CEU
Universidad
Cardenal Herrera

BSM models in Vector Boson Scattering processes
Lisbon, December 5, 2019

Non-linear EFT and BSM models

Ignasi Rosell
Universidad CEU Cardenal Herrera
València (Spain)

In collaboration with:
C. Krause (Fermilab, Chicago, USA)
A. Pich (IFIC, UV-CSIC, València, Spain)
J. Santos (UPV, València, Spain)
J.J. Sanz-Cillero (UCM, Madrid, Spain)

CPAN
Ingenio 2010

JHEP 05 (**2019**) 092 [arXiv: 1810.10544]
JHEP 04 (**2017**) 012 [arXiv: 1609.06659]
PRD 93 (**2016**) no.5, 055041 [arXiv: 1510.03114]
JHEP 01 (**2014**) 157 [arXiv: 1310.3121]
PRL 110 (**2013**) 181801 [arXiv: 1212.6769]

OUTLINE

1) Motivation

2) The effective Lagrangians

   1) Low energies: the non-linear Electroweak Effective Theory
   2) High energies: Resonance Lagrangian
   3) Matching low and high energies

3) Phenomenology

   1) S and T at NLO
   2) Estimation of the bosonic LECs
   3) Contact four-fermion operators

4) Conclusions

OUTLINE

1) Motivation

Also known as HEFT or EWChL

2) The effective Lagrangians

   1) Low energies: the non-linear Electroweak Effective Theory
   2) High energies: Resonance Lagrangian
   3) Matching low and high energies

3) Phenomenology

   1) S and T at NLO
   2) Estimation of the bosonic LECs
   3) Contact four-fermion operators

4) 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 given negative results: Higgs couplings compatible with the SM and no new states. Therefore we can use EFTs because we have a mass gap.

  → Effective Field Theories

* CMS and ATLAS Collaborations.

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 given negative results: Higgs couplings compatible with the SM and no new states. Therefore we can use EFTs because we have a mass gap. ➔ Effective Field Theories

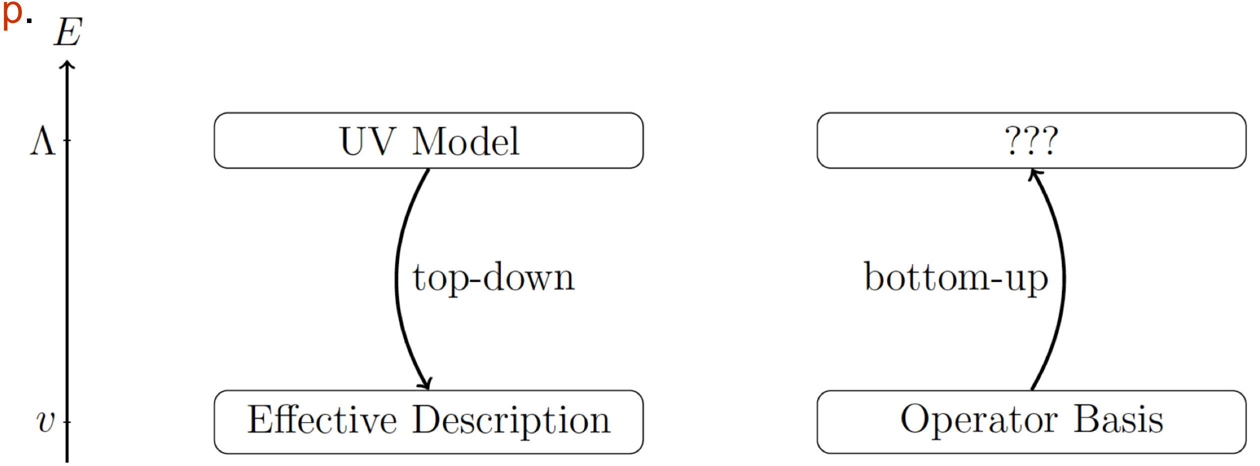


Diagram by C. Krause [PhD thesis, 2016]

* CMS and ATLAS Collaborations.

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

Talk by I. Brivio

- The more common decoupling (linear) EFT: SMEFT
  - SM-Higgs (forming a doublet with the EW Goldstones, as in the SM)
  - Weakly coupled
  - LO: SM
  - Expansion in canonical dimensions

- The more general non-decoupling (non-linear) EFT: EWET, HEFT, EWChL
  - Non-SM Higgs (being a scalar singlet)
  - Strongly coupled
  - LO: Higgsless SM + scalar h + 3 GB (chiral Lagrangian)
  - Expansion in loops or chiral dimensions
  - Some composite Higgs models can be described within the EWET.

Talks by D. Buorque and G. Cacciapaglia

* LHCHXSWG Yellow Report '16

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

Talk by I. Brivio

- The more common decoupling (linear) EFT: SMEFT
  - SM-Higgs (forming a doublet with the EW Goldstones, as in the SM)
  - Weakly coupled
  - LO: SM
  - Expansion in canonical dimensions

- The more general non-decoupling (non-linear) EFT: EWET, HEFT, EWChL
  - Non-SM Higgs (being a scalar singlet)
  - Strongly coupled
  - LO: Higgsless SM + scalar h + 3 GB (chiral Lagrangian)
  - Expansion in loops or chiral dimensions
  - Some composite Higgs models can be described within the EWET.

Talks by D. Buorque and G. Cacciapaglia

* LHCHXSWG Yellow Report '16

What do we want to do?

