

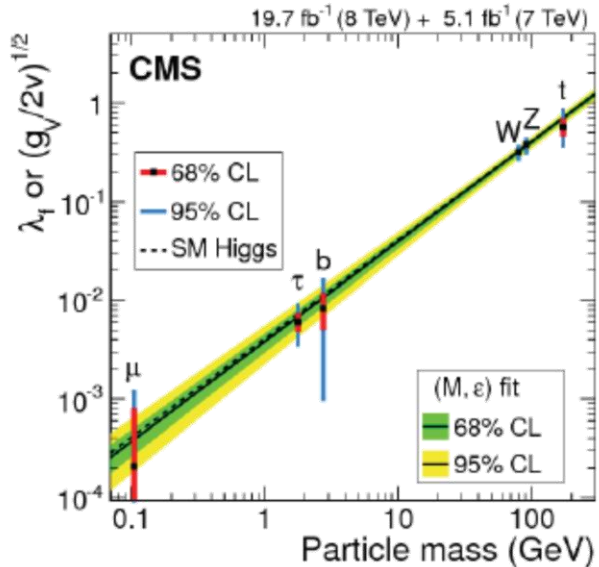
*Resonances and loops:  
scale interplay  
in the Higgs effective theory*

*Juan José Sanz-Cillero (UCM)*

Guo,Ruiz-Femenía,SC, PRD92 (2015) 074005  
Du,Guo,Ruiz-Femenía,SC, in preparation.

Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012  
Krause,Pich,Rosell,Santos,SC, in preparation

# Motivation



*“We are so close to SM, so why not simply using SMEFT with the  $\phi$  Higgs doublet? Isn't this enough?”*

**NO, in general not enough;  
only true if “tiny”  $\ll$  “tiny”**

- OUTLINE:**
- 1) LIN. vs NON-LIN.
  - 2) Loops in  $EW\chi L$
  - 3) Resonances and NLO couplings in  $EW\chi L$

# Low-energy EFT (SM + ...): representations

- Higgs field representation: a matter of taste?

## 1) Linear\* (SMEFT): in terms of a doublet $\phi = (1+h/v) U(\omega^a) \langle \phi \rangle$

$$\begin{aligned}\mathcal{L}_{\text{EFT}}^{\text{L}} &= (D_\mu \phi)^\dagger D_\mu \phi - \frac{1}{\Lambda^2} (\phi^\dagger \phi) \square (\phi^\dagger \phi) + \dots \\ &= \frac{(v+h)^2}{4} \langle (D_\mu U)^\dagger D_\mu U \rangle + \frac{1}{2} (1 + P(h)) (\partial_\mu h)^2 + \dots\end{aligned}$$

$$\begin{aligned}\frac{dh^{\text{NL}}}{dh^{\text{L}}} &= \sqrt{1 + P(h^{\text{L}})} \\ h^{\text{NL}} &= \int_0^{h^{\text{L}}} \sqrt{1 + P(h)} dh\end{aligned}$$

$$\mathcal{L}_{\text{EFT}}^{\text{NL}} = \frac{v^2}{4} \mathcal{F}_c(h) \langle (D_\mu U)^\dagger D_\mu U \rangle + \frac{1}{2} (\partial_\mu h)^2 + \dots$$

$$\mathcal{F}_c(h) = 1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \mathcal{O}(h^3)$$

$$\frac{v^2}{2} \mathcal{F}_c(h^{\text{NL}}) = \frac{(v+h^{\text{L}})^2}{2} = \phi^\dagger \phi$$

if there exists an  $SU(2)_L \times SU(2)_R$   
fixed point  $\mathcal{F}_c(h^*)=0$  (x)

## 2) Non-linear\* (HEFT or EW $\chi$ L): in terms of 1 singlet h + 3 NGB in $U(\omega^a)$

(x) Transformations:

Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045  
Alonso, Jenkins, Manohar, JHEP 1608 (2016) 101

\* Jenkins, Manohar, Trott, [1308.2627]  
\* LHCHSWG Yellow Report [1610.07922]

- It is not a question about how you write it:

**- Starting from SMEFT\*:**

$$\mathcal{L}_{\text{EFT}}^{\text{L}} = (D_\mu \phi)^\dagger D_\mu \phi - \frac{1}{\Lambda^2} (\phi^\dagger \phi) \square (\phi^\dagger \phi) + \dots$$

$$= \frac{(v+h)^2}{4} \langle (D_\mu U)^\dagger D_\mu U \rangle + \frac{1}{2} (1 + P(h)) (\partial_\mu h)^2 + \dots$$

$$\mathcal{F}_C(h) = 1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \mathcal{O}(h^3)$$

(if no Custodial)  $a^2 = 1 + \Delta(a^2) = 1 - \frac{2v^2}{\Lambda^2} + \dots$ ,  $b = 1 + \Delta b = 1 - \frac{4v^2}{\Lambda^2} + \dots \Rightarrow 2\Delta(a^2) = \Delta b$

(D ≥ 8 operators: corrections  $v^4/\Lambda^4, v^6/\Lambda^6 \dots$ )

**- Non-linear scenarios:** e.g., dilaton models <sup>(x)</sup>  $\longrightarrow \Delta(a^2) = \Delta b$

if you want to write it like the SMEFT, large  $D \geq 8$  operators needed  $\rightarrow$  SMEFT exp. breakdown

\* Jenkins, Manohar, Trott, [1308.2627]

\* LHCHSWG Yellow Report [1610.07922]

(x) Goldberger, Grinstein, Skiba, PRL100 (2008) 111802

# EW $\chi$ L

- The problem of the possible breakdown solved with the chiral expansion <sup>(x)</sup>
- 1 h (singlet) & 3 NGB (triplet) non-linearly realized:  $U(\omega^a) = 1 + i \omega^a \sigma^a / v + \dots$
- Lagrangian organized according to chiral exp. in  $p^2, p^4, p^6 \dots$  : <sup>(x), (+), \*</sup>

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \dots$$

$$\mathcal{L}_2 = \frac{v^2}{4} \mathcal{F}_C \langle u_\mu u^\mu \rangle + \frac{1}{2} (\partial_\mu h)^2 - \mathbf{V}_h + \mathcal{L}_{YM} + i \bar{\psi} \not{D} \psi - v^2 \langle J_S \rangle,$$

- Amplitudes organized according to chiral exp.: <sup>(x), \*</sup>

- **Dominant corrections:**
- **Subdominant corrections:**

Deviations from SM in  $O(p^2)$  operators  
 $O(p^4)$  operators +  $O(p^2)$  loops  
*(heavier states)*      *(non-linearity)*

- More general but more cumbersome:

less trivial expansion, more operators, more vertices, more diagrams, subtle cancellations...

(x) Buchalla, Catà, Krause '13  
 (x) Hirn, Stern '05  
 (x) Delgado, Dobado, Herrero, SC, JHEP1407 (2014) 149  
 (x) Pich, Rosell, Santos, SC, JHEP 1704 (2017) 012  
 (+) LHCHSWG Yellow Report [1610.07922]

\* Manohar, Georgi, NPB234 (1984) 189  
 \* Buchalla, Catà, Krause '13  
 \* Alonso et al, Phys.Lett. B722 (2013) 330.  
 \* Delgado, Dobado, Herrero, SC, JHEP1407 (2014) 149  
 \* Pich, Rosell, Santos, SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012

\* Weinberg '79  
 \* Longhitano, PRD22, 1166 (1980) 26;  
 NPB188, 118 (1981);  
 Appelquist, Bernard, PRD22, 200 (1980).

