XII Quark Confinement and the Hadron Spectrum
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Integrating out resonances in strongly-coupled electroweak scenarios

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PRD 93 (**2016**) no.5, 055041 [arXiv: 1510.03114]
JHEP 01 (**2014**) 157 [arXiv:1310.3121]
PRL 110 (**2013**) 181801 [arXiv:1212.6769]
JHEP 08 (**2012**) 106 [arXiv: 1206.3454]

OUTLINE

1) Motivation

2) Building the Lagrangian

    1) Low energies (no resonances)
    2) High energies: Proca vs. antisymmetric formalism

3) Estimation of the LECs

4) Short-distance constraints and the purely bosonic sector

5) Conclusions

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

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 Effective Theory (EWET)

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

Phenomenology → What values for resonance masses are required from phenomenology?

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)*^.

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

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:

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

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

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

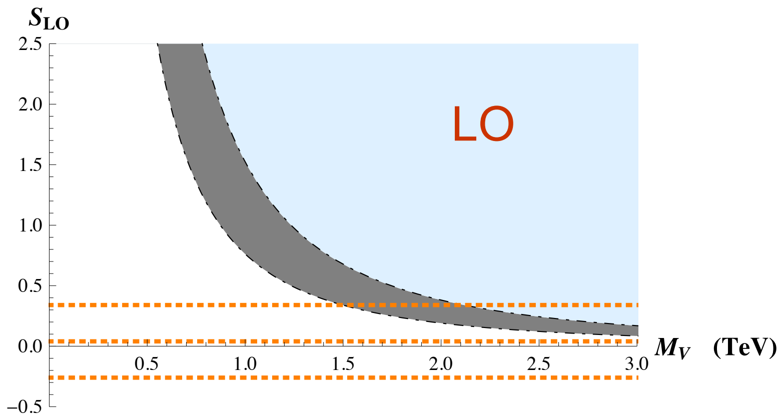
* Weinberg '79
* Gasser and Leutwyler '84 '85
* Bijnens et al. '99 '00

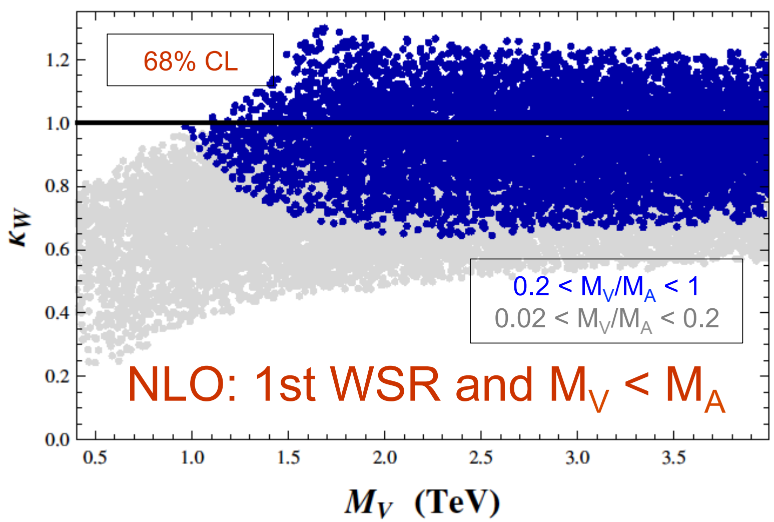
^Dobado, Espriu and Herrero '91
^Espriu and Herrero '92
^Herrero and Ruiz-Morales '94

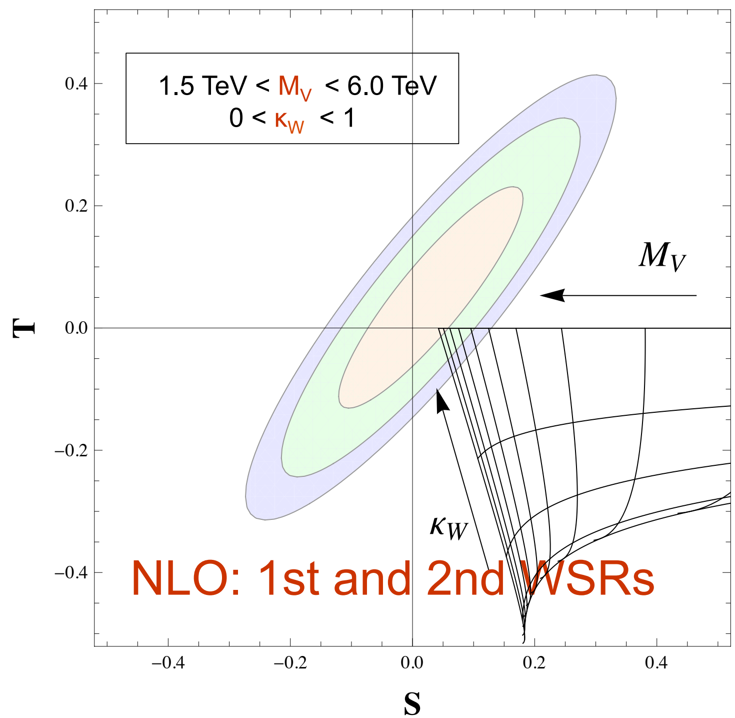
**Ecker et al. '89
** Cirigliano et al. '06

Looking at the phenomenology*

- ✓ Oblique electroweak observables** (S and T)
- ✓ Dispersive relations for both S** and T*
- ✓ Short-distance constraints: two-Goldstone VFF, Higgs-Goldstone VFF, Weinberg Sum Rules







Room for these scenarios
$\kappa_W \cong 1$
$M_R \approx$ TeV

* Pich, IR and Sanz-Cillero '12 '13 '14
** Peskin and Takeuchi '92

2. Building the Lagrangian

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

- ✓ The aim of this work:

  Estimation of the Low-Energy Couplings (LECs) in terms of resonance parameters

- ✓ Steps:
  1. Building the EWET and resonance Lagrangian
  2. Matching the two effective theories

- ✓ High-energy constraints
  1. From QCD we know the importance of sum-rules and form factos at large energies.
  2. Operators with a large number of derivatives tend to violate the asymptotic behaviour.
  3. The constraints are required to reduce the number of unknown resonance parameters.
  4. The underlying theory is less known than in the case of QCD.

