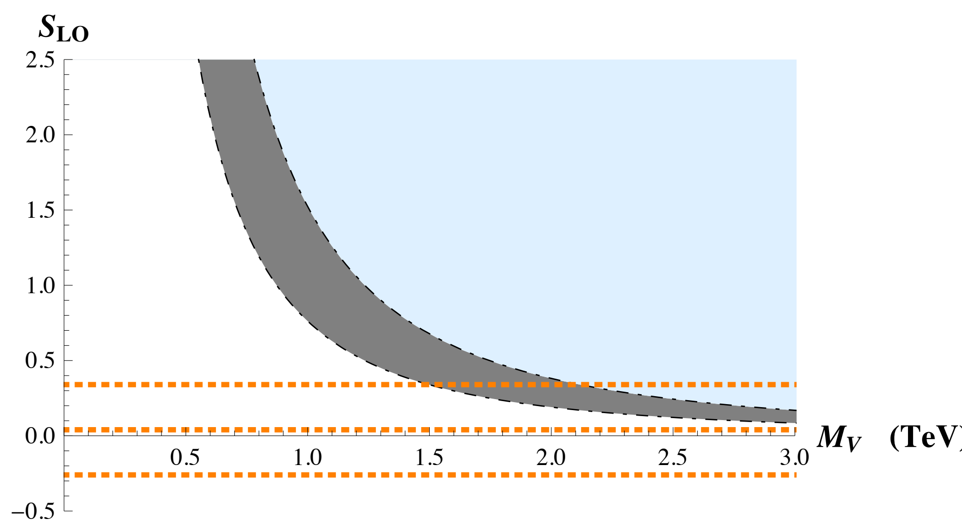
$$S_{\rm LO} = \frac{4\pi v^2}{M_V^2}\left(1+\frac{M_V^2}{M_A^2}\right)$$

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

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