# Low-energy chiral expansion

• Though not the simplest organization, it is the most general

• **Expansion** in non-linear EFT's: \*

$$\mathcal{M}(2 \rightarrow 2) \approx \frac{p^2}{v^2} \left[ \underbrace{1}_{\text{LO (tree)}} + \underbrace{\left( \frac{c_k^r p^2}{v^2} - \frac{\Gamma_k p^2}{16\pi^2 v^2} \ln \frac{p}{\mu} + \dots \right)}_{\substack{\text{NLO (tree)} \\ \text{suppression} \\ \sim 1/M^2 + \dots \\ \text{(heavier states)}}} + \underbrace{\left( \frac{\Gamma_k p^2}{16\pi^2 v^2} \ln \frac{p}{\mu} + \dots \right)}_{\substack{\text{NLO (1-loop)} \\ \text{Typical loop suppression} \\ \sim \mathcal{R} / (16\pi^2 v^2) \\ \text{(non-linearity)}}} + \mathcal{O}(p^4) \right]$$

Finite pieces from loops  
(amplitude dependent) <sup>(+)</sup>

↑

\*\* Catà, EPJC74 (2014) 8, 2991  
 \*\* Pich, Rosell, Santos, SC, [1501.07249]; 'forthcoming FTUAM-15-20  
 \*\* Pich, Rosell and SC, JHEP 1208 (2012) 106;  
 PRL 110 (2013) 181801

↑

100% determined  
 by  $\mathcal{L}_2$   
 [ Guo, Ruiz-Femenia, SC,  
 PRD92 (2015) 074005 ]

# Scale suppression of loops

• 1 loop corrections: previous computations <sup>(-)</sup>

• 1 loop of h & ω<sup>a</sup> in path integral: <sup>\*, (x)</sup> **Heat kernel**

$$\mathcal{L}_2 = \underbrace{\mathcal{L}_2^{\mathcal{O}(\eta^0)}}_{\text{Tree-level}} + \underbrace{\mathcal{L}_2^{\mathcal{O}(\eta^1)}}_{\text{EoM}} + \underbrace{\mathcal{L}_2^{\mathcal{O}(\eta^2)}}_{\text{1-loop}} + \underbrace{\mathcal{O}(\eta^3)}_{\text{Higher loops}}$$

$$\mathcal{L}_2^{\mathcal{O}(\eta^2)} = -\frac{1}{2} \vec{\eta}^T (d_\mu d^\mu + \Lambda) \vec{\eta}$$

→ 1 loop UV-div:<sup>(+)</sup>

$$S^{1\ell} = -\frac{\mu^{d-4}}{16\pi^2(d-4)} \int d^d x \text{Tr} \left\{ \frac{1}{12} [d_\mu, d_\nu] [d^\mu, d^\nu] + \frac{1}{2} \Lambda^2 \right\} + \text{finite}$$

$$= -\frac{\mu^{d-4}}{16\pi^2(d-4)} \int d^d x \sum_k \Gamma_k \mathcal{O}_k + \text{finite}$$

→ O(p<sup>4</sup>) renormalization: <sup>\*, (x)</sup>

$$\delta\mathcal{L}_2 + \delta\mathcal{L}_4^{\text{Fer}} + \delta\mathcal{L}_4^{\text{Bos}}$$

- Espriu, Yenko, PRD 87 (2013) 055017

- Espriu, Mescia, Yenko, PRD88 (2013) 055002

- Delgado, Dobado, Llanes-Estrada, JHEP1402 (2014) 121

- Delgado, Dobado, Herrero, SC, JHEP1407 (2014) 149

- Gavela, Kanshin, Machado, Saa, JHEP 1503 (2015) 043

- Azatov, Contino, Di Iura, Galloway, PRD88 (2013) 7, 075019

- Azatov, Grojean, Paul, Salvioni, Zh.Eksp.Teor.Fiz. 147 (2015) 410, Exp.Theor.Phys. 120 (2015) 354

\* Guo, Ruiz-Femenia, SC, PRD92 (2015) 074005

(x) Fermions & gauge boson loops:

Du, Guo, Ruiz-Femenia, SC, in preparation.

(+) 't Hooft, NPB 62 (1973) 444; Ramond, Front. Phys. 74 (1989) 1; DeWitt, Int. Ser. Monogr. Phys. 114 (2003) 1; D. V. Vassilevich, Phys. Rept. 388 (2003) 279

A. O. Barvinsky and G. A. Vilkovisky, Phys. Rept. 119 (1985) 1; C. Lee, T. Lee and H. Min, PRD 39 (1989) 1681; R. D. Ball, Phys. Rept. 182 (1989) 1

• **O(D<sup>4</sup>) operators (purely bosonic)** <sup>\*,(x)</sup>

[ full UV-div. provided by scalar loops ]

$c_k$	Operator $\mathcal{O}_k$	$\Gamma_k$	$\Gamma_{k,0}$
$c_1$	$\frac{1}{4} \langle f_+^{\mu\nu} f_{+\mu\nu} - f_-^{\mu\nu} f_{-\mu\nu} \rangle$	$\frac{1}{24} (\mathcal{K}^2 - 4)$	$-\frac{1}{6} (1 - a^2)$
$(c_2 - c_3)$	$\frac{i}{2} \langle f_+^{\mu\nu} [u_\mu, u_\nu] \rangle$	$\frac{1}{24} (\mathcal{K}^2 - 4)$	$-\frac{1}{6} (1 - a^2)$
$c_4$	$\langle u_\mu u_\nu \rangle \langle u^\mu u^\nu \rangle$	$\frac{1}{96} (\mathcal{K}^2 - 4)^2$	$\frac{1}{6} (1 - a^2)^2$
$c_5$	$\langle u_\mu u^\mu \rangle^2$	$\frac{1}{192} (\mathcal{K}^2 - 4) + \frac{1}{128} \mathcal{F}_C^2 \Omega^2$	$\frac{1}{8} (a^2 - b)^2 + \frac{1}{12} (1 - a^2)^2$
$c_6$	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2} \langle u_\nu u^\nu \rangle$	$\frac{1}{16} \Omega (\mathcal{K}^2 - 4) - \frac{1}{96} \mathcal{F}_C \Omega^2$	$-\frac{1}{6} (a^2 - b)(7a^2 - b - 6)$
$c_7$	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2} \langle u^\mu u^\nu \rangle$	$\frac{1}{24} \mathcal{F}_C \Omega^2$	$\frac{2}{3} (a^2 - b)^2$
$c_8$	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	$\frac{3}{32} \Omega^2$	$\frac{3}{2} (a^2 - b)^2$
$c_9$	$\frac{(\partial_\mu h)}{v} \langle f_-^{\mu\nu} u_\nu \rangle$	$\frac{1}{24} \mathcal{F}_C^{\frac{1}{2}} \mathcal{K} \Omega$	$-\frac{1}{3} a (a^2 - b)$
$c_{10}$	$\frac{1}{2} \langle f_+^{\mu\nu} f_{+\mu\nu} + f_-^{\mu\nu} f_{-\mu\nu} \rangle$	$-\frac{1}{48} (\mathcal{K}^2 + 4)$	$-\frac{1}{12} (1 + a^2)$

$$\mathcal{K} = \mathcal{F}_C^{-1/2} \mathcal{F}'_C, \quad (\mathcal{K}^2 - 4) = (\mathcal{F}'_C)^2 / \mathcal{F}_C - 4, \quad \Omega = 2\mathcal{F}''_C / \mathcal{F}_C - (\mathcal{F}'_C / \mathcal{F}_C)^2$$

\* Guo,Ruiz-Femenia,SC, PRD92 (2015) 074005

(x)  $\mathcal{L}_2 + \mathcal{L}_4^{\text{Fer}}$  corrected by fermions & gauge boson loops: Du,Guo,Ruiz-Femenía,SC, in preparation.