- ✓ 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 '16 [and in progress]
** Cirigliano et al. '06
*** Ecker et al. '89

How do we build 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* power counting*

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

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

* 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 '16 [and in progress]

2.1. Low energies (no resonances)*

$$\mathcal{L}_{\rm EWET}^{(4)} = \sum_{i=1}^{11} \mathcal{F}_i\, \mathcal{O}_i + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i\, \widetilde{\mathcal{O}}_i + \sum_{i=1}^{7} \mathcal{F}_i^{\psi^2}\, \mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{\psi^2}\, \widetilde{\mathcal{O}}_i^{\psi^2} + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4}\, \mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2} \widetilde{\mathcal{F}}_i^{\psi^4}\, \widetilde{\mathcal{O}}_i^{\psi^4}$$

i	$\mathcal{O}_i$	$\widetilde{\mathcal{O}}_i$
1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\mu\nu} - f_-^{\mu\nu} f_{-\mu\nu}\rangle$	$\frac{i}{2}\langle f_-^{\mu\nu}[u_\mu, u_\nu]\rangle$
2	$\frac{1}{2}\langle f_+^{\mu\nu} f_{+\mu\nu} + f_-^{\mu\nu} f_{-\mu\nu}\rangle$	$\langle f_+^{\mu\nu} f_{-\mu\nu}\rangle$
3	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle$	$\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu} u_\nu\rangle$
4	$\langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle$	
5	$\langle u_\mu u^\mu\rangle^2$	
6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle$	
7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle$	
8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	
9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu} u_\nu\rangle$	
10	$\langle \mathcal{T} u_\mu\rangle^2$	
11	$\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$	

i	$\mathcal{O}_i^{\psi^2}$	$\widetilde{\mathcal{O}}_i^{\psi^2}$	$\mathcal{O}_i^{\psi^4}$	$\widetilde{\mathcal{O}}_i^{\psi^4}$
1	$\langle J_S\rangle\langle u_\mu u^\mu\rangle$	$\langle J_T^{\mu\nu} f_{-\mu\nu}\rangle$	$\langle J_S J_S\rangle$	$\langle J_V^\mu J_{A,\mu}\rangle$
2	$i\langle J_T^{\mu\nu}[u_\mu, u_\nu]\rangle$	$\frac{\partial_\mu h}{v}\langle u_\nu J_T^{\mu\nu}\rangle$	$\langle J_P J_P\rangle$	$\langle J_V^\mu\rangle\langle J_{A,\mu}\rangle$
3	$\langle J_T^{\mu\nu} f_{+\mu\nu}\rangle$	$\langle J_V^\mu\rangle\langle u_\mu \mathcal{T}\rangle$	$\langle J_S\rangle\langle J_S\rangle$	
4	$\hat{X}_{\mu\nu}\langle J_T^{\mu\nu}\rangle$		$\langle J_P\rangle\langle J_P\rangle$	
5	$\frac{\partial_\mu h}{v}\langle u^\mu J_P\rangle$		$\langle J_V^\mu J_{V,\mu}\rangle$	
6	$\langle J_A^\mu\rangle\langle u_\mu \mathcal{T}\rangle$		$\langle J_A^\mu J_{A,\mu}\rangle$	
7	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle J_S\rangle$		$\langle J_V^\mu\rangle\langle J_{V,\mu}\rangle$	
8			$\langle J_A^\mu\rangle\langle J_{A,\mu}\rangle$	
9			$\langle J_T^{\mu\nu} J_{T\,\mu\nu}\rangle$	
10			$\langle J_T^{\mu\nu}\rangle\langle J_{T\,\mu\nu}\rangle$	

* Longhitano '80 '81
* Buchalla and Catà '12 '14
* Alonso et al. '13
* Guo, Ruiz-Femenia and Sanz-Cillero '15
* Pich, IR, Santos and Sanz-Cillero '16 [and in progress]

2.2. High energies (with resonances)*

$$\mathcal{L}_{\rm RT} \;=\; \mathcal{L}_{\rm R}[R,\chi,\psi] + \mathcal{L}_{\rm non-R}[\chi,\psi]$$

$$\mathcal{L}^{(P)}_{\rm non-R} = \sum_{i=1}^{11} \mathcal{F}_i^{(\rm P)}\, \mathcal{O}_i + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{(\rm P)}\, \widetilde{\mathcal{O}}_i + \sum_{i=1}^{7} \mathcal{F}_i^{\psi^2,(\rm P)}\, \mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{\psi^2,(\rm P)}\, \widetilde{\mathcal{O}}_i^{\psi^2} + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4,(\rm P)}\, \mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2} \widetilde{\mathcal{F}}_i^{\psi^4,(\rm P)}\, \widetilde{\mathcal{O}}_i^{\psi^4}$$

$$\mathcal{L}^{(A)}_{\rm non-R} = \sum_{i=1}^{11} \mathcal{F}_i^{(\rm A)}\, \mathcal{O}_i + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{(\rm A)}\, \widetilde{\mathcal{O}}_i + \sum_{i=1}^{7} \mathcal{F}_i^{\psi^2,(\rm A)}\, \mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{\psi^2,(\rm A)}\, \widetilde{\mathcal{O}}_i^{\psi^2} + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4,(\rm A)}\, \mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2} \widetilde{\mathcal{F}}_i^{\psi^4,(\rm A)}\, \widetilde{\mathcal{O}}_i^{\psi^4}$$

i) Spin-0 (S, S_1, P, P_1)

$$\begin{aligned}
\mathcal{L}_R &= \frac{1}{2} < \nabla^\mu R\, \nabla_\mu R \,-\, M_R^2\, R^2 > \,+\, < R\, \chi_R > \qquad (R = S,\, P)\,, \\
\mathcal{L}_{R_1} &= \frac{1}{2} \left(\partial^\mu R_1\, \partial_\mu R_1 \,-\, M_{R_1}^2\, R_1^2\right) \,+\, R_1\, \chi_{R_1} \qquad (R_1 = S_1,\, P_1)\,.
\end{aligned}$$

$$\begin{aligned}
\chi_{S_1} &= \lambda_{hS_1}\, v\, h^2 \,+\, \frac{c_d}{\sqrt{2}} < u_\mu u^\mu > \,+\, \frac{c_1^{S_1}}{\sqrt{2}} < J_S > \\
\chi_{P_1} &= \frac{c_1^{P_1}}{\sqrt{2}} < J_P > \\
\chi_S &= c_1^S\, J_S \\
\chi_P &= c_1^P\, J_P \,+\, d_P\, \frac{(\partial_\mu h)}{v}\, u^\mu
\end{aligned}$$

