CEU
Universidad
Cardenal Herrera

ICHEP 2018
Seoul (Korea), July 6, 2018

Heavy resonances and the electroweak effective theory

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CPAN
Ingenio 2010

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Work in progress
JHEP 04 (**2017**) 012 [arXiv: 1609.06659]
PRD 93 (**2016**) no.5, 055041 [arXiv: 1510.03114]

OUTLINE

1) Motivation

2) Building the Lagrangian

   1) Low energies: the Electroweak Effective Theory (EWET)
   2) High energies: Resonance Lagrangian

3) Estimation of the LECs: tracks of resonances in the EWET

4) Phenomenology in the purely bosonic sector

5) Conclusions

1. Motivation

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

- 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

- Up to now all searches for New Physics have been negative so far. Therefore we can use EFTs because we have a mass gap.

  ➡ Effective Field Theories

* CMS and ATLAS Collaborations.

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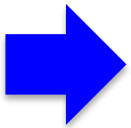

Effective Field Theories

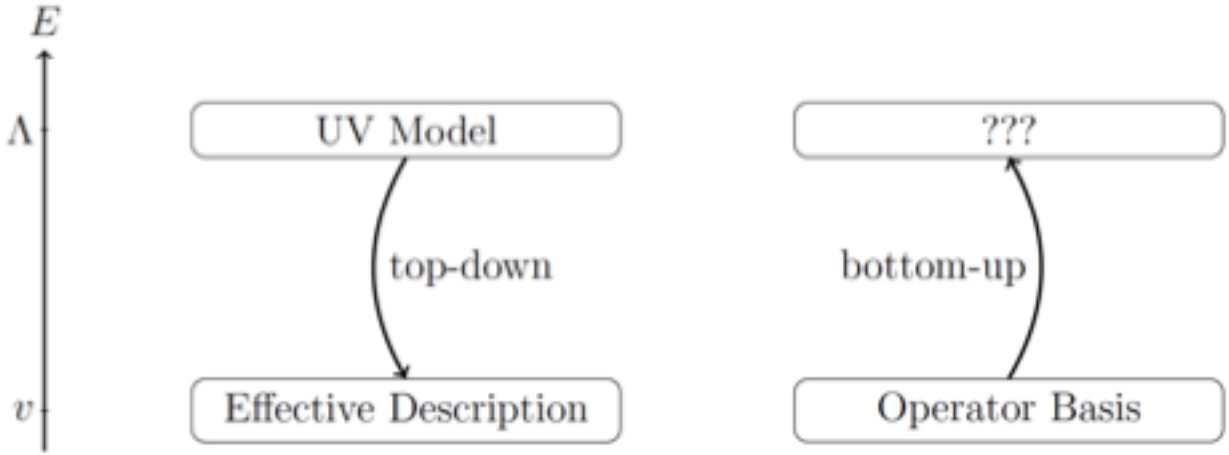

Diagram by C. Krause [PhD thesis, 2016]

* CMS and ATLAS Collaborations.

- Depending on the nature of the EWSB we have two possibilities for these EFTs* (or something in between):

  - Decoupling (linear) EFT: SMEFT

    - SM-Higgs (forming a doublet with the EW Goldstones)
    - Weakly coupled
    - LO: SM
    - Expansion in canonical dimensions

  - Non-decoupling (non-linear) EFT: EWET, HEFT, EWChL

    - Non-SM Higgs (being a scalar singlet)
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    - LO: Higgsless SM + scalar h + 3 GB (chiral Lagrangian)
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* LHCHXSWG Yellow Report '16

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  - Non-decoupling (non-linear) EFT: EWET, HEFT, EWChL [see Rosenlyst's and Cacciapaglia's talks, in the spirit of Composite Higgs models, where the electroweak scale is dynamically generated]

    - Non-SM Higgs (being a scalar singlet)
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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?