- Beautiful geometric connection to this result \*

provided by the curvature <sup>(x)</sup> of the scalar manifold metric

$$g_{ij}(\phi) = \begin{bmatrix} F(h)^2 g_{ab}(\varphi) & 0 \\ 0 & 1 \end{bmatrix}$$

$$\mathcal{R}_4 = (1 - v^2(F')^2) F^2 = (1 - \mathcal{K}^2/4) \mathcal{F}_C,$$

$$\mathcal{R}_2 = (1 - v^2(F')^2) - \frac{v^2 F'' F}{(N_\varphi - 1)} = (1 - \mathcal{K}^2/4) - \frac{\mathcal{F}_C \Omega}{8},$$

$$\mathcal{R}_0 = 2\mathcal{F}_C^{-1} \mathcal{R}_2 - \mathcal{F}_C^{-2} \mathcal{R}_4,$$

$$F = \mathcal{F}_C^{1/2} \quad N_\varphi = 3$$

- NDA gives you the suppression of individual diagrams  $\sim 1 / (4\pi v)^2$   
but the full loop suppression is  $\sim \mathcal{R}_k / (4\pi v)^2$  &  $\sim \mathcal{R}_k^2 / (4\pi v)^2$
- SM:  $\mathcal{R}_0 = \mathcal{R}_2 = \mathcal{R}_4 = 0 \rightarrow$  No  $O(p^4)$  renormalization

\* Guo,Ruiz-Femenia,SC, PRD92 (2015) 074005

(x) Alonso,Jenkins,Manohar, PLB754 (2016) 335; PLB756 (2016) 358; JHEP 1608 (2016) 101

# Resonance contributions to $\mathcal{L}_4$ at tree level \*

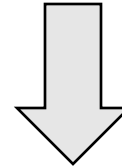
Custodial symmetry

+

Resonance Lagrangian

+

UV completion hypothesis

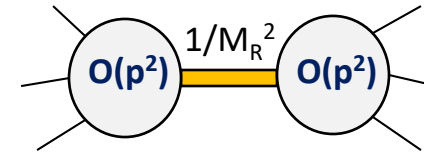


Resonance contributions \*,\*\*  
to the NLO low-energy couplings

$SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$

V,A,S,P singlet & triplet

Sum-rules



$$e^{iS[\chi,\psi]_{\text{EFT}}} = \int [dR] e^{iS[\chi,\psi,R]}$$

$$\stackrel{\text{tree-level}}{=} e^{iS[\chi,\psi,R_{\text{cl.}}]}$$

$4\pi v \approx 3 \text{ TeV}$

$M_R$

Mass gap

t  
h  
W,Z

SM content

- Bosons:  
singlet h,  
EW Goldstones  $U(\omega^a)$ ,  
gauge bosons
- Fermion  $\Psi_{L,R}$

\* Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012;  
Krause,Pich,Rosell,Santos,SC, in preparation

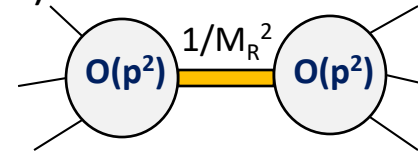
\*\* See also: Alboteanu, Kilian, Reuter, JHEP 0811 (2008) 010; Pappadopulo, Thamm, Torre, Wulzer, JHEP 1409 (2014) 060; Corbett, Joglekar, Li, Yu, [arXiv:1705.02551 [hep-ph]]; Corbett,Éboli,Gonzalez-Garcia,PRD93 (2016) no.1, 015005; Buchalla, Cata, Celis, Krause, NPB917 (2017) 209.

# High-energy Lagrangian

$$\mathcal{L}^{\text{HE}}[\mathbf{R}, \text{light}] = \mathcal{L}_2[\text{light}] + \mathcal{L}_{\mathbf{R}}[\mathbf{R}, \text{light}] + \mathcal{L}_4^{\text{HE}}[\text{light}]$$

with the most general linear resonance  $\mathcal{O}(p^2)$  operators (chiral + CP invariance)

$$\mathcal{L}_{\mathbf{R}} = \mathcal{L}_{\mathbf{R}}^{\text{Kin}}[\mathbf{R}] + \mathbf{R} \chi_{\mathbf{R}}[\text{light}] + \mathcal{O}(\mathbf{R}^2)$$



(e.g., a vector triplet  $\chi_V^{\mu\nu(2)} = \frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{i G_V}{2\sqrt{2}} [u^\mu, u^\nu] + \frac{\tilde{F}_V}{2\sqrt{2}} f_-^{\mu\nu} + \frac{\tilde{\lambda}_1^{hV}}{\sqrt{2}} [(\partial^\mu h) u^\nu - (\partial^\nu h) u^\mu] + C_0^V J_T^{\mu\nu}$  )

# Low-energy Lagrangian (tree-level)

- Solve R eom at low energies:  $\mathbf{R}_{\text{cl}}[\text{light}] \sim \frac{1}{M_{\mathbf{R}}^2} \chi_{\mathbf{R}}[\text{light}] + \mathcal{O}\left(\frac{p^4}{M_{\mathbf{R}}^4}\right)$

(e.g., for a vector triplet  $\mathbf{V}_{\text{cl}}^{\mu\nu} = -\frac{2}{M_V^2} \left( \chi_V^{\mu\nu} - \frac{1}{2} \langle \chi_V^{\mu\nu} \rangle \right) + \mathcal{O}\left(\frac{p^4}{M_V^4}\right)$  )

- Evaluate  $\mathcal{L}^{\text{EFT}}[\text{light}] = \mathcal{L}^{\text{HE}}[\mathbf{R}_{\text{cl}}[\text{light}], \text{light}] \sim \mathcal{L}_2[\text{light}] + \frac{1}{M_{\mathbf{R}}^2} (\chi_{\mathbf{R}}[\text{light}])^2 + \dots$

\* Pich, Rosell, Santos, SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; inclusion of color & fermionic Res, Krause, Pich, Rosell, Santos, SC, in preparation