* Pich, IR, Santos and Sanz-Cillero '16 [and in progress]

ii) Spin-1 (V, V_1, A, A_1) with Proca formalism*

$$\mathcal{L}_{\hat R}^{(P)} = -\frac{1}{4} < \hat R_{\mu\nu}\, \hat R^{\mu\nu} - 2\, M_{\hat R}^2\, \hat R_\mu \hat R^\mu > + < \hat R_\mu\, \hat\chi_{\hat R}^\mu + \hat R_{\mu\nu}\, \hat\chi_{\hat R}^{\mu\nu} > \qquad (\hat R = \hat V,\, \hat A)\,,$$

$$\mathcal{L}_{\hat R_1}^{(P)} = -\frac{1}{4} \left(\hat R_{1\,\mu\nu}\, \hat R_1^{\mu\nu} - 2\, M_{\hat R_1}^2\, \hat R_{1\,\mu} \hat R_1^\mu\right) + \hat R_{1\,\mu}\, \hat\chi_{\hat R_1}^\mu + \hat R_{1\,\mu\nu}\, \hat\chi_{\hat R_1}^{\mu\nu} \qquad (\hat R_1 = \hat V_1,\, \hat A_1)\,,$$

$$\hat R_{\mu\nu} = \nabla_\mu \hat R_\nu - \nabla_\nu \hat R_\mu$$

$$\hat\chi_{\hat V}^{\mu\nu} = \frac{f_{\hat V}}{2\sqrt2} f_+^{\mu\nu} + \frac{i\, g_{\hat V}}{2\sqrt2} [u^\mu, u^\nu] + \frac{\widetilde f_{\hat V}}{2\sqrt2} f_-^{\mu\nu} + \frac{\widetilde\lambda_1^{h\hat V}}{\sqrt2} \left[(\partial^\mu h)\, u^\nu - (\partial^\nu h)\, u^\mu\right] + c_0^{\hat V} J_T^{\mu\nu}$$

$$\hat\chi_{\hat A}^{\mu\nu} = \frac{f_{\hat A}}{2\sqrt2} f_-^{\mu\nu} + \frac{\lambda_1^{h\hat A}}{\sqrt2} \left[(\partial^\mu h)\, u^\nu - (\partial^\nu h)\, u^\mu\right] + \frac{\widetilde f_{\hat A}}{2\sqrt2} f_+^{\mu\nu} + \frac{i\, \widetilde g_{\hat A}}{2\sqrt2} [u^\mu, u^\nu] + \widetilde c_0^{\hat A} J_T^{\mu\nu}$$

$$\hat\chi_{\hat V_1}^{\mu\nu} = f_{\hat V_1} X^{\mu\nu} + \frac{c_0^{\hat V_1}}{\sqrt2} < J_T^{\mu\nu} > \qquad \hat\chi_{\hat A_1}^{\mu\nu} = \widetilde f_{\hat A_1} X^{\mu\nu} + \frac{\widetilde c_0^{\hat A_1}}{\sqrt2} < J_T^{\mu\nu} >$$

$$\hat\chi_{\hat V}^{\mu} = c_1^{\hat V} J_V^\mu + \widetilde c_1^{\hat V} J_A^\mu \qquad \hat\chi_{\hat A}^{\mu} = c_1^{\hat A} J_A^\mu + \widetilde c_1^{\hat A} J_V^\mu$$

$$\hat\chi_{\hat V_1}^{\mu} = \widetilde c_{\mathcal T}^{\hat V_1} < u^\mu \mathcal T > + \frac{c_1^{\hat V_1}}{\sqrt2} < J_V^\mu > + \frac{\widetilde c_1^{\hat V_1}}{\sqrt2} < J_A^\mu >$$

$$\hat\chi_{\hat A_1}^{\mu} = c_{\mathcal T}^{\hat A_1} < u^\mu \mathcal T > + \frac{c_1^{\hat A_1}}{\sqrt2} < J_A^\mu > + \frac{\widetilde c_1^{\hat A_1}}{\sqrt2} < J_V^\mu >$$

* Pich, IR, Santos and Sanz-Cillero ‘16 [and in progress]

iii) Spin-1 (V, V_1, A, A_1) with antisymmetric formalism*

$$\mathcal{L}_R^{(A)} = -\frac{1}{2} < \nabla^\lambda R_{\lambda\mu} \nabla_\sigma R^{\sigma\mu} - \frac{1}{2} M_R^2 R_{\mu\nu} R^{\mu\nu} > + < R_{\mu\nu} \chi_R^{\mu\nu} > \qquad (R = V,\ A)\,,$$

$$\mathcal{L}_{R_1}^{(A)} = -\frac{1}{2} \left(\partial^\lambda R_{1\,\lambda\mu}\, \partial_\sigma R_1^{\sigma\mu} - \frac{1}{2} M_{R_1}^2 R_{1\,\mu\nu} R_1^{\mu\nu} \right) + R_{1\,\mu\nu}\, \chi_{R_1}^{\mu\nu} \qquad (R_1 = V_1,\ A_1)\,,$$

$$\chi_V^{\mu\nu}\Big|_{\mathrm{Bos}} = \frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{i\,G_V}{2\sqrt{2}} [u^\mu, u^\nu] + \frac{\widetilde{F}_V}{2\sqrt{2}} f_-^{\mu\nu} + \frac{\widetilde{\lambda}_1^{hV}}{\sqrt{2}} [(\partial^\mu h)\, u^\nu - (\partial^\nu h)\, u^\mu]$$

$$\chi_A^{\mu\nu}\Big|_{\mathrm{Bos}} = \frac{F_A}{2\sqrt{2}} f_-^{\mu\nu} + \frac{\lambda_1^{hA}}{\sqrt{2}} [(\partial^\mu h)\, u^\nu - (\partial^\nu h)\, u^\mu] + \frac{\widetilde{F}_A}{2\sqrt{2}} f_+^{\mu\nu} + \frac{i\,\widetilde{G}_A}{2\sqrt{2}} [u^\mu, u^\nu]$$

$$\chi_{V_1}^{\mu\nu}\Big|_{\mathrm{Bos}} = F_{V_1} X^{\mu\nu} + \frac{\widetilde{C}_{\mathcal{T}}^{V_1}}{2} (\partial^\mu < u^\nu \mathcal{T} > - \partial^\nu < u^\mu \mathcal{T} >)$$