Estimation of the LECs	Estimation of the Low Energy Couplings (LECs) of the EWET in terms of resonance parameters.
Short-distance constraints	Short-distance contraints are fundamental because we understand the resonance Lagrangian as an interpolation between low- and high energies and in order to reduce the number of resonance parameters.
Phenomenology	Following a typical bottom-up approach, what values for resonance masses from phenomenology?

What do we want to do?

Estimation of the LECs → Estimation of the Low Energy Couplings (LECs) of the EWET in terms of resonance parameters.

Short-distance constraints → Short-distance contraints are fundamental because we understand the resonance Lagrangian as an interpolation between low- and high energies and in order to reduce the number of resonance parameters.

Phenomenology → Following a typical bottom-up approach, what values for resonance masses from phenomenology?

What do we want to do?

Estimation of the LECs → Estimation of the Low Energy Couplings (LECs) of the EWET in terms of resonance parameters.

Short-distance constraints → Short-distance contraints are fundamental because we understand the resonance Lagrangian as an interpolation between low- and high energies and in order to reduce the number of resonance parameters.

Phenomenology → Following a typical bottom-up approach, what values for resonance masses from phenomenology?

Similarities to Chiral Symmetry Breaking in QCD

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

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

What do we want to do?

Estimation of the LECs → Estimation of the Low Energy Couplings (LECs) of the EWET in terms of resonance parameters.

Short-distance constraints → Short-distance contraints are fundamental because we understand the resonance Lagrangian as an interpolation between low- and high energies and in order to reduce the number of resonance parameters.

Phenomenology → Following a typical bottom-up approach, what values for resonance masses from phenomenology?

Similarities to Chiral Symmetry Breaking in QCD

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

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

2. The effective Lagrangians

- ✓ 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 and phenomenological consequences: constraining the BSM heavy masses.

- ✓ Steps:

  1. Building the EWET and resonance Lagrangian
  2. Matching the two effective theories
  3. Phenomenology at low energies.

- ✓ 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.

- ✓ 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 '19

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

2. The effective Lagrangians

- ✓ 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 and phenomenological consequences: constraining the BSM heavy masses.

- ✓ Steps:

  1. Building the EWET and resonance Lagrangian
  2. Matching the two effective theories
  3. Phenomenology at low energies.

  Bottom-up approach

- ✓ 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.

- ✓ 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 '19

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

How do we build the Lagrangian?

Talk by I. Brivio

- ✓ 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
* Buchalla, Catá and Krause '13
* Brivio et al. '13
* Delgado et al. '14
* Pich, IR, Santos and Sanz-Cillero '16 '17
* Krause, Pich, IR, Santos and Sanz-Cillero '19

How do we build the Lagrangian?

✓ Custodial symmetry

Talk by I. Brivio

✓ 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*

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

Finite pieces from loops (amplitude dependent)

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

LO (tree)

NLO (tree) suppression ~1/M² + ... (heavier states)

NLO (1-loop) Typical loop suppression ~ 1/(16π²v²) (non-linearity)

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

* 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 '17
* Krause, Pich, IR, Santos and Sanz-Cillero '19

How do we build the Lagrangian?

✓ Custodial symmetry

Talk by I. Brivio

✓ 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*

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

Finite pieces from loops (amplitude dependent)

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

LO (tree)

NLO (tree) suppression ~1/M² + ... (heavier states)

NLO (1 loop) Typical loop suppression ~ 1/(16π²v²) (non-linearity)

Order-by-order renormalization

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

* 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 '17
* Krause, Pich, IR, Santos and Sanz-Cillero '19

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

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

* Longhitano '80 '81
* Buchalla et al. '12 '14
* Alonso et al. '13
* Guo, Ruiz-Femenia and Sanz-Cillero '15
* Pich, IR, Santos and Sanz-Cillero '16 '17
* Krause, Pich, IR, Santos and Sanz-Cillero '19

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

$$\mathcal{L}_{\rm EWET}^{(4)} = \sum_{i=1}^{12} \mathcal{F}_i\, \mathcal{O}_i + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i\, \widetilde{\mathcal{O}}_i + \sum_{i=1}^{8} \mathcal{F}_i^{\psi^2}\, \mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{\psi^2}\, \widetilde{\mathcal{O}}_i^{\psi^2} + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4}\, \mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2} \widetilde{\mathcal{F}}_i^{\psi^4}\, \widetilde{\mathcal{O}}_i^{\psi^4}$$

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	$\langle \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\rangle_3$	—

* Longhitano '80 '81
* Buchalla et al. '12 '14
* Alonso et al. '13
* Guo, Ruiz-Femenia and Sanz-Cillero '15
* Pich, IR, Santos and Sanz-Cillero '16 '17
* Krause, Pich, IR, Santos and Sanz-Cillero '19

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

$$\mathcal{L}_{\rm EWET}^{(4)} = \sum_{i=1}^{12} \mathcal{F}_i\, \mathcal{O}_i + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i\, \widetilde{\mathcal{O}}_i + \sum_{i=1}^{8} \mathcal{F}_i^{\psi^2}\, \mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{\psi^2}\, \widetilde{\mathcal{O}}_i^{\psi^2} + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4}\, \mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2} \widetilde{\mathcal{F}}_i^{\psi^4}\, \widetilde{\mathcal{O}}_i^{\psi^4}$$

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	2	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 '19

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

$$\mathcal{L}_{\rm EWET}^{(4)} = \sum_{i=1}^{12} \mathcal{F}_i\, \mathcal{O}_i + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i\, \widetilde{\mathcal{O}}_i + \sum_{i=1}^{8} \mathcal{F}_i^{\psi^2}\, \mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i^{\psi^2}\, \widetilde{\mathcal{O}}_i^{\psi^2} + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4}\, \mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2} \widetilde{\mathcal{F}}_i^{\psi^4}\, \widetilde{\mathcal{O}}_i^{\psi^4}$$

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

2.3. Matching low and high energies

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

- ✓ Integration of the heavy modes
- ✓ Similar to the ChPT case***
- ✓ EWET LECs in terms of resonance parameters**
- ✓ Tracks of resonances in the EWET.