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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) occurring in QCD, *i.e.*, similar to the "pion" Lagrangian of Chiral Perturbation Theory (ChPT)*^, by replacing f_π by $v=1/\sqrt{(2G_F)}=246$ GeV. Rescaling naïvely we expect resonances at the TeV scale.

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

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

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

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Similarities to Chiral Symmetry Breaking in QCD

QCD $(q_a,\ G_{\mu\nu})$	Fundamental EW Theory (??)
$\updownarrow$	$\updownarrow$
Resonance Chiral Theory $(\sigma,\ \rho,\ \ldots)$	**Resonance EW Theory** $(M_V,\ M_A,\ \ldots)$
$\updownarrow$	$\updownarrow$
Chiral Perturbation Theory $(f_\pi,\ \pi_i)$	EW Effective Theory $(v,\ \phi_i)$

Diagram by J. Santos [VIII CPAN days, 2016]

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

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

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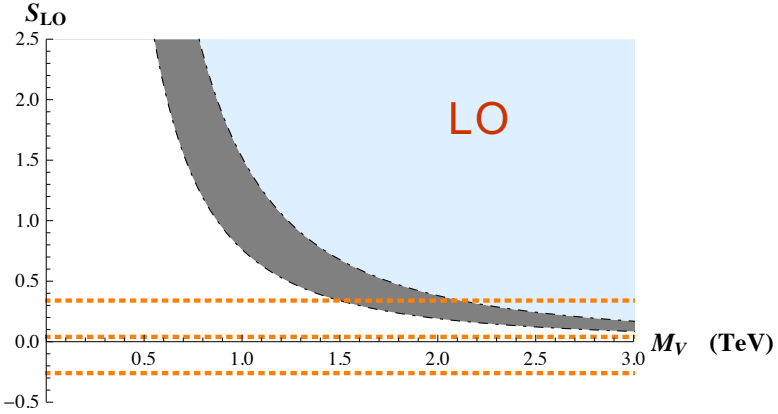

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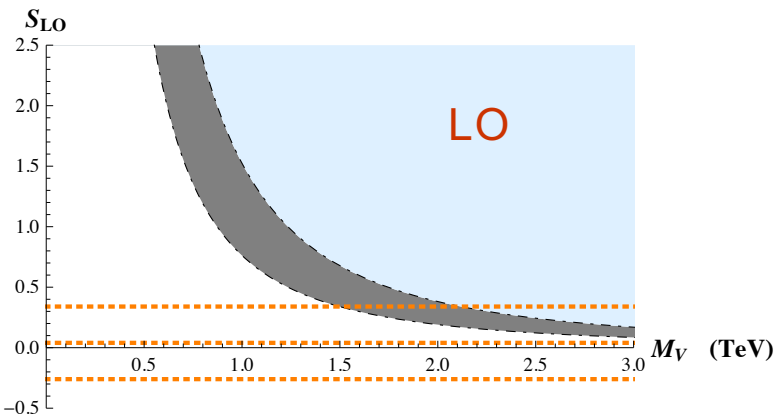