$$\chi_{A_1}^{\mu\nu}\Big|_{\mathrm{Bos}} = \widetilde{F}_{A_1} X^{\mu\nu} + \frac{C_{\mathcal{T}}^{A_1}}{2} (\partial^\mu < u^\nu \mathcal{T} > - \partial^\nu < u^\mu \mathcal{T} >)$$

$$\chi_V^{\mu\nu}\Big|_{\mathrm{Fer}} = C_0^V J_T^{\mu\nu} + \frac{C_1^V}{2} (\nabla^\mu J_V^\nu - \nabla^\nu J_V^\mu) + \frac{\widetilde{C}_1^V}{2} (\nabla^\mu J_A^\nu - \nabla^\nu J_A^\mu)$$

$$\chi_A^{\mu\nu}\Big|_{\mathrm{Fer}} = \widetilde{C}_0^A J_T^{\mu\nu} + \frac{C_1^A}{2} (\nabla^\mu J_A^\nu - \nabla^\nu J_A^\mu) + \frac{\widetilde{C}_1^A}{2} (\nabla^\mu J_V^\nu - \nabla^\nu J_V^\mu)$$

$$\chi_{V_1}^{\mu\nu}\Big|_{\mathrm{Fer}} = \frac{C_0^{V_1}}{\sqrt{2}} < J_T^{\mu\nu} > + \frac{C_1^{V_1}}{2\sqrt{2}} < \partial^\mu J_V^\nu - \partial^\nu J_V^\mu > + \frac{\widetilde{C}_1^{V_1}}{2\sqrt{2}} < \partial^\mu J_A^\nu - \partial^\nu J_A^\mu >$$

$$\chi_{A_1}^{\mu\nu}\Big|_{\mathrm{Fer}} = \frac{\widetilde{C}_0^{A_1}}{\sqrt{2}} < J_T^{\mu\nu} > + \frac{C_1^{A_1}}{2\sqrt{2}} < \partial^\mu J_A^\nu - \partial^\nu J_A^\mu > + \frac{\widetilde{C}_1^{A_1}}{2\sqrt{2}} < \partial^\mu J_V^\nu - \partial^\nu J_V^\mu >$$

* Pich, IR, Santos and Sanz-Cillero ‘16 [and in progress]

Proca vs. antisymmetric formalism*

✓ By using path integral and changes of variables both formalisms are proven to be equivalent:

- ✓ The following set of relations between resonance parameters emerges:

$$
\begin{aligned}
&F_R = f_{\hat{R}} M_R\,, \quad G_R = g_{\hat{R}} M_R\,, \quad \lambda_1^{hR} = \lambda_1^{h\hat{R}} M_R\,, \quad C_0^R = c_0^{\hat{R}} M_R\,,\\
&\widetilde{F}_R = \widetilde{f}_{\hat{R}} M_R\,, \quad \widetilde{G}_R = \widetilde{g}_{\hat{R}} M_R\,, \quad \widetilde{\lambda}_1^{hR} = \widetilde{\lambda}_1^{h\hat{R}} M_R\,, \quad \widetilde{C}_0^R = \widetilde{c}_0^{\hat{R}} M_R\,,\\
&C_{\mathcal{T}}^R = c_{\mathcal{T}}^{\hat{R}}/M_R\,, \quad \widetilde{C}_{\mathcal{T}}^R = \widetilde{c}_{\mathcal{T}}^{\hat{R}}/M_R\,, \quad C_1^R = c_1^{\hat{R}}/M_R\,, \quad \widetilde{C}_1^R = \widetilde{c}_1^{\hat{R}}/M_R\,.
\end{aligned}
$$

- ✓ The couplings of the non-resonant operators are different: $\mathcal{L}^{(P)}_{\mathrm{non-R}} \neq \mathcal{L}^{(A)}_{\mathrm{non-R}}$

✓ By using high-energy behaviour:

$$
\mathbb{F}^{\mathcal{V}}_{\varphi\varphi}(s) = \begin{cases} 1 + \dfrac{F_V\, G_V}{v^2}\,\dfrac{s}{M_V^2 - s} + \dfrac{\widetilde{F}_A\, \widetilde{G}_A}{v^2}\,\dfrac{s}{M_A^2 - s} - 2\,\mathcal{F}_3^{\mathrm{SDA}}\,\dfrac{s}{v^2} & \text{(A)} \\[2ex] 1 + \dfrac{f_{\hat{V}}\, g_{\hat{V}}}{v^2}\,\dfrac{s^2}{M_V^2 - s} + \dfrac{\widetilde{f}_{\hat{A}}\, \widetilde{g}_{\hat{A}}}{v^2}\,\dfrac{s^2}{M_A^2 - s} - 2\,\mathcal{F}_3^{\mathrm{SDP}}\,\dfrac{s}{v^2} & \text{(P)} \end{cases}
$$

$$
\Rightarrow \quad \mathcal{F}_3^{\mathrm{SDA}} = 0\,, \qquad \mathcal{F}_3^{\mathrm{SDP}} = -\,\frac{f_{\hat{V}}\, g_{\hat{V}}}{2} - \frac{\widetilde{f}_{\hat{A}}\, \widetilde{g}_{\hat{A}}}{2}
$$

* Ecker et al. '89
* Bijnens and Pallante '96
* Kampf, Novotny and Trnka '07
* Pich, IR, Santos and Sanz-Cillero '16 [and in progress]

Proca vs. antisymmetric formalism*

- ✓ By using path integral and changes of variables both formalisms are proven to be equivalent:
  - ✓ The following set of relations between resonance parameters emerges:

$$
\begin{array}{llll}
F_R = f_{\hat{R}} M_R\,, & G_R = g_{\hat{R}} M_R\,, & \lambda_1^{hR} = \lambda_1^{h\hat{R}} M_R\,, & C_0^R = c_0^{\hat{R}} M_R\,, \\
\widetilde{F}_R = \widetilde{f}_{\hat{R}} M_R\,, & \widetilde{G}_R = \widetilde{g}_{\hat{R}} M_R\,, & \widetilde{\lambda}_1^{hR} = \widetilde{\lambda}_1^{h\hat{R}} M_R\,, & \widetilde{C}_0^R = \widetilde{c}_0^{\hat{R}} M_R\,, \\
C_{\mathcal{T}}^R = c_{\mathcal{T}}^{\hat{R}}/M_R\,, & \widetilde{C}_{\mathcal{T}}^R = \widetilde{c}_{\mathcal{T}}^{\hat{R}}/M_R\,, & C_1^R = c_1^{\hat{R}}/M_R\,, & \widetilde{C}_1^R = \widetilde{c}_1^{\hat{R}}/M_R\,.
\end{array}
$$