- For instance, **P-even bosonic** low-energy EFT at  $O(p^4)$ : \*

$\mathcal{O}_1 = \frac{1}{4} \langle f_+^{\mu\nu} f_{\mu\nu}^+ - f_-^{\mu\nu} f_{\mu\nu}^- \rangle$	$\mathcal{F}_1 = \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2} = -\frac{v^2}{4} \left( \frac{1}{M_V^2} + \frac{1}{M_A^2} \right)$
$\mathcal{O}_2 = \frac{1}{2} \langle f_+^{\mu\nu} f_{\mu\nu}^+ + f_-^{\mu\nu} f_{\mu\nu}^- \rangle$	$\mathcal{F}_2 = -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2} = -\frac{v^2 (M_V^4 + M_A^4)}{8M_V^2 M_A^2 (M_A^2 - M_V^2)}$
$\mathcal{O}_3 = \frac{i}{2} \langle f_+^{\mu\nu} [u_\mu, u_\nu] \rangle$	$\mathcal{F}_3 = -\frac{F_V G_V}{2M_V^2} = -\frac{v^2}{2M_V^2}$
$\mathcal{O}_4 = \langle u_\mu u_\nu \rangle \langle u^\mu u^\nu \rangle$	$\mathcal{F}_4 = \frac{G_V^2}{4M_V^2} = \frac{(M_A^2 - M_V^2)v^2}{4M_V^2 M_A^2}$
$\mathcal{O}_5 = \langle u_\mu u^\mu \rangle^2$	$\mathcal{F}_5 = \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} = \frac{c_d^2}{4M_{S_1}^2} - \frac{(M_A^2 - M_V^2)v^2}{4M_V^2 M_A^2}$
$\mathcal{O}_6 = \frac{1}{v^2} (\partial_\mu h)(\partial^\mu h) \langle u_\nu u^\nu \rangle$	$\mathcal{F}_6 = -\frac{(\lambda_1^{hA})^2 v^2}{M_A^2} = -\frac{M_V^2 (M_A^2 - M_V^2)v^2}{M_A^6}$
$\mathcal{O}_7 = \frac{1}{v^2} (\partial_\mu h)(\partial_\nu h) \langle u^\mu u^\nu \rangle$	$\mathcal{F}_7 = \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2 v^2}{M_A^2} = \frac{d_P^2}{2M_P^2} + \frac{M_V^2 (M_A^2 - M_V^2)v^2}{M_A^6}$
$\mathcal{O}_8 = \frac{1}{v^4} (\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)$	$\mathcal{F}_8 = 0$
$\mathcal{O}_9 = \frac{1}{v} (\partial_\mu h) \langle f_-^{\mu\nu} u_\nu \rangle$	$\mathcal{F}_9 = -\frac{F_A \lambda_1^{hA} v}{M_A^2} = -\frac{M_V^2 v^2}{M_A^4}$

Same operators as in the 1-loop eff. action

\* Pich, Rosell, Santos, SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012

## Then, is SMEFT enough?

Can't we drop the chiral loops?

- It will depend on whether

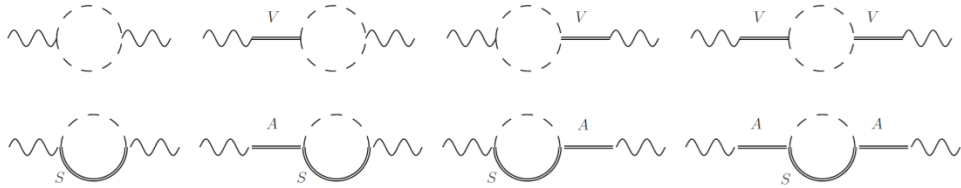
“tiny” [ $O(p^4)$  1-loop]  $\ll$  “tiny” [  $O(p^4)$  tree coupling ]

- Also, it is convenient to compare observables to discern whether SMEFT is appropriate \*

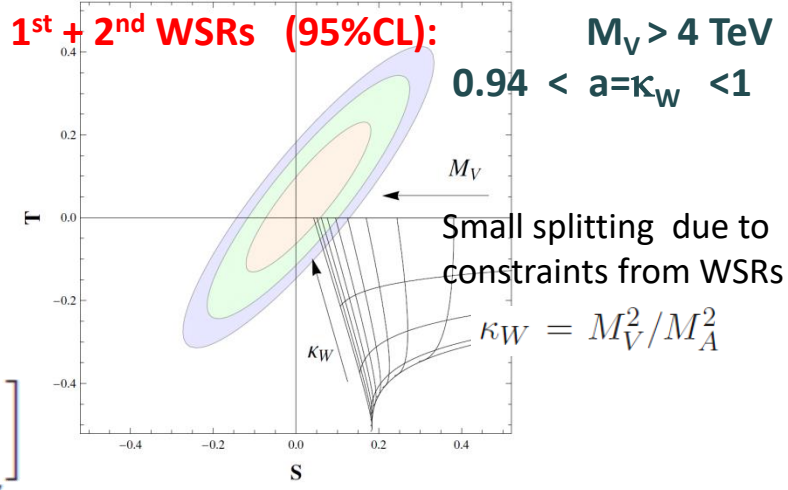
\* Brivio, Corbett, Éboli, Gavela, Gonzalez-Fraile, Gonzalez-Garcia, Merlo, Rigolin JHEP 1403 (2014) 024

\* Brivio, Gonzalez-Fraile, Gonzalez-Garcia, Merlo, EPJC76 (2016) no.7, 416

**EXAMPLE 1: \*, (x) S-parameter + 2 WSRs**



V,A resonances + 1-loop + 2 WSRs



$$S = -16\pi \left[ \underbrace{a_1^r(M_V)}_{\sim -2 \times 10^{-3}} + \underbrace{\frac{a^2 - 1}{192\pi^2} \left( \ln \frac{M_V^2}{m_h^2} + \frac{5}{6} \right)}_{\sim -6 \times 10^{-5}} \right]$$

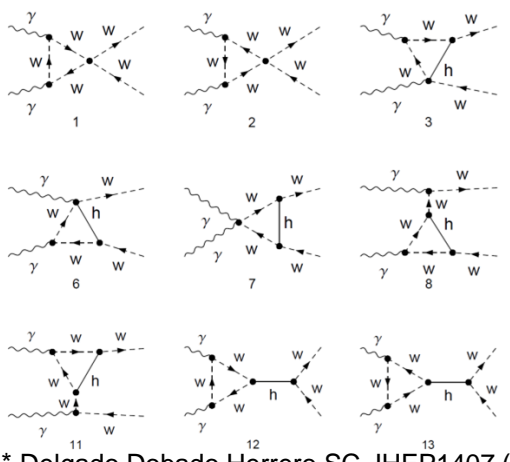
$\Lambda^{-2} \sim (5 \text{ TeV})^{-2}$        $\Lambda^{-2} \sim (30 \text{ TeV})^{-2}$

$$-\frac{v^2}{4M_V^2} - \frac{v^2}{4M_A^2} + \dots$$

$$-\mathcal{R}_4 / 192\pi^2$$

**EXAMPLE 2: \*, (x), (+)  $\gamma\gamma \rightarrow W_L W_L$**

(only charged shown here)



$$A_{\text{NLO}}^{\gamma\gamma \rightarrow W_L^+ W_L^-} = \frac{1}{v^2} \left[ \underbrace{2ac_\gamma^r}_{\sim 6 \times 10^{-3}} + \underbrace{8(a_1^r - a_2^r + a_3^r)}_{\sim 0.5 \times 10^{-3}} + \underbrace{\frac{a^2 - 1}{8\pi^2 v^2}}_{\sim -1.5 \times 10^{-3}} \right]$$