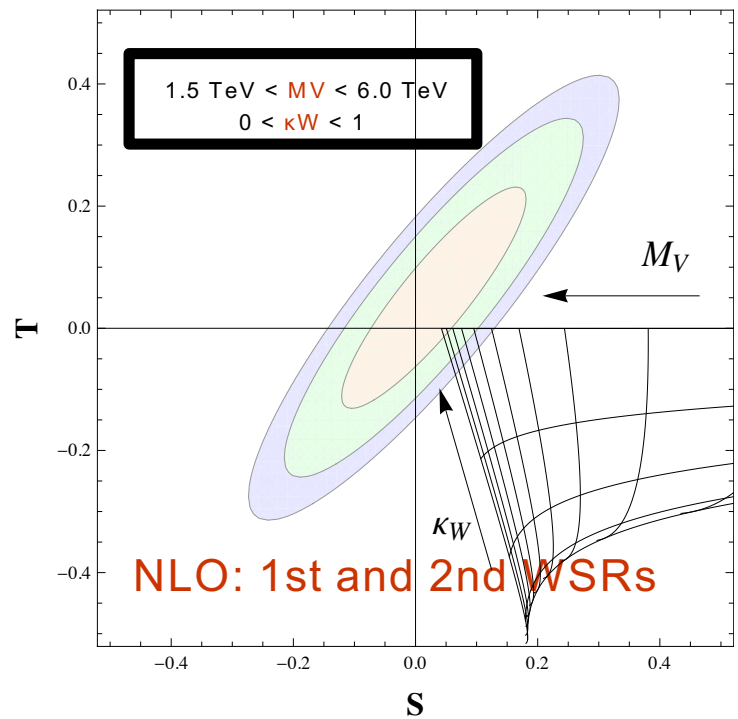

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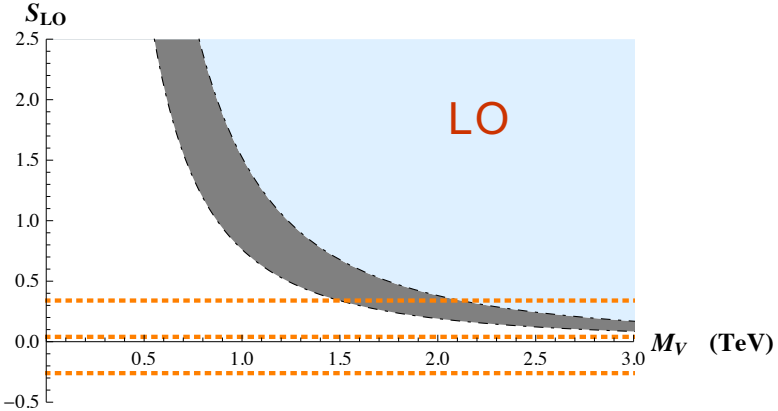