  - ✓ The couplings of the non-resonant operators are different: $\mathcal{L}^{(P)}_{\mathrm{non-R}} \neq \mathcal{L}^{(A)}_{\mathrm{non-R}}$

- ✓ By using high-energy behaviour:
  - ✓ LECs with resonance contributions coming from $\chi_R^{\mu\nu}$ do not contain local contributions, $\mathcal{F}_i^{\mathrm{SDA}} = \widetilde{\mathcal{F}}_i^{\mathrm{SDA}} = 0$, so then the antisymmetric formalism is the best choice.
  - ✓ LECs with resonance contributions coming from $\hat{\chi}_{\hat{R}}^{\mu}$ do not contain local contributions, $\mathcal{F}_i^{\mathrm{SDP}} = \widetilde{\mathcal{F}}_i^{\mathrm{SDP}} = 0$, so then Proca is the best choice.

* Ecker et al. ’89
* Bijnens and Pallante '96
* Kampf, Novotny and Trnka '07
* Pich, IR, Santos and Sanz-Cillero ‘16 [and in progress]

3. Estimation of the LECs

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

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

* Ecker et al. ‘89
** Pich, IR, Santos and Sanz-Cillero ‘16 [and in progress]

3. Estimation of the LECs

- ✓ Integration of the heavy modes
- ✓ Similar to the ChPT case*
- ✓ Results**
  - ✓ Purely bosonic operators

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

i	$\Delta\mathcal{F}_i$	$\Delta\widetilde{\mathcal{F}}_i$
1	$-\frac{F_V^2-\widetilde{F}_V^2}{4M_V^2}+\frac{F_A^2-\widetilde{F}_A^2}{4M_A^2}$	$-\frac{\widetilde{F}_V G_V}{2M_V^2}-\frac{F_A\widetilde{G}_A}{2M_A^2}$
2	$-\frac{F_V^2+\widetilde{F}_V^2}{8M_V^2}-\frac{F_A^2+\widetilde{F}_A^2}{8M_A^2}$	$-\frac{F_V\widetilde{F}_V}{4M_V^2}-\frac{F_A\widetilde{F}_A}{4M_A^2}$
3	$-\frac{F_V G_V}{2M_V^2}-\frac{\widetilde{F}_A\widetilde{G}_A}{2M_A^2}$	$-\frac{F_V\widetilde{\lambda}_1^{hV}v}{M_V^2}-\frac{\widetilde{F}_A\lambda_1^{hA}v}{M_A^2}$
4	$\frac{G_V^2}{4M_V^2}+\frac{\widetilde{G}_A^2}{4M_A^2}$	—
5	$\frac{c_d^2}{4M_{S_1}^2}-\frac{G_V^2}{4M_V^2}-\frac{\widetilde{G}_A^2}{4M_A^2}$	—
6	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_V^2}-\frac{\lambda_1^{hA\,2}v^2}{M_A^2}$	—
7	$\frac{d_P^2}{2M_P^2}+\frac{\lambda_1^{hA\,2}v^2}{M_A^2}+\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_V^2}$	—
8	0	—
9	$-\frac{F_A\lambda_1^{hA}v}{M_A^2}-\frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M_V^2}$	—
10	$-\frac{(\widetilde{c}_T^{V_1})^2}{2M_{V_1}^2}-\frac{(c_T^{A_1})^2}{2M_{A_1}^2}$	—
11	$-\frac{F_{V_1}^2}{M_{V_1}^2}-\frac{\widetilde{F}_{A_1}^2}{M_{A_1}^2}$	—

* Ecker et al. '89

** Pich, IR, Santos and Sanz-Cillero '16 [and in progress]

3. Estimation of the LECs

- ✓ Integration of the heavy modes
- ✓ Similar to the ChPT case*
- ✓ Results**
  - ✓ Purely bosonic operators
  - ✓ Two-fermion operators

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

i	$\Delta\mathcal{F}_i^{\psi^2}$	$\Delta\widetilde{\mathcal{F}}_i^{\psi^2}$
1	$\frac{c_d c_1^{S_1}}{2M_{S_1}^2}$	$-\frac{\widetilde{F}_V C_0^V}{\sqrt{2}M_V^2}-\frac{F_A\widetilde{C}_0^A}{\sqrt{2}M_A^2}$
2	$-\frac{G_V C_0^V}{\sqrt{2}M_V^2}-\frac{\widetilde{G}_A\widetilde{C}_0^A}{\sqrt{2}M_A^2}$	$-\frac{2\sqrt{2}v\widetilde{\lambda}_1^{hV}C_0^V}{M_V^2}-\frac{2\sqrt{2}v\lambda_1^{hA}\widetilde{C}_0^A}{M_A^2}$
3	$-\frac{F_V C_0^V}{\sqrt{2}M_V^2}-\frac{\widetilde{F}_A\widetilde{C}_0^A}{\sqrt{2}M_A^2}$	$-\frac{\widetilde{c}_T^{\hat{V}_1}c_1^{\hat{V}_1}}{\sqrt{2}M_{V_1}^2}-\frac{c_T^{\hat{A}_1}\widetilde{c}_1^{\hat{A}_1}}{\sqrt{2}M_{A_1}^2}$
4	$-\frac{\sqrt{2}F_{V_1}C_0^{V_1}}{M_{V_1}^2}-\frac{\sqrt{2}\widetilde{F}_{A_1}\widetilde{C}_0^{A_1}}{M_{A_1}^2}$	—
5	$\frac{d_P c_1^P}{M_P^2}$	—
6	$-\frac{\widetilde{c}_T^{\hat{V}_1}\widetilde{c}_1^{\hat{V}_1}}{\sqrt{2}M_{V_1}^2}-\frac{c_T^{\hat{A}_1}c_1^{\hat{A}_1}}{\sqrt{2}M_{A_1}^2}$	—
7	0	—

* Ecker et al. '89
** Pich, IR, Santos and Sanz-Cillero '16 [and in progress]