$\Lambda^{-2} \sim (3 \text{ TeV})^{-2}$        $\Lambda^{-2} \sim (10 \text{ TeV})^{-2}$        $\Lambda^{-2} \sim (6 \text{ TeV})^{-2}$

$$\propto \frac{1}{M^2}$$

$$\propto \frac{\mathcal{R}_k}{16\pi^2 v^2}$$

+30 more

(x) Pich, Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801  
 (+) **Inputs:** Buchalla, Catà, Celis, Krause, EPJC76 (2016) no.5, 233

# Conclusions

✓ Is SMEFT the appropriate EFT? **No experimental indication yet**

- *The description in terms of  $\phi$  does not always give a good expansion*
- *The interplay between corrections in  $\mathcal{F}_C(h)$  crucial*

✓ **The EW $\chi$ L & the chiral expansion solve this issue** (*though more tedious*

*...and at the end, SMEFT may be just fine)*

✓ **Two contributions potentially of the same order in the EW $\chi$ L:**

- **O(p<sup>4</sup>) 1-loop corrections:**
  - *Calculation in path integral  $\rightarrow$  O(p<sup>4</sup>) UV-div. show up*
  - *Geometric interpretation of the non-linearity*
- **O(p<sup>4</sup>) coupling corrections (tree-level):**
  - *Calculation in path integral  $\rightarrow$  O(p<sup>4</sup>) pattern from heavy states*

✓ **More than 1 scale in the EFT observables:**

- *Phenomenology does not tells us yet if O(p<sup>4</sup>) loops are negligible*
- *This depends on the observable, on the underlying BSM (and on finding NP)*



# BACKUP

**(i) SM content:**

- Bosons  $\chi$ : Higgs  $h$  + gauge bosons  $W^a_\mu, B_\mu$  (and QCD)  
+ EW Goldstones  $\omega^\pm, z$  [non-linearly realized via  $U(\omega^a)$  (x)]
- Fermions  $\psi$ : (t,b)-type doublets

**(ii) Symmetries:**

- SM symmetry: Gauge sym. group  $G_{SM} = SU(2)_L \times U(1)_Y$  (and QCD)  
Spont. Breaking (EWSB)  $G_{SM} \rightarrow H_{SM} = U(1)_{EM}$

• Symmetry of the SM scalar sector:

Global sym.  $G = SU(2)_L \times SU(2)_R \times U(1)_{B-L} \supset G_{SM}$   
 Spont. Breaking  $G \rightarrow H = SU(2)_{L+R} \times U(1)_{B-L} \supset H_{SM}$   
 Explicit Breaking:  $L \leftrightarrow R$  asymmetry of the gauge sector ( $g, g' \neq 0$ )  
 $t \leftrightarrow b$  splitting ( $\lambda_t \neq \lambda_b$ )

- Other approximate symmetries: B, L, CP-invariance, Fermion flavour

**(iii) Chiral power counting:**

	[boson]	$\Leftrightarrow$	order 0	( $\sim p^0$ )
[ $g W^\mu$ ] = [ $g' B^\mu$ ] = [ $d_\mu$ ] = [ $g$ ] = [ $\lambda_\psi$ ] = [ $m_{\chi,\psi}$ ] = [ $\psi\psi$ ]		$\Leftrightarrow$	order 1	( $\sim p^1$ )

• HXSWG Yellow Report (non-linear EFT Sec.) '2016

## SUMMARY: 'CHIRAL' COUNTING

- “Chiral” counting \*

$$\frac{\chi}{v} \sim \mathcal{O}(p^0), \quad \frac{\psi}{v} \sim \mathcal{O}(p^{\frac{1}{2}}), \quad \partial_\mu, m_\chi, m_\psi \sim \mathcal{O}(p)$$

and for the building blocks,  $u(\varphi/v), U(\varphi/v), \frac{h}{v}, \frac{W_\mu^a}{v}, \frac{B_\mu}{v} \sim \mathcal{O}(p^0),$

$$D_\mu U, u_\mu, \hat{W}_\mu, \hat{B}_\mu \sim \mathcal{O}(p),$$

$$\hat{W}_{\mu\nu}, \hat{B}_{\mu\nu}, f_{\pm\mu\nu} \sim \mathcal{O}(p^2),$$

$$\partial_{\mu_1} \partial_{\mu_2} \dots \partial_{\mu_n} \mathcal{F}(h/v) \sim \mathcal{O}(p^n),$$

$$\frac{\xi}{v} \sim \mathcal{O}(p^{\frac{1}{2}})$$

- Assignment of the ‘chiral’ dimension: \*

$$\mathcal{L}_{p^{\hat{d}}} \sim a_{(\hat{d})} p^{\hat{d} - N_F/2} \left( \frac{\bar{\psi}\psi}{v^2} \right)^{N_F/2} \sum_j \left( \frac{\chi}{v} \right)^j$$

\* Manohar, Georgi, NPB234 (1984) 189

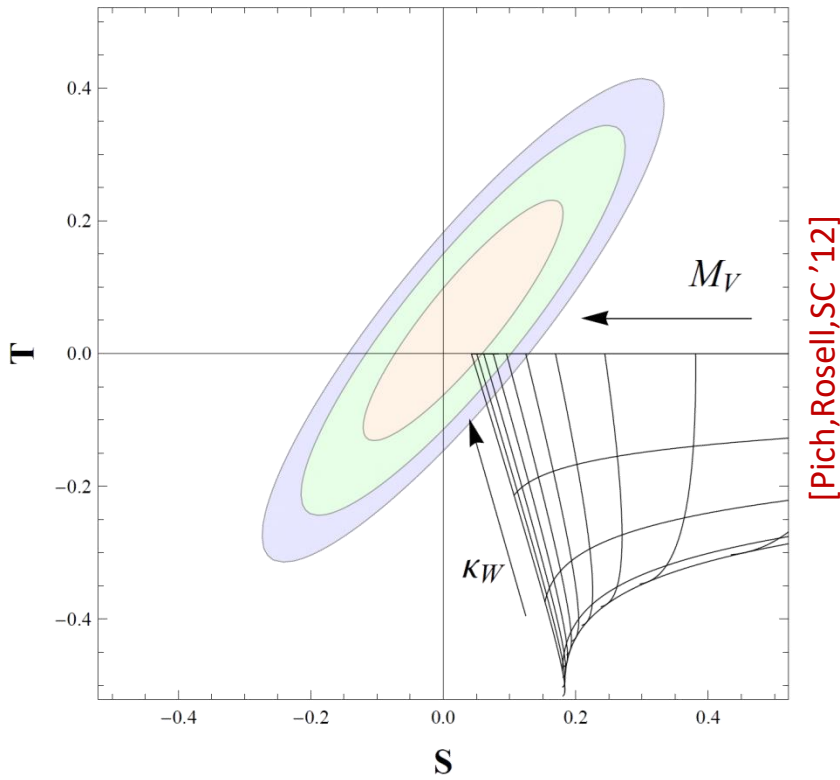
\* Hirn, Stern '05

\* Buchalla, Catà, Krause '13

\* Pich, Rosell, Santos, SC, forthcoming

# NLO results: 1st and 2nd WSRs

(asymptotically-free theories)



[Pich, Rosell, SC '12]