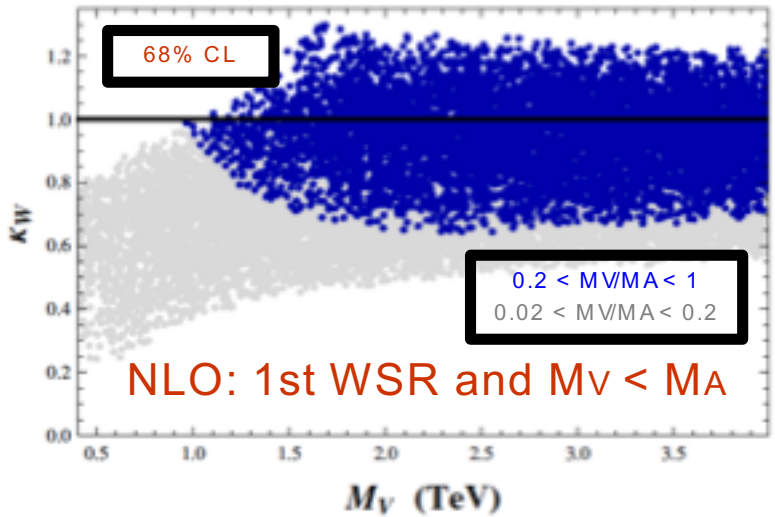

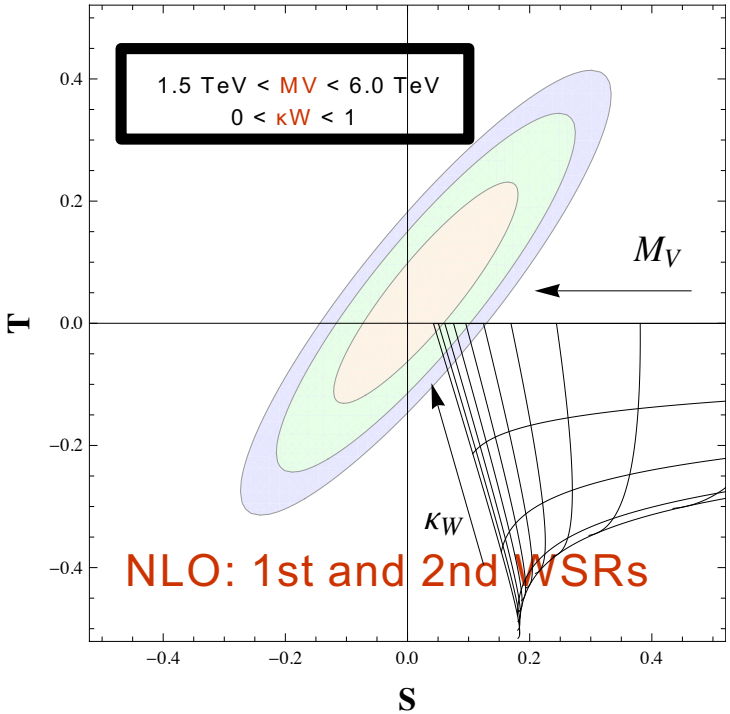

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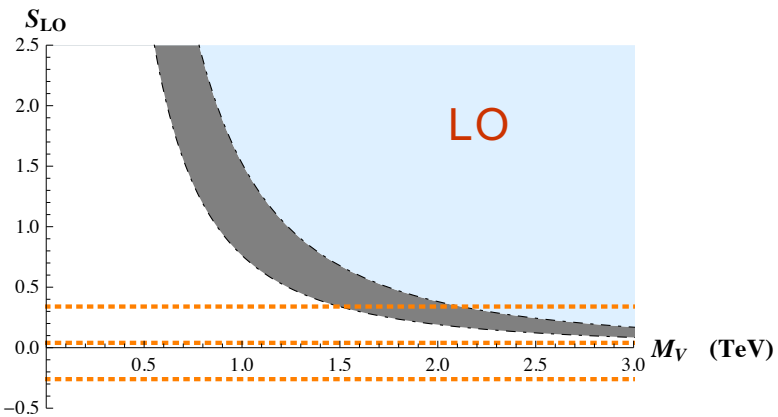