3. Estimation of the LECs

- Integration of the heavy modes
- Similar to the ChPT case*
- Results**
  - Purely bosonic operators
  - Two-fermion operators
  - Four-fermion operators

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

i	$\Delta\mathcal{F}_i^{\psi^4}$	$\Delta\widetilde{\mathcal{F}}_i^{\psi^4}$
1	$\frac{(c_1^{S})^2}{2M_S^2}$	$-\frac{c_1^{\hat{V}}\widetilde{c}_1^{\hat{V}}}{M_V^2} - \frac{c_1^{\hat{A}}\widetilde{c}_1^{\hat{A}}}{M_A^2}$
2	$\frac{(c_1^{P})^2}{2M_P^2}$	$\frac{c_1^{\hat{V}}\widetilde{c}_1^{\hat{V}}}{2M_V^2} + \frac{c_1^{\hat{A}}\widetilde{c}_1^{\hat{A}}}{2M_A^2} - \frac{c_1^{\hat{V}_1}\widetilde{c}_1^{\hat{V}_1}}{2M_{V_1}^2} - \frac{c_1^{\hat{A}_1}\widetilde{c}_1^{\hat{A}_1}}{2M_{A_1}^2}$
3	$-\frac{(c_1^{S})^2}{4M_S^2} + \frac{(c_1^{S_1})^2}{4M_{S_1}^2}$	—
4	$-\frac{(c_1^{P})^2}{4M_P^2} + \frac{(c_1^{P_1})^2}{4M_{P_1}^2}$	—
5	$-\frac{(c_1^{\hat{V}})^2}{2M_V^2} - \frac{(\widetilde{c}_1^{\hat{A}})^2}{2M_A^2}$	—
6	$-\frac{(\widetilde{c}_1^{\hat{V}})^2}{2M_V^2} - \frac{(c_1^{\hat{A}})^2}{2M_A^2}$	—
7	$\frac{(c_1^{\hat{V}})^2}{4M_V^2} + \frac{(\widetilde{c}_1^{\hat{A}})^2}{4M_A^2} - \frac{(c_1^{\hat{V}_1})^2}{4M_{V_1}^2} - \frac{(\widetilde{c}_1^{\hat{A}_1})^2}{4M_{A_1}^2}$	—
8	$\frac{(\widetilde{c}_1^{\hat{V}})^2}{4M_V^2} + \frac{(c_1^{\hat{A}})^2}{4M_A^2} - \frac{(\widetilde{c}_1^{\hat{V}_1})^2}{4M_{V_1}^2} - \frac{(c_1^{\hat{A}_1})^2}{4M_{A_1}^2}$	—
9	$-\frac{(C_0^{V})^2}{M_V^2} - \frac{(\widetilde{C}_0^{A})^2}{M_A^2}$	—
10	$\frac{(C_0^{V})^2}{2M_V^2} - \frac{(C_0^{V_1})^2}{2M_{V_1}^2} + \frac{(\widetilde{C}_0^{A})^2}{2M_A^2} - \frac{(\widetilde{C}_0^{A_1})^2}{2M_{A_1}^2}$	—

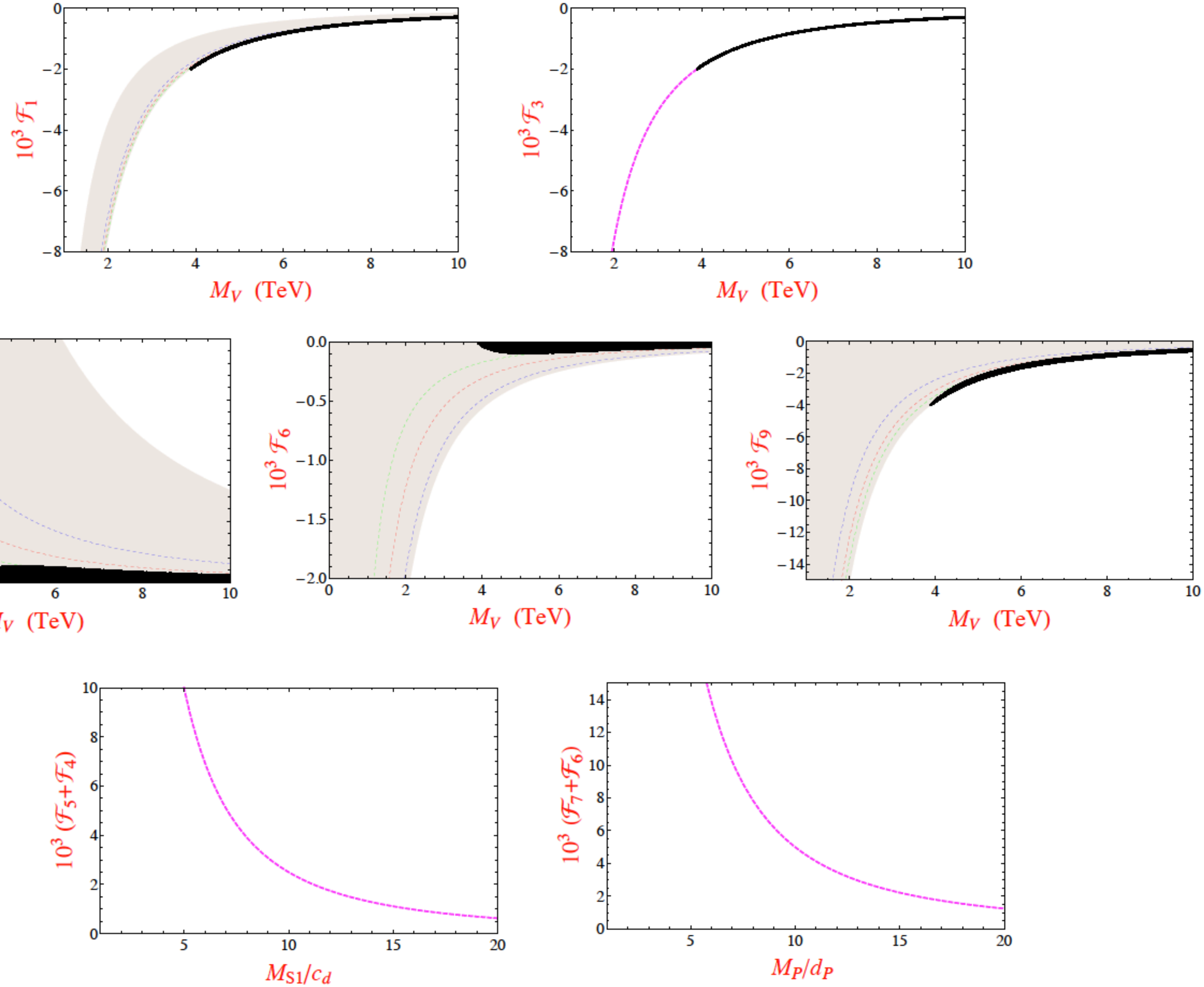
* Ecker et al. '89
** Pich, IR, Santos and Sanz-Cillero '16 [and in progress]