Talk by I. Brivio

** Pich, IR, Santos and Sanz-Cillero '16 '17
** Krause, Pich, IR, Santos and Sanz-Cillero '19

*** Ecker et al. '89

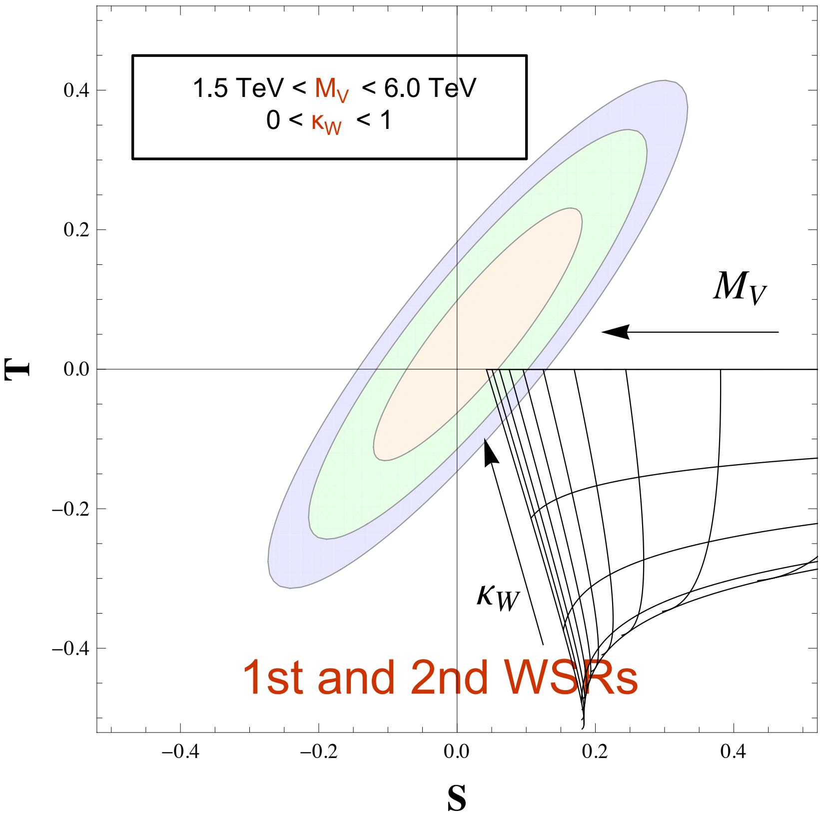
3. Phenomenology I: S and T at NLO*

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

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

3. Phenomenology I: S and T at NLO*

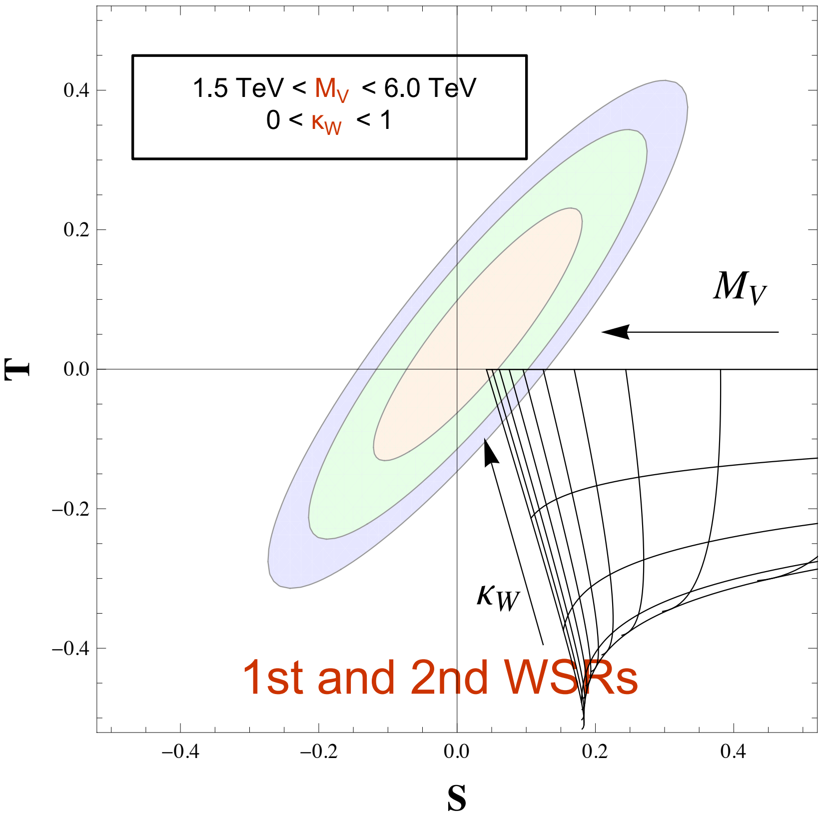
- ✓ Oblique electroweak observables** (S and T)
- ✓ Dispersive relations for both S** and T*
- ✓ Short-distance constraints: two-Goldstone and Higgs-Goldstone form factors, Weinberg Sum Rules