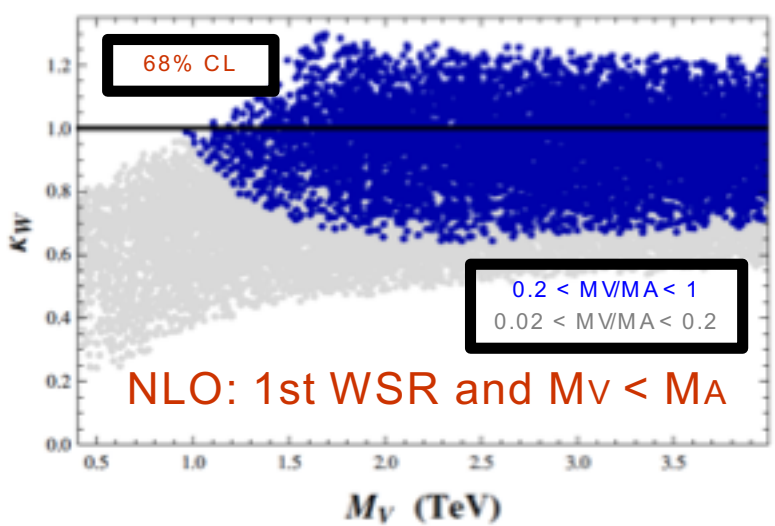

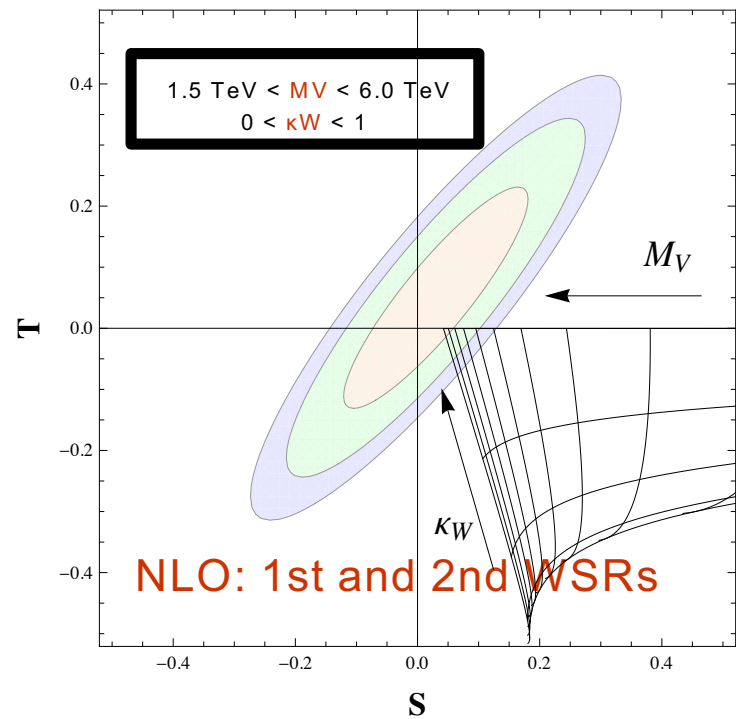

Room for these scenarios
$\kappa_W \cong 1$
$M_R \approx$ TeV

* 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 Lagrangians 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 (bottom-up approach).
- ✓ 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 '17

* Krause, Pich, IR, Santos and Sanz-Cillero [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 and fermionic)
- ✓ *Chiral* power counting*

$$\frac{\chi}{v} \sim \mathcal{O}\left(p^0\right) \qquad \frac{\psi}{v} \sim \mathcal{O}\left(p\right) \qquad \partial_\mu, m \sim \mathcal{O}(p) \qquad \mathcal{T} \sim \mathcal{O}(p) \qquad g, g' \sim \mathcal{O}(p)$$

* 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
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Finite pieces from loops (amplitude dependent)

$$\mathcal{M}(2\to 2) \approx \frac{p^2}{v^2}\left[\underbrace{1}_{\text{LO (tree)}} + \left(\underbrace{\frac{c_k^r\, p^2}{v^2}}_{\text{NLO (tree)}} - \underbrace{\frac{\Gamma_k\, p^2}{16\pi^2 v^2}\ln\frac{p}{\mu}}_{\text{NLO (1-loop)}} + \ldots\right) + \mathcal{O}(p^4)\right]$$

suppression $\sim 1/M^2 + \ldots$ **(heavier states)**

Typical loop suppression $\sim \mathcal{L}/(16\pi^2 v^2)$ **(non-linearity)**

Diagram by J.J. Sanz-Cillero [HEP 2017]

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2.1. Low energies: the Electroweak Effective Theory (no resonances)*

$$\mathcal{L}^{(2)}_{\rm EWET} = \sum_{\xi} \left(i\,\bar{\xi}\gamma^\mu d_\mu \xi - v\,\left(\,\bar{\xi}_L\,\mathcal{Y}\,\xi_R\,+\,\text{h.c.}\right)\right)$$
$$- \frac{1}{2g^2}\langle \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\rangle_2 - \frac{1}{2g'^2}\langle \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\rangle_2 - \frac{1}{2g_s^2}\langle \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\rangle_3$$
$$+ \frac{1}{2}\partial_\mu h\,\partial^\mu h\,-\,\frac{1}{2}\,m_h^2\,h^2\,-\,V(h/v)\,+\,\frac{v^2}{4}\,\mathcal{F}_u(h/v)\,\langle u_\mu u^\mu\rangle_2$$

* Longhitano '80 '81
* Buchalla and Catà '12 '14
* Alonso et al. '13
* Guo, Ruiz-Femenia and Sanz-Cillero '15
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$$\mathcal{L}^{(4)}_{\rm EWET} = \sum_{i=1}^{12} \mathcal{F}_i\, \mathcal{O}_i + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i\, \widetilde{\mathcal{O}}_i + \sum_{i=1}^{8} \mathcal{F}_i^{\psi^2}\, \mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{\psi^2}\, \widetilde{\mathcal{O}}_i^{\psi^2} + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4}\, \mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2} \widetilde{\mathcal{F}}_i^{\psi^4}\, \widetilde{\mathcal{O}}_i^{\psi^4}$$