4. Short-distance constraints and the purely bosonic sector*

- ✓ Only P-even bosonic operators
- ✓ Short-distance constraints coming from two-Goldstone and Higgs-Goldstone vector form factors and Weinberg Sum Rules.
- ✓ Results in terms of a few resonance parameters:

$$
\begin{aligned}
\mathcal{F}_1 &= \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2} = -\frac{v^2}{4}\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right) \\
\mathcal{F}_2 &= -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2} = -\frac{v^2(M_V^4+M_A^4)}{8M_V^2M_A^2(M_A^2-M_V^2)} \\
\mathcal{F}_3 &= -\frac{F_VG_V}{2M_V^2} = -\frac{v^2}{2M_V^2} \\
\mathcal{F}_4 &= \frac{G_V^2}{4M_V^2} = \frac{(M_A^2-M_V^2)v^2}{4M_V^2M_A^2} \\
\mathcal{F}_5 &= \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} = \frac{c_d^2}{4M_{S_1}^2} - \frac{(M_A^2-M_V^2)v^2}{4M_V^2M_A^2} \\
\mathcal{F}_6 &= -\frac{(\lambda_1^{hA})^2v^2}{M_A^2} = -\frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6} \\
\mathcal{F}_7 &= \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2v^2}{M_A^2} = \frac{d_P^2}{2M_P^2} + \frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6} \\
\mathcal{F}_8 &= 0 \\
\mathcal{F}_9 &= -\frac{F_A\lambda_1^{hA}v}{M_A^2} = -\frac{M_V^2v^2}{M_A^4}
\end{aligned}
$$

* Pich, IR, Santos and Sanz-Cillero '16



$10^3\,\mathcal{F}_1$
M_V (TeV)
$10^3\,\mathcal{F}_3$
M_V (TeV)
$10^3\,\mathcal{F}_4$
M_V (TeV)
$10^3\,\mathcal{F}_6$
M_V (TeV)
$10^3\,\mathcal{F}_9$
M_V (TeV)
$10^3\,(\mathcal{F}_5+\mathcal{F}_4)$
M_{S1}/c_d
$10^3\,(\mathcal{F}_7+\mathcal{F}_6)$
M_P/d_P

5. 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* power counting and short-distance constraints.

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

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Estimation of the LECs

1. Building the low-energy and high-energy Lagrangian
2. Equivalence between Proca and antisymmetric formalism
3. Integrating out the resonances
4. Estimation of the LECs
5. Short-distance constraints

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

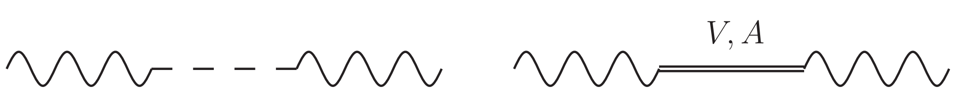
$$\mathcal{L} = \frac{v^2}{4}\langle u_\mu u^\mu\rangle\left(1+\frac{2\,\kappa_W}{v}\,h\right)$$ ← π and h sector

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

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

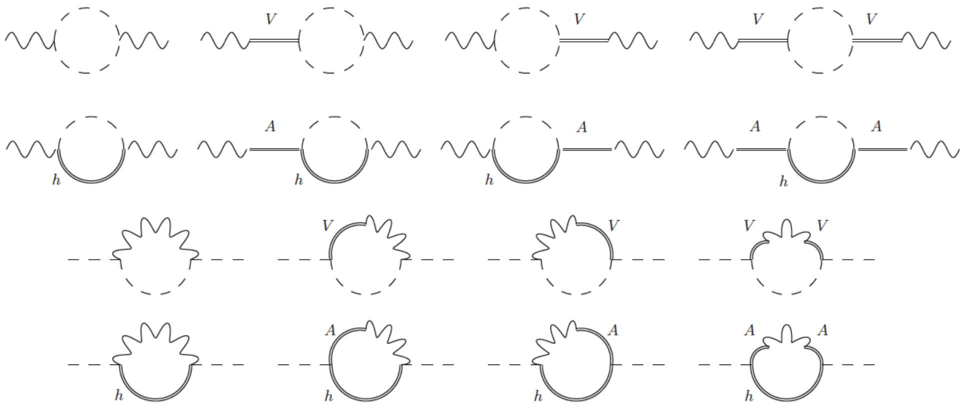


$$S_{\rm LO}=4\pi\left(\frac{F_V^2}{M_V^2}-\frac{F_A^2}{M_A^2}\right)$$

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

* 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 not known.
- ✓ Weinberg Sum-Rules (WSR)***:

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

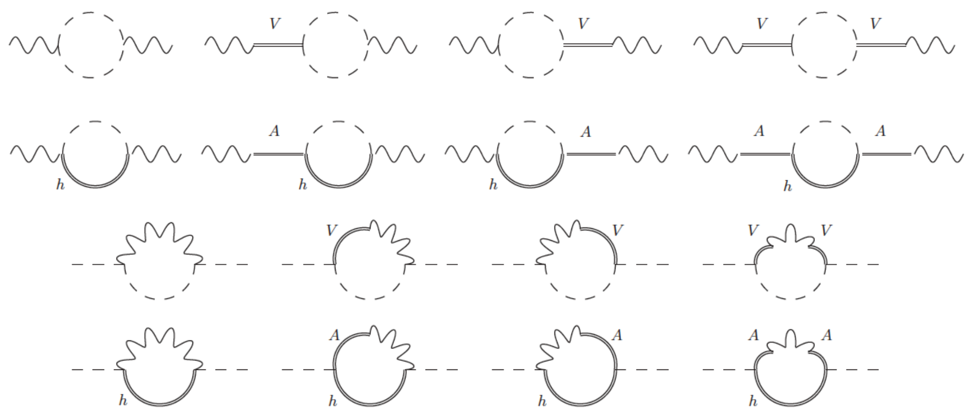
- ✓ We have 7 resonance parameters and up to 5 constraints:
  - ✓ With both, the 1st and the 2nd WSR: κ_W and M_V as free parameters
  - ✓ With only the 1st WSR: κ_W, M_V and M_A as free parameters

* 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.