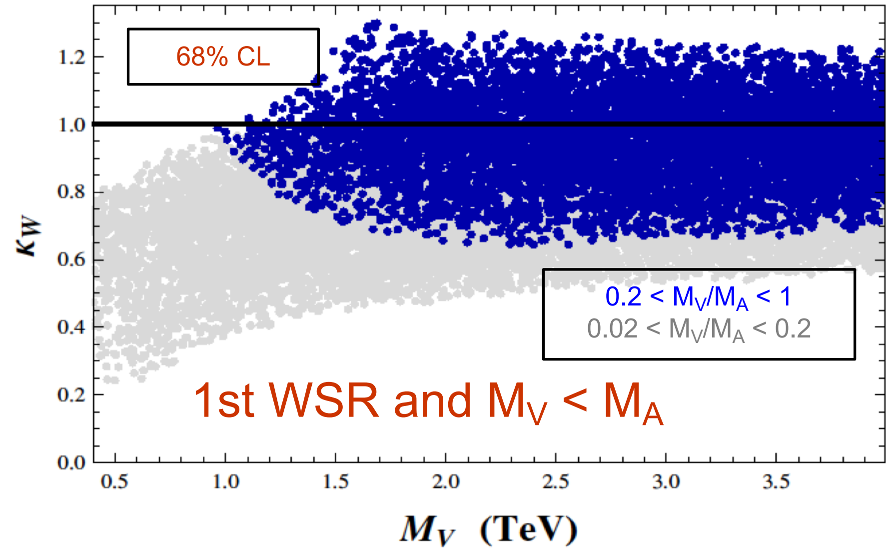


* Pich, IR and Sanz-Cillero '12 '13 '14
** Peskin and Takeuchi '92

3. Phenomenology I: S and T at NLO*

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

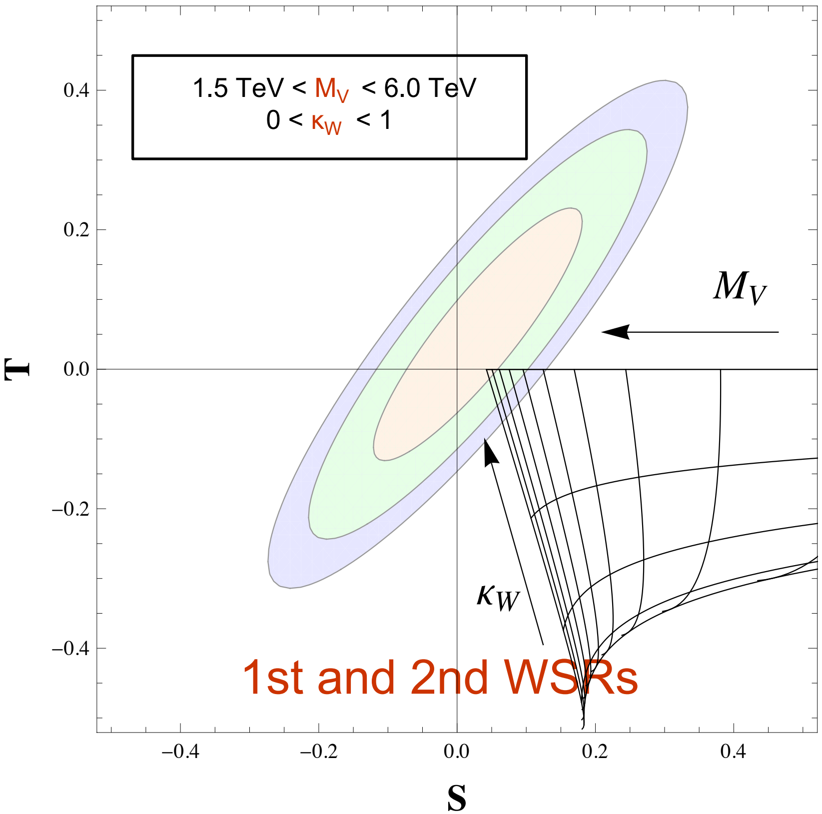


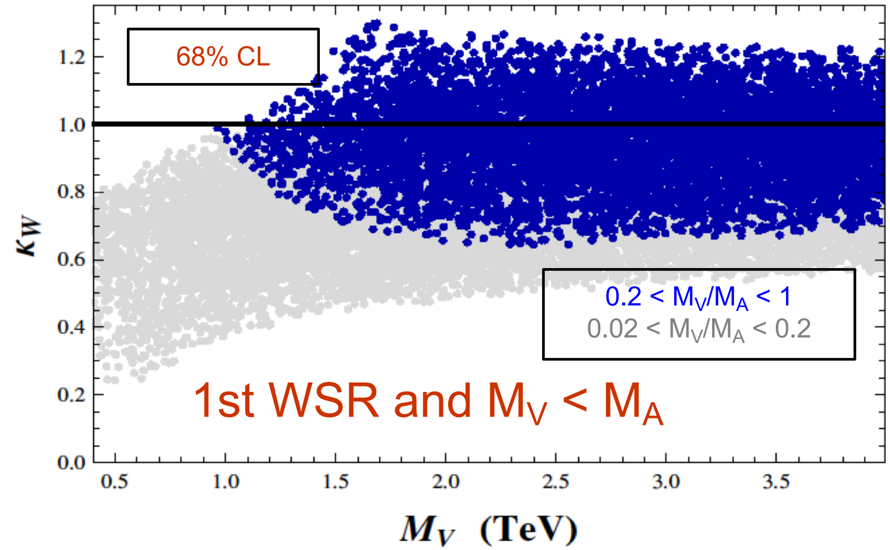


* Pich, IR and Sanz-Cillero '12 '13 '14
** Peskin and Takeuchi '92

3. Phenomenology I: S and T at NLO*

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





Room for these scenarios
κ_W (also a) ≅ 1
M_R ≈ TeV

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

3. Phenomenology II: estimation of the bosonic LECs*

✓ Integration of the heavy modes

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

✓ The case of P-even bosonic operators**:

i	$\mathcal{O}_i$	$\mathcal{F}_i$
1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\rangle_2$	$-\frac{F_V^2-\widetilde{F}_V^2}{4M_{V_3^1}^2}+\frac{F_A^2-\widetilde{F}_A^2}{4M_{A_3^1}^2}$
3	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu,u_\nu]\rangle_2$	$-\frac{F_V G_V}{2M_{V_3^1}^2}-\frac{\widetilde{F}_A\widetilde{G}_A}{2M_{A_3^1}^2}$
4	$\langle u_\mu u_\nu\rangle_2\langle u^\mu u^\nu\rangle_2$	$\frac{G_V^2}{4M_{V_3^1}^2}+\frac{\widetilde{G}_A^2}{4M_{A_3^1}^2}$
5	$\langle u_\mu u^\mu\rangle_2\langle u_\nu u^\nu\rangle_2$	$\frac{c_d^2}{4M_{S_1^1}^2}-\frac{G_V^2}{4M_{V_3^1}^2}-\frac{\widetilde{G}_A^2}{4M_{A_3^1}^2}$
6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle_2$	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_{V_3^1}^2}-\frac{\lambda_1^{hA\,2}v^2}{M_{A_3^1}^2}$
7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle_2$	$\frac{d_P^2}{2M_{P_3^1}^2}+\frac{\lambda_1^{hA\,2}v^2}{M_{A_3^1}^2}+\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_{V_3^1}^2}$
8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	0
9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu}u_\nu\rangle_2$	$-\frac{F_A\lambda_1^{hA}v}{M_{A_3^1}^2}-\frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M_{V_3^1}^2}$

** Pich, IR, Santos and Sanz-Cillero '17
** Krause, Pich, IR, Santos and Sanz-Cillero '19

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

3. Phenomenology II: estimation of the bosonic LECs*

✓ Integration of the heavy modes

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

Talks by K. Long and D. Bachas

✓ The case of P-even bosonic operators**:

i	$\mathcal{O}_i$	$\mathcal{F}_i$
1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\rangle_2$	$-\frac{F_V^2-\widetilde{F}_V^2}{4M_{V_3^1}^2} + \frac{F_A^2-\widetilde{F}_A^2}{4M_{A_3^1}^2}$
3	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu,u_\nu]\rangle_2$	$-\frac{F_V G_V}{2M_{V_3^1}^2} - \frac{\widetilde{F}_A\widetilde{G}_A}{2M_{A_3^1}^{\;2}}$
4	$\langle u_\mu u_\nu\rangle_2\langle u^\mu u^\nu\rangle_2$	$\frac{G_V^2}{4M_{V_3^1}^2} + \frac{\widetilde{G}_A^2}{4M_{A_3^1}^2}$
5	$\langle u_\mu u^\mu\rangle_2\langle u_\nu u^\nu\rangle_2$	$\frac{c_d^2}{4M_{S_1^1}^2} - \frac{G_V^2}{4M_{V_3^1}^2} - \frac{\widetilde{G}_A^2}{4M_{A_3^1}^2}$
6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle_2$	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_{V_3^1}^2} - \frac{\lambda_1^{hA\,2}v^2}{M_{A_3^1}^2}$
7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle_2$	$\frac{d_P^2}{2M_{P_3^1}^2} + \frac{\lambda_1^{hA\,2}v^2}{M_{A_3^1}^2} + \frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_{V_3^1}^2}$
8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	0
9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu}u_\nu\rangle_2$	$-\frac{F_A\lambda_1^{hA}v}{M_{A_3^1}^2} - \frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M_{V_3^1}^2}$

✓ Experimental constraints:

LEC	Ref.
$0.97 < \kappa_W < 1.13$	ATLAS'19
$-0.0024 < \mathcal{F}_1 < 0.0016$	S and PDG'18†
$-0.06 < \mathcal{F}_3 < 0.20$	Da Silva et al.'19†
$-0.0006 < \mathcal{F}_4 < 0.0006$	CMS'19†
$-0.0010 < \mathcal{F}_4 + \mathcal{F}_5 < 0.0010$	CMS'19†