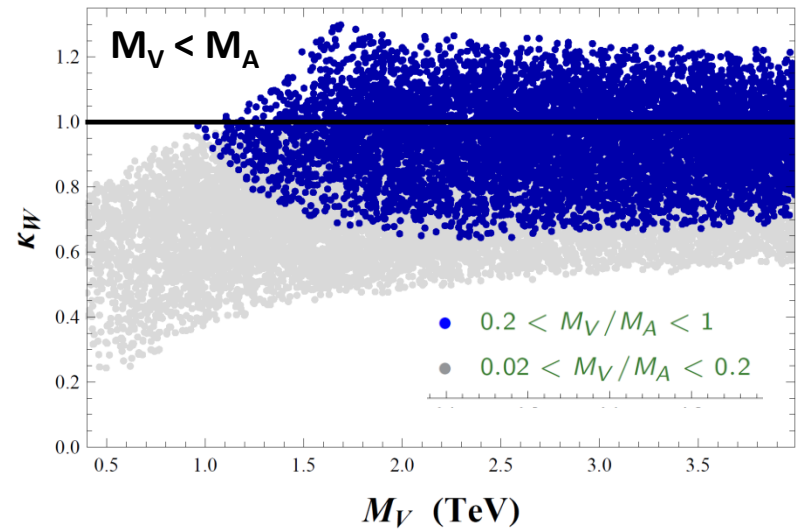
At NLO with the 1<sup>st</sup> and 2<sup>nd</sup> WSRs

$M_V > 5.4 \text{ TeV}$ ,  $0.97 < \kappa_W < 1$  at 68% CL

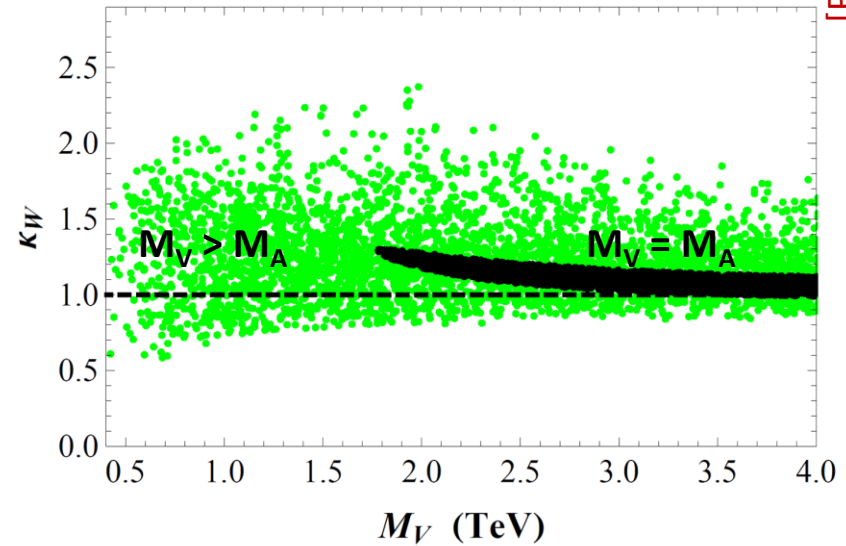
Small splitting  $(M_V/M_A)^2 = \kappa_W$

# NLO results: only 1<sup>st</sup> WSR

(walking & conformal TC, extra dimensions,...)



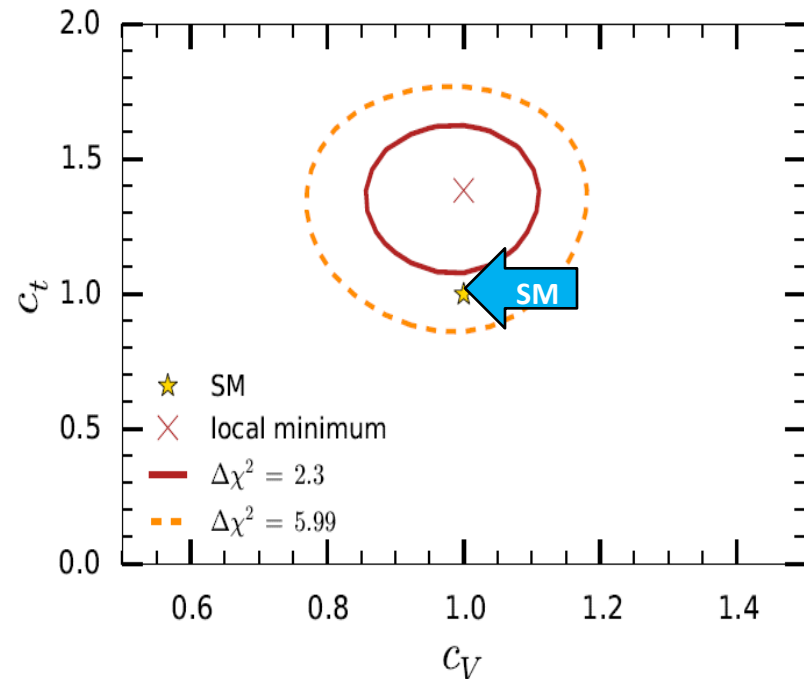
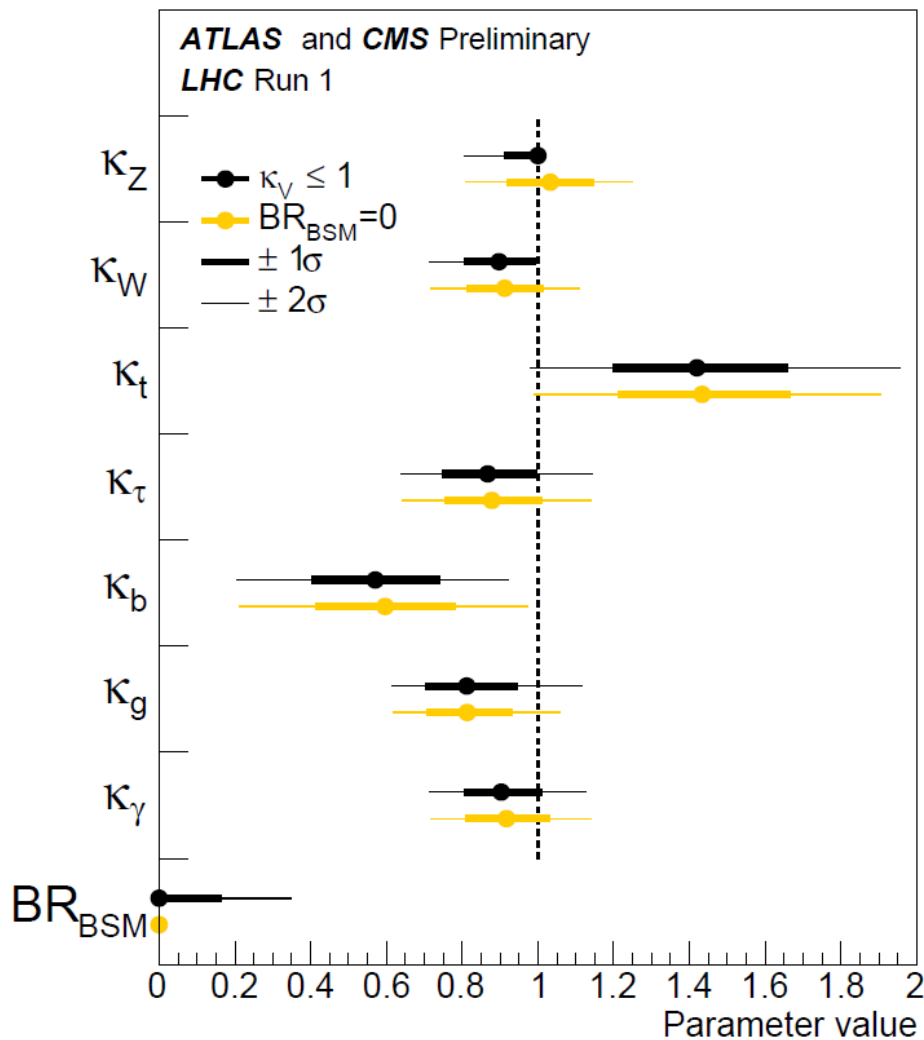
[Pich, Rosell, SC '12]



$$\begin{aligned}
\mathcal{L}_2 = & -\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{q}i\not{D}q + \bar{l}i\not{D}l + \bar{u}i\not{D}u + \bar{d}i\not{D}d + \bar{e}i\not{D}e \\
& + \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle (1 + F_U(h)) + \frac{1}{2}\partial_\mu h\partial^\mu h - V(h) \\
& - v\left[\bar{q}\left(Y_u + \sum_{n=1}^{\infty}Y_u^{(n)}\left(\frac{h}{v}\right)^n\right)UP_{+r} + \bar{q}\left(Y_d + \sum_{n=1}^{\infty}Y_d^{(n)}\left(\frac{h}{v}\right)^n\right)UP_{-r}\right. \\
& \left. + \bar{l}\left(Y_e + \sum_{n=1}^{\infty}Y_e^{(n)}\left(\frac{h}{v}\right)^n\right)UP_{-\eta} + \text{h.c.}\right]
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_4 = & a_1g'g\langle UT_3B_{\mu\nu}U^\dagger W^{\mu\nu}\rangle + ia_2g'\langle UT_3B_{\mu\nu}U^\dagger[V^\mu, V^\nu]\rangle - ia_3g\langle W_{\mu\nu}[V^\mu, V^\nu]\rangle \\
& + a_4\langle V_\mu V_\nu\rangle\langle V^\mu V^\nu\rangle + a_5\langle V_\mu V^\mu\rangle\langle V_\nu V^\nu\rangle + \frac{e^2}{16\pi^2}c_{\gamma\gamma}\frac{h}{v}F_{\mu\nu}F^{\mu\nu} \\
& + \frac{g^{hh}}{v^4}(\partial_\mu h\partial^\mu h)^2 + \frac{d^{hh}}{v^2}(\partial_\mu h\partial^\mu h)\langle D_\nu U^\dagger D^\nu U\rangle + \frac{e^{hh}}{v^2}(\partial_\mu h\partial^\nu h)\langle D^\mu U^\dagger D_\nu U\rangle + \dots
\end{aligned}$$

$\mathcal{O}_1 = \frac{1}{4}\langle f_+^{\mu\nu}f_{\mu\nu}^+ - f_-^{\mu\nu}f_{\mu\nu}^- \rangle$	$\mathcal{O}_6 = \frac{1}{v^2}(\partial_\mu h)(\partial^\mu h)\langle u_\nu u^\nu \rangle$
$\mathcal{O}_2 = \frac{1}{2}\langle f_+^{\mu\nu}f_{\mu\nu}^+ + f_-^{\mu\nu}f_{\mu\nu}^- \rangle$	$\mathcal{O}_7 = \frac{1}{v^2}(\partial_\mu h)(\partial_\nu h)\langle u^\mu u^\nu \rangle$
$\mathcal{O}_3 = \frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu] \rangle$	$\mathcal{O}_8 = \frac{1}{v^4}(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)$
$\mathcal{O}_4 = \langle u_\mu u_\nu \rangle\langle u^\mu u^\nu \rangle$	$\mathcal{O}_9 = \frac{1}{v}(\partial_\mu h)\langle f_-^{\mu\nu}u_\nu \rangle$
$\mathcal{O}_5 = \langle u_\mu u^\mu \rangle^2$	



EFT global fit:  
Buchalla, Catà, Celis, Krause, EPJC76 (2016) no.5, 233

Figure 14: Fit results for the two parameterisations allowing BSM loop couplings, with  $\kappa_V \leq 1$ , where  $\kappa_V$  stands for  $\kappa_Z$  or  $\kappa_W$ , or without additional BSM contributions to the Higgs boson width, i.e.  $BR_{BSM} = 0$ . The measured results for the combination of ATLAS and CMS are reported together with their uncertainties. The error bars indicate the  $1\sigma$  (thick lines) and  $2\sigma$  (thin lines) intervals. The uncertainties are not indicated when the parameters are constrained and hit a boundary, namely  $\kappa_V = 1$  or  $BR_{BSM} = 0$ .

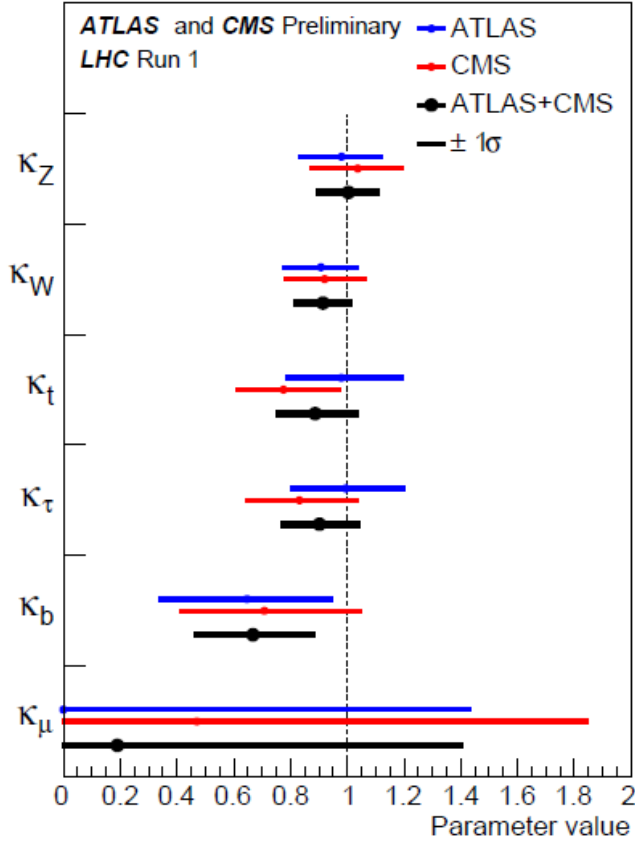


Table 15: Fit results for the parameterisation assuming the absence of BSM particles in the loops,  $BR_{\text{BSM}} = 0$ , and  $\kappa_j \geq 0$ . The measured results with their measured and expected uncertainties are reported for the combination of ATLAS and CMS, together with the measured results with their uncertainties for each experiment. The uncertainties are not indicated when the parameters are constrained and hit a boundary, namely  $\kappa_j = 0$ .