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



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- ✓ We have seven resonance parameters: importance of short-distance information.
- ✓ In contrast to QCD, the underlying theory is not known.
- ✓ Weinberg Sum-Rules (WSR)***:

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

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

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

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

* 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.
^ Ecker et al. '89
^^Pich, IR and Sanz-Cillero '08

Backup slides: S and T at LO and at NLO

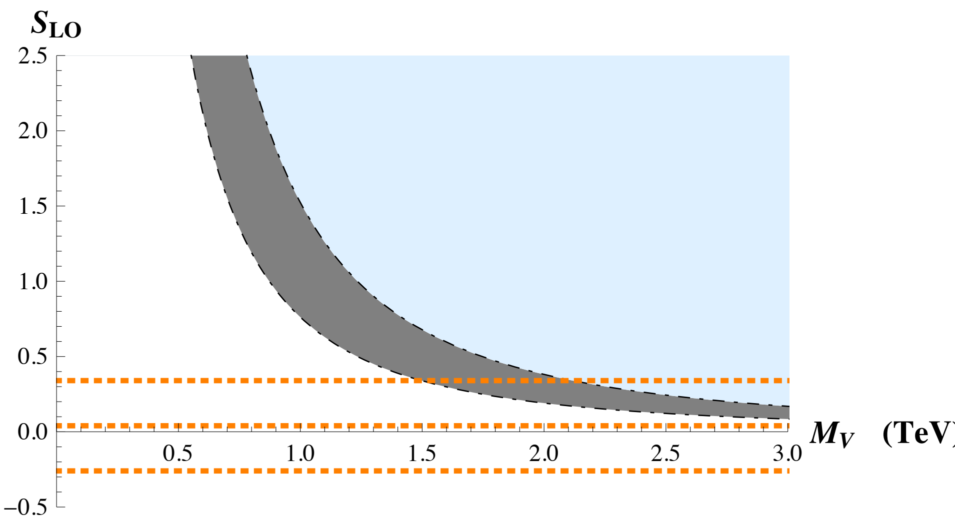
S = 0.03 ± 0.10 * (M_H=0.126 TeV)
T = 0.05 ± 0.12 * (M_H=0.126 TeV)

i) LO results

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

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

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



i.ii) Only 1st WSR***

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

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

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

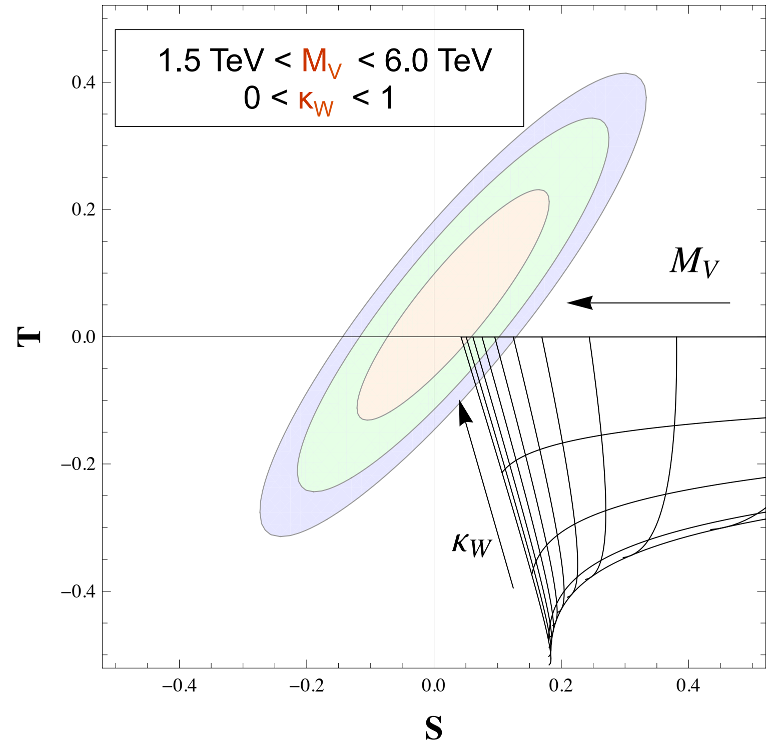
* Gfitter
* LEP EWWG
* Zfitter

** Peskin and Takeuchi '92

*** Pich, IR and Sanz-Cillero '12

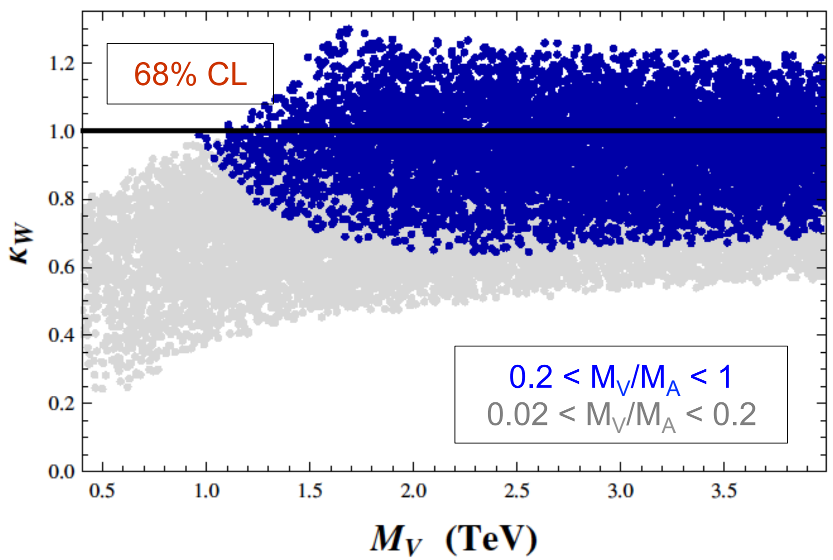
ii) NLO results: 1st and 2nd WSRs*

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



Similar conclusions, but softened

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



- ✓ 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.

iv) 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]