Bosonic sector

i	$\mathcal{O}_i$	$\widetilde{\mathcal{O}}_i$
1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\mu\nu} - f_-^{\mu\nu} f_{-\mu\nu}\rangle_2$	$\frac{i}{2}\langle f_-^{\mu\nu}[u_\mu, u_\nu]\rangle_2$
2	$\frac{1}{2}\langle f_+^{\mu\nu} f_{+\mu\nu} + f_-^{\mu\nu} f_{-\mu\nu}\rangle_2$	$\langle f_+^{\mu\nu} f_{-\mu\nu}\rangle_2$
3	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle_2$	$\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu} u_\nu\rangle_2$
4	$\langle u_\mu u_\nu\rangle_2 \langle u^\mu u^\nu\rangle_2$	—
5	$\langle u_\mu u^\mu\rangle_2^2$	—
6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle_2$	—
7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle_2$	—
8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	—
9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu} u_\nu\rangle_2$	—
10	$\langle \mathcal{T} u_\mu\rangle_2^2$	—
11	$\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$	—
12	$\langle \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\rangle_3$	—

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2.2. High energies: Resonance Lagrangian (with resonances)**

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

- Bosonic resonances:
  - V, A, S and P
  - SU(2) singlets and triplets
  - SU(3) singlets and octets
  - Spin-1 resonances with Proca or antisymmetric formalism
- Fermionic doublet resonances:
  - Including operators with one heavy fermionic resonance

Field (R^{QCD}_{EW})	R^1_1	R^1_3	R^8_1	R^8_3
S	3	1	1	1
P	1	1	1	1
V with Proc	3	2	2	2
A with Proc	3	2	2	2
V with ant.	2	5	2	1
A with ant.	2	5	2	1
Fermionic	6			

** Pich, IR, Santos and Sanz-Cillero '16 '17

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

3. Estimation of the LECs: tracks of resonances in EWET

- ✓ Integration of the heavy modes
- ✓ Similar to the ChPT case*
- ✓ The result: LECs in terms of resonance couplings**
- ✓ LHC dibosons analysis useful for four-fermion operators (HVT models) [see Grevtsov's talk]
- ✓ As an example we show a simplified case of bosonic operators:

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

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

P-even operators, color singlets, neither explicit breaking of custodial symmetry nor U(1)x field strength tensor.

Importance of short-distance constraints (two-Goldstone and Higgs-Goldstone vector form factors and Weinberg Sum Rules).