Parameter	ATLAS+CMS	ATLAS+CMS	ATLAS	CMS
$\kappa_j \geq 0$	Measured	Expected uncertainty	Measured	Measured
$\kappa_Z$	$1.00^{+0.10}_{-0.11}$	$+0.10$ $-0.10$	$0.98^{+0.14}_{-0.14}$	$1.04^{+0.15}_{-0.16}$
$\kappa_W$	$0.91^{+0.09}_{-0.09}$	$+0.09$ $-0.09$	$0.91^{+0.12}_{-0.13}$	$0.92^{+0.14}_{-0.14}$
$\kappa_t$	$0.89^{+0.15}_{-0.13}$	$+0.14$ $-0.13$	$0.98^{+0.21}_{-0.18}$	$0.78^{+0.20}_{-0.16}$
$\kappa_\tau$	$0.90^{+0.14}_{-0.13}$	$+0.15$ $-0.14$	$0.99^{+0.20}_{-0.18}$	$0.83^{+0.20}_{-0.18}$
$\kappa_b$	$0.67^{+0.22}_{-0.20}$	$+0.23$ $-0.22$	$0.65^{+0.29}_{-0.30}$	$0.71^{+0.34}_{-0.29}$
$\kappa_\mu$	$0.2^{+1.2}_{-0.2}$	$+0.9$ $-1.0$	$0.0^{+1.4}$	$0.5^{+1.4}_{-0.5}$

Figure 17: Best-fit values of parameters for the combination of ATLAS and CMS and separately for each experiment, for the parameterisation assuming the absence of BSM particles in the loops,  $BR_{\text{BSM}} = 0$ , and  $\kappa_j \geq 0$ . The uncertainties are not indicated when the parameters are constrained and hit a boundary, namely  $\kappa_j = 0$ .

## Geometric interpretation of the HEFT

$$g_{ij}(\phi) = \begin{bmatrix} F(h)^2 g_{ab}(\varphi) & 0 \\ 0 & 1 \end{bmatrix}$$

$$\widehat{R}_{abcd}(\varphi) = \frac{1}{v^2} (g_{ac}(\varphi)g_{bd}(\varphi) - g_{ad}(\varphi)g_{bc}(\varphi))$$

$$\widehat{R}_{bd}(\varphi) = \frac{1}{v^2} (N_\varphi - 1)g_{bd}(\varphi) = \frac{2}{v^2} g_{bd}(\varphi)$$

$$\widehat{R} = \frac{1}{v^2} N_\varphi (N_\varphi - 1) = \frac{6}{v^2},$$

$$R_{abcd}(\phi) = \left[ \frac{1}{v^2} - (F'(h))^2 \right] F(h)^2 (g_{ac}g_{bd} - g_{ad}g_{bc}),$$

$$R_{ahbh}(\phi) = -F(h)F''(h)g_{ab},$$

$$R_{bd}(\phi) = \left\{ \left[ \frac{1}{v^2} - (F'(h))^2 \right] (N_\varphi - 1) - F''(h)F(h) \right\} g_{bd},$$

$$R_{hh}(\phi) = -\frac{N_\varphi F''(h)}{F(h)},$$

$$R(h) = \left[ \frac{1}{v^2} - (F'(h))^2 \right] \frac{N_\varphi (N_\varphi - 1)}{F(h)^2} - \frac{2N_\varphi F''(h)}{F(h)}.$$

$$\mathfrak{R}_4(h) = \left[ 1 - v^2 (F'(h))^2 \right] F(h)^2,$$

$$\mathfrak{R}_{2h}(h) = -\frac{v^2 F(h)F''(h)}{N_\varphi - 1},$$

$$\mathfrak{R}_2(h) = \frac{\mathfrak{R}_4(h)}{F(h)^2} + \mathfrak{R}_{2h}(h),$$

$$\mathfrak{R}_{0h}(h) = \frac{\mathfrak{R}_{2h}(h)}{F(h)^2},$$

$$\mathfrak{R}_0(h) = \frac{\mathfrak{R}_4(h)}{F(h)^4} + \frac{2\mathfrak{R}_{2h}(h)}{F(h)^2},$$

$$R_{abcd} = \mathfrak{R}_4(h) \widehat{R}_{abcd},$$

$$R_{ahbh} = \mathfrak{R}_{2h}(h) \widehat{R}_{ab}$$

$$R_{bd} = \mathfrak{R}_2(h) \widehat{R}_{bd},$$

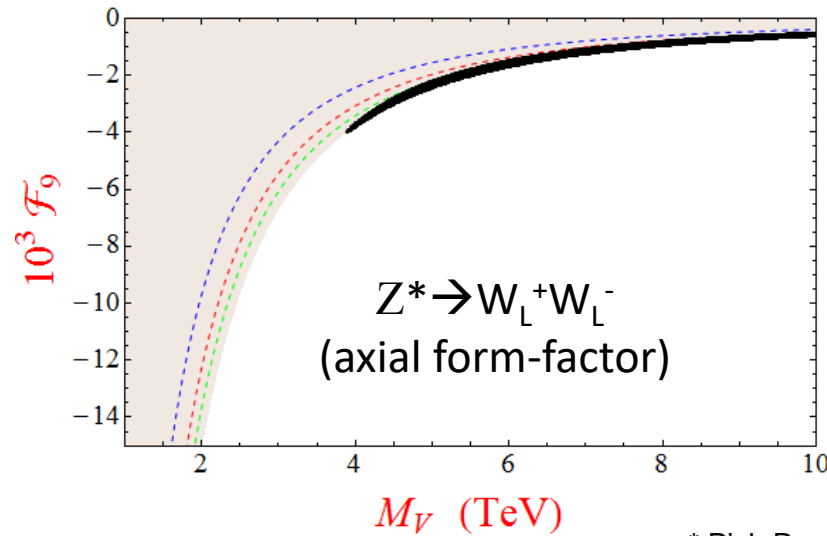
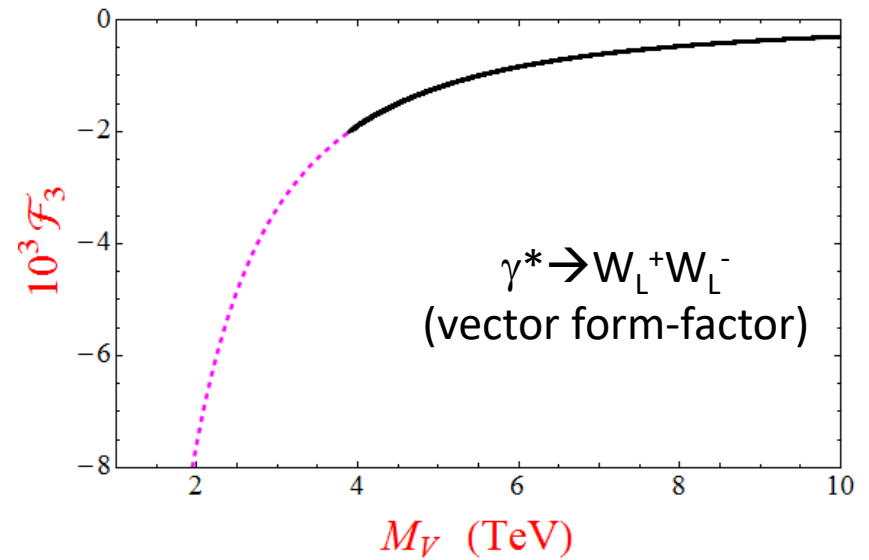