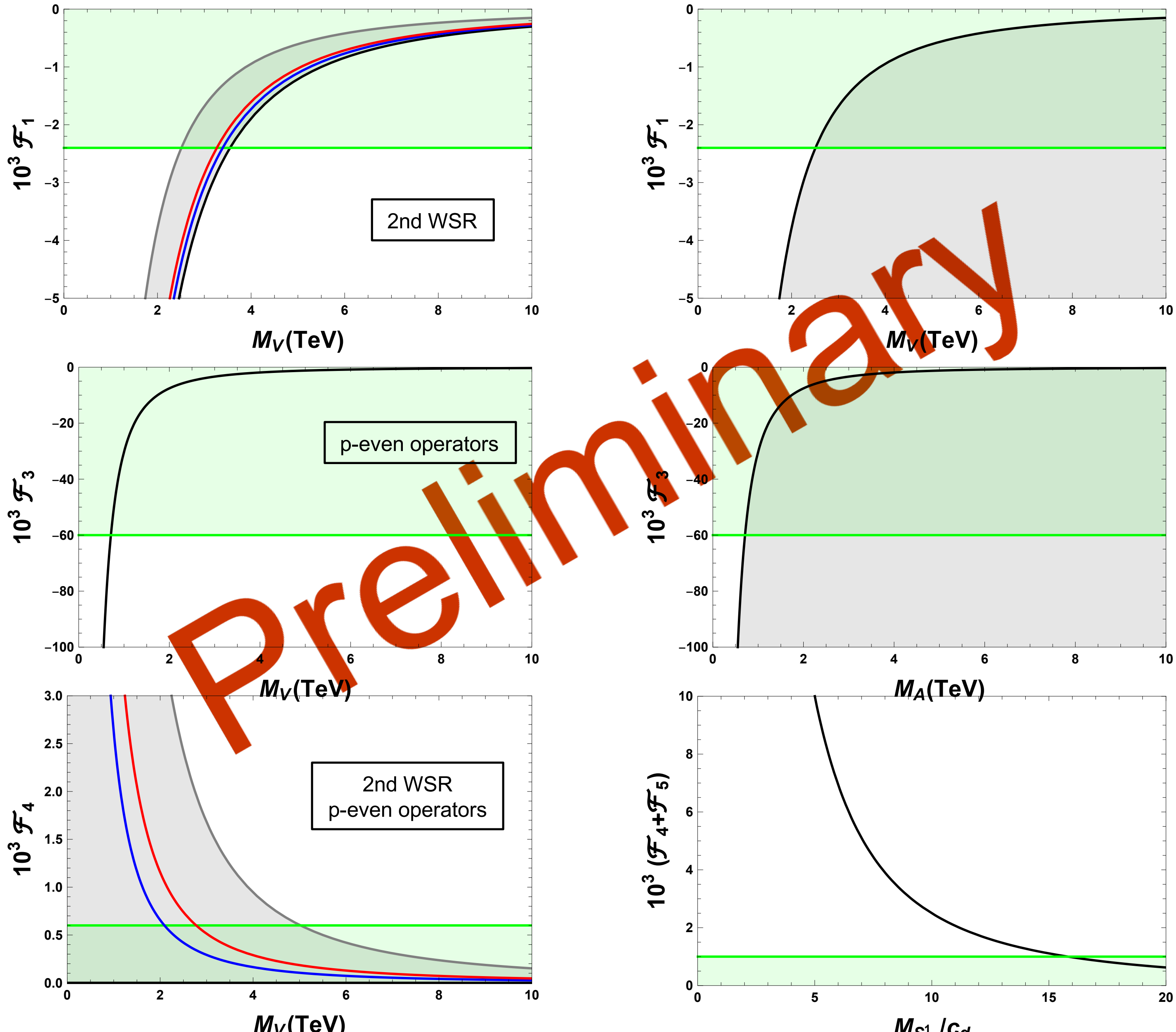
From one-loop considerations one would expect $F_i \approx 1/(4\pi^2) \approx 10^{-3}$.

The running is known***: $|F_i(\mu = M_R) - F_i(\mu = m_h)| \approx 10^{-3}$

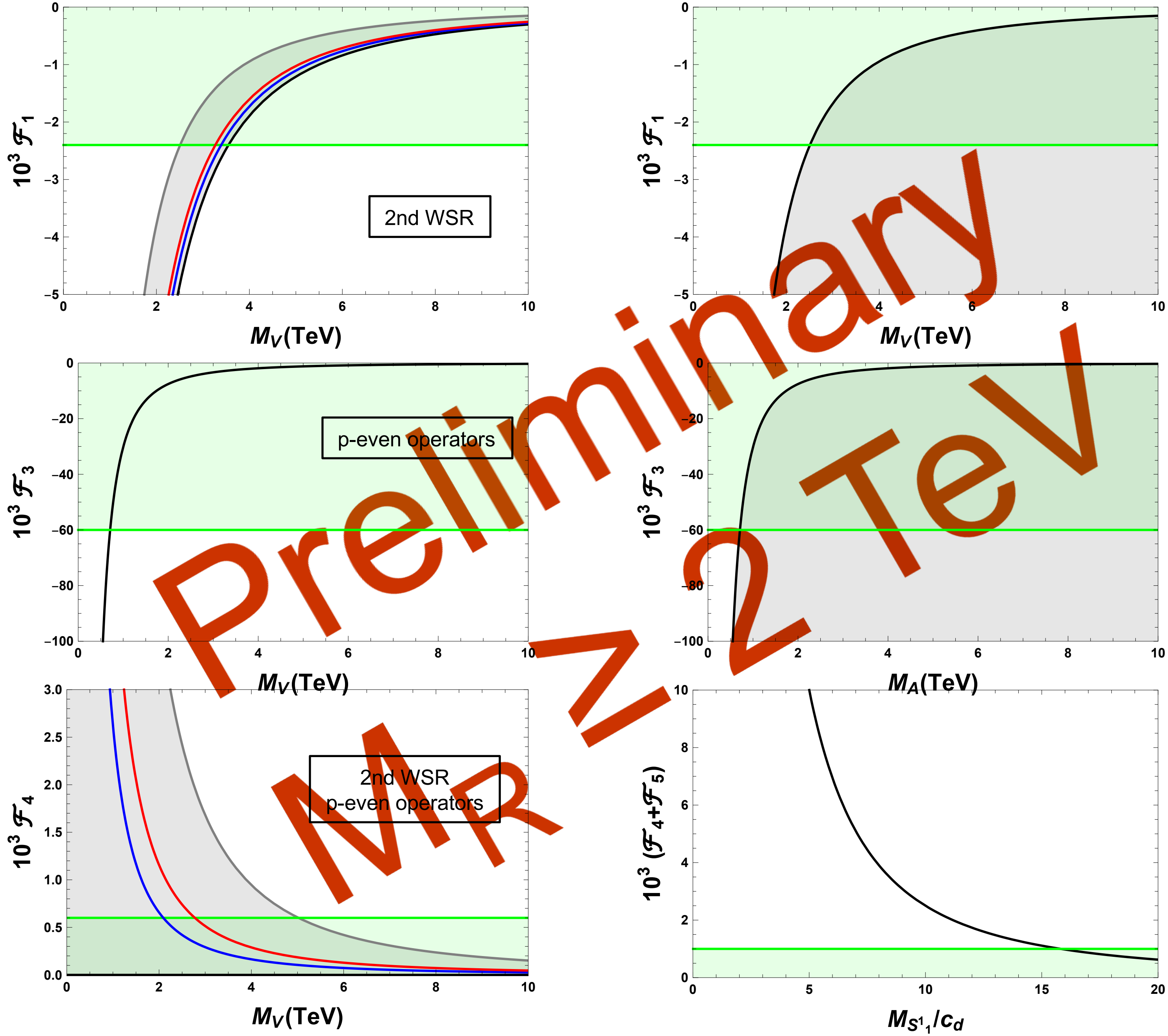
† M.J. Herrero and Ruiz-Morales '94
† Delgado et al. '14
† M. Rauch'16
† C. Garcia-Garcia et al. '19

** Pich, IR, Santos and Sanz-Cillero '17
** Krause, Pich, IR, Santos and Sanz-Cillero '19
*** Guo, Ruiz-Femenía and Sanz-Cillero '15

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



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



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

3. Phenomenology III: contact four-fermion operators*

- ✓ With light leptons and/or quarks
  - ✓ From dijet production

    $\Lambda \geq$ 21.8 TeV from ATLAS
    $\Lambda \geq$ 18.6 TeV from CMS
    $\Lambda \geq$ 16.2 TeV from LEP

  - ✓ From dilepton production

    $\Lambda \geq$ 26.3 TeV from ATLAS
    $\Lambda \geq$ 19.0 TeV from CMS
    $\Lambda \geq$ 24.6 TeV from LEP

- ✓ Including top and bottom quarks
  - ✓ From high-energy collider studies

    $\Lambda \geq$ 1.5 TeV from multi-top production at LHC and Tevatron
    $\Lambda \geq$ 2.3 TeV from t and $t\bar{t}$ production at LHC and Tevatron
    $\Lambda \geq$ 4.7 TeV drom dilepton production at LHC

  - ✓ From low-energy studies

    $\Lambda \geq$ 14.5 TeV from $B_s - \bar{B}_s$ mixing
    $\Lambda \geq$ 3.3 TeV from semileptonic B decays

* See references in Krause, Pich, IR, Santos and Sanz-Cillero '19

3. Phenomenology III: contact four-fermion operators*

✓ With light leptons and/or quarks

✓ From dijet production

$\Lambda \geq$ 21.8 TeV from ATLAS
$\Lambda \geq$ 18.6 TeV from CMS
$\Lambda \geq$ 16.2 TeV from LEP

✓ From dilepton production

$\Lambda \geq$ 26.3 TeV from ATLAS
$\Lambda \geq$ 19.0 TeV from CMS
$\Lambda \geq$ 24.6 TeV from LEP

✓ Including top and bottom quarks

✓ From high-energy collider studies

$\Lambda \geq$ 1.5 TeV from multi-top production at LHC and Tevatron
$\Lambda \geq$ 2.3 TeV from t and $t\bar{t}$ production at LHC and Tevatron
$\Lambda \geq$ 4.7 TeV drom dilepton production at LHC

✓ From low-energy studies

$\Lambda \geq$ 14.5 TeV from $B_s - \bar{B}_s$ mixing
$\Lambda \geq$ 3.3 TeV from semileptonic B decays

$$\Lambda \sim \mathcal{O}(\text{TeV})$$

* See references in Krause, Pich, IR, Santos and Sanz-Cillero '19

4. Conclusions

- ✓ Up to now all searches for New Physics have given negative results: Higgs couplings compatible with the SM and no new states. Therefore we can use EFTs because we have a mass gap.

- ✓ As a consequence of the mass gap, bottom-up EFTs are appropriate to search for BSM. 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 (HEFT or EWChL)
        - ✓ Non-SM Higgs and strongly coupled
        - ✓ Expansion in loops or chiral dimensions

Why?

4. Conclusions

- ✓ Up to now all searches for New Physics have given negative results: Higgs couplings compatible with the SM and no new states. Therefore we can use EFTs because we have a mass gap.

- ✓ As a consequence of the mass gap, bottom-up EFTs are appropriate to search for BSM. 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 (HEFT or EWChL)
    - ✓ Non-SM Higgs and strongly coupled
    - ✓ Expansion in loops or chiral dimensions

Why?

4. Conclusions

- ✓ Up to now all searches for New Physics have given negative results: Higgs couplings compatible with the SM and no new states. Therefore we can use EFTs because we have a mass gap.

- ✓ As a consequence of the mass gap, bottom-up EFTs are appropriate to search for BSM. 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 (HEFT or EWChL)
    - ✓ Non-SM Higgs and strongly coupled
    - ✓ Expansion in loops or chiral dimensions

- ✓ Similarities to ChSB of QCD -> ChPT and RChT

- ✓ Phenomenology

  - ✓ Estimation of the LECs by using resonance Lagrangians and short-distance constraints.

  - ✓ NLO calculation of S and T.

Why?

What?

4. Conclusions

- ✓ Up to now all searches for New Physics have given negative results: Higgs couplings compatible with the SM and no new states. Therefore we can use EFTs because we have a mass gap.

- ✓ As a consequence of the mass gap, bottom-up EFTs are appropriate to search for BSM. 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 (HEFT or EWChL)
    - ✓ Non-SM Higgs and strongly coupled
    - ✓ Expansion in loops or chiral dimensions

- ✓ Similarities to ChSB of QCD -> ChPT and RChT

- ✓ Phenomenology

  - ✓ Estimation of the LECs by using resonance Lagrangians and short-distance constraints.

  - ✓ NLO calculation of S and T.

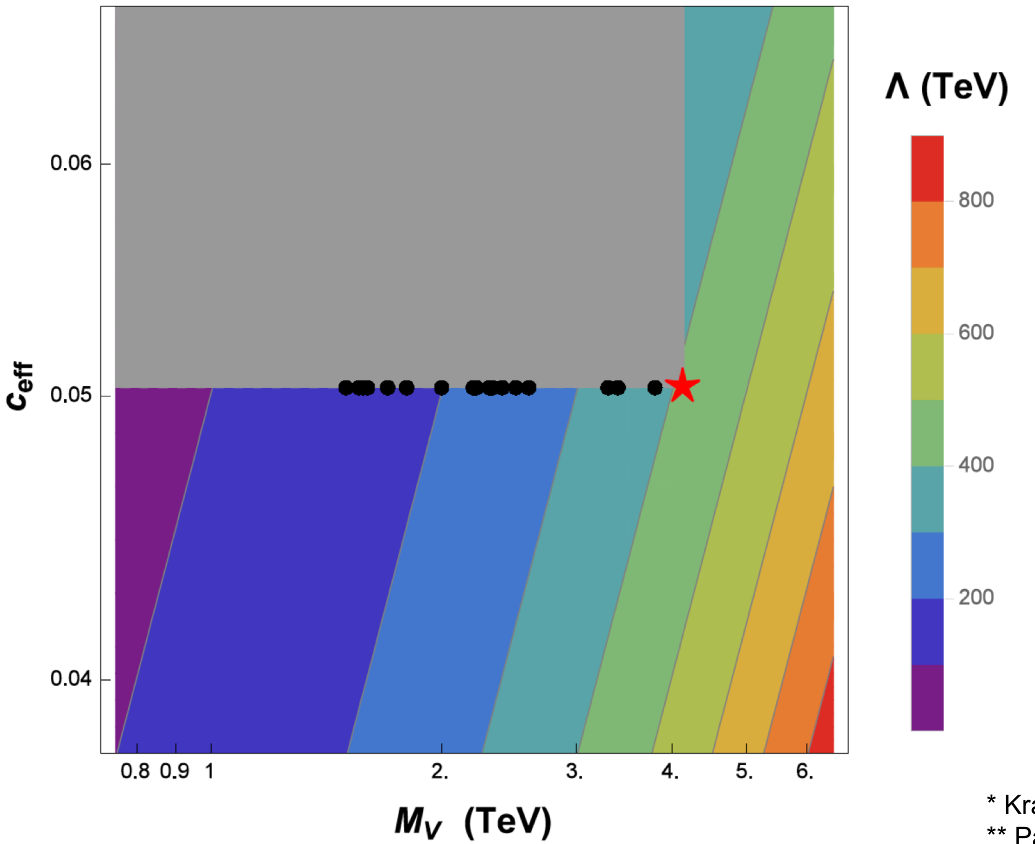
Why?

What?

Room for these BSM scenarios and $M_R \geq 2$ TeV.

Phenomenology IV: HVT diboson searches*

- ✓ Our model-independent approach can be related to the popular Heavy Vector Triplet simplifed model (HVT)**.
- ✓ LHC diboson production experimental analysis (ATLAS and CMS).
- ✓ Exclusion in the (mass, coupling) plane and the scale Λ



Integration of heavy modes

$$\frac{2\pi}{\Lambda^2} \equiv \mathcal{F}_7^{\psi^4} + \mathcal{F}_8^{\psi^4} + \frac{\mathcal{F}_{10}^{\psi^4}}{4} = \frac{c_{\rm eff}^2}{4M_V^2}$$

EWET

Resonance Lagrangian

* Krause, Pich, IR, Santos and Sanz-Cillero ‘19
** Pappadopulo 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: $\mathcal{L}^{(P)}_{\mathrm{non-R}} \neq \mathcal{L}^{(A)}_{\mathrm{non-R}}$

* Ecker et al. ‘89
* Bijnens and Pallante '96
* Kampf, Novotny and Trnka '07
* Pich, IR, Santos and Sanz-Cillero ‘16 ’17
* Krause, Pich, IR, Santos and Sanz-Cillero ‘19

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: $\mathcal{L}_{\rm non-R}^{(P)} \neq \mathcal{L}_{\rm non-R}^{(A)}$
- ✓ High-energy behaviour is fundamental:

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

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

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

* Ecker et al. '89
* Bijnens and Pallante '96
* Kampf, Novotny and Trnka '07
* Pich, IR, Santos and Sanz-Cillero '16 '17
* Krause, Pich, IR, Santos and Sanz-Cillero '19