* Ecker et al. '89
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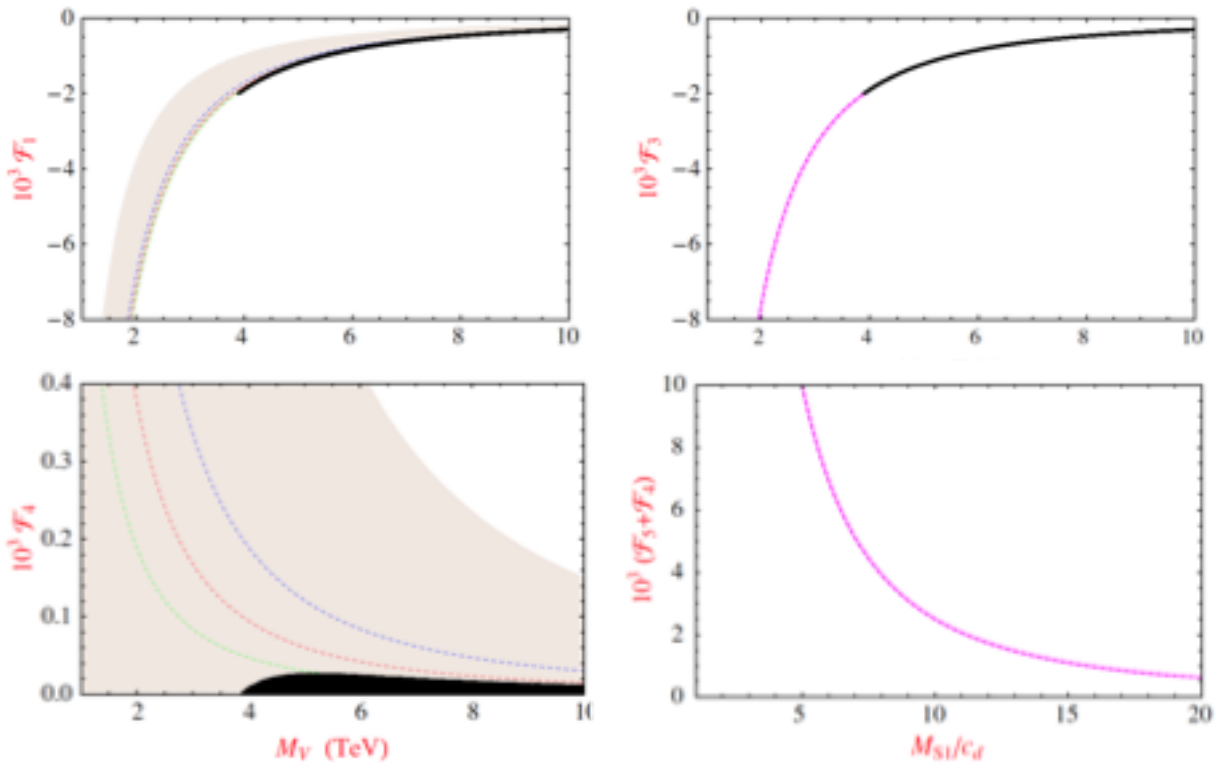
S-T allowed region (95% CL)

$M_A > M_V$

$k_W = M_V^2/M_A^2 = 0.8, 0.9, 0.95$



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From ChPT one would expect $F_i \approx 1/(4\pi^2) \approx 10^{-3}$.

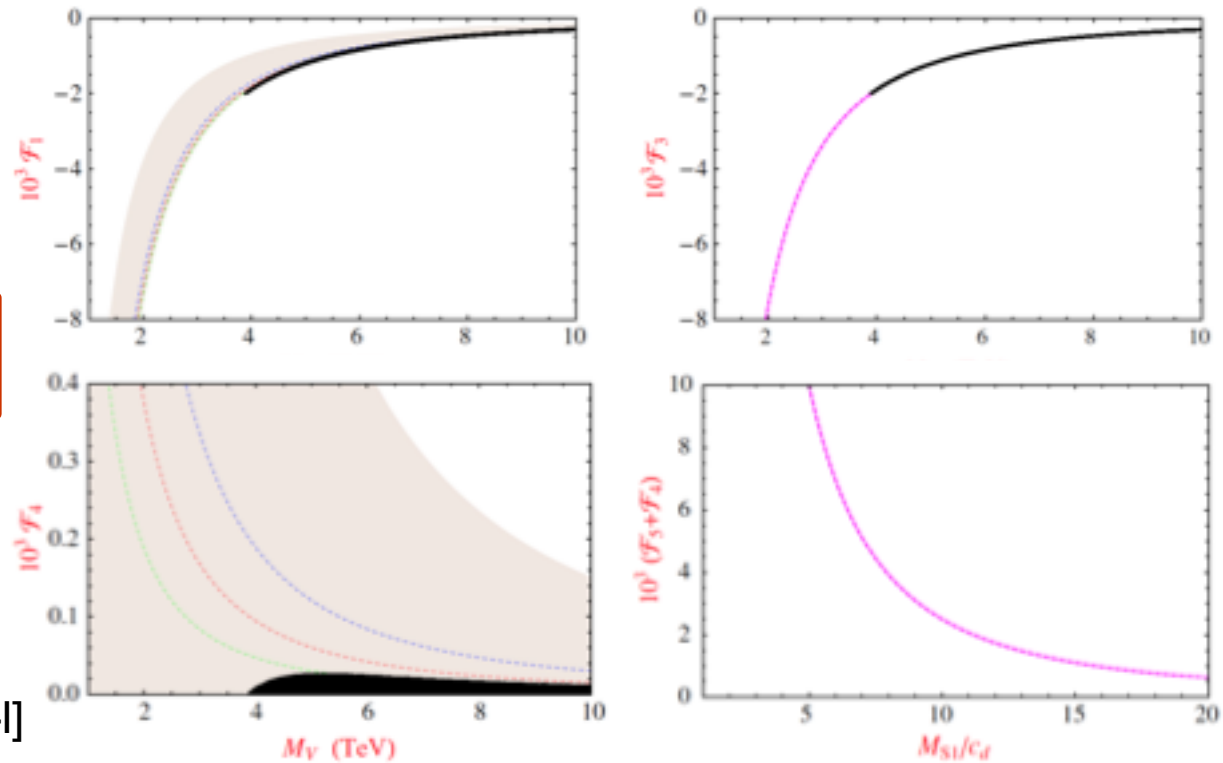
$-2\cdot 10^{-3} < F_1 < 0$ [LEP-I, LEP-II]

$-0.11 < F_3 < 0.12$ [LEP, collider data]

$-0.024 < F_4 < 0.030$ [LHC run-I]

$-0.037 < F_4+F_5 < 0.045$ [LHC run-I]

$0.79 < k_W < 1.01$ (68% CL)[LHC run-I]



5. Conclusions

- ✓ The SM provides a successful description of the electroweak and strong interactions.
- ✓ The LHC discovered a new particle around 125 GeV.
- ✓ Bottom-up EFTs are appropriate, since there is a mass gap between SM and New Physics. Depending on the nature of the EWSB we have two possibilities:
  - ✓ Decoupling (linear) EFT: SMEFT
    - ✓ SM-Higgs and weakly coupled
    - ✓ Expansion in canonical dimensions
  - ✓ Non-decoupling (non-linear) EFT: EWET
    - ✓ Non-SM Higgs and strongly coupled
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- ✓ Similarities to ChSB of QCD -> ChPT and RChT
  - ✓ Room for these strongly-coupled scenarios and $M_R \approx$ TeV*.
  - ✓ Colored fields and fermionic doublet resonances^.
  - ✓ Renormalizable order by order à la ChPT.
  - ✓ Proca and antisymmetric formalisms for the spin-1 resonances are equivalent*^.
- ✓ **Estimation of the LECs by using Resonance Lagrangians and short-distance constraints*^.**

Why?

What?

* Pich, IR, Santos and Sanz-Cillero '16 '17

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

What do we add now* to our previous projects**?

1. Colored fields to the EWET
2. Colored bosonic resonances
3. Fermionic doublet resonances
4. Comparison with other EWET basis***

* Krause, Pich, IR, Santos and Sanz-Cillero [in progress]
** Pich et al. '16 '17
*** Buchalla et al. '14

Proca vs. antisymmetric formalism*

- ✓ By using path integral and changes of variables both formalisms are proven to be equivalent:
  - ✓ A set of relations between resonance parameters emerges.
  - ✓ The couplings of the non-resonant operators are different: $\mathcal{L}^{(P)}_{\rm non-R} \neq \mathcal{L}^{(A)}_{\rm non-R}$

* Ecker et al. '89
* Bijnens and Pallante '96
* Kampf, Novotny and Trnka '07
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- ✓ High-energy behaviour is fundamental:

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

$$\mathcal{F}_3^{\rm SDA} = 0$$

$$\mathcal{F}_3^{\rm SDP} = -\frac{f_{\hat{V}}\, g_{\hat{V}}}{2} - \frac{\widetilde{f}_{\hat{A}}\, \widetilde{g}_{\hat{A}}}{2}$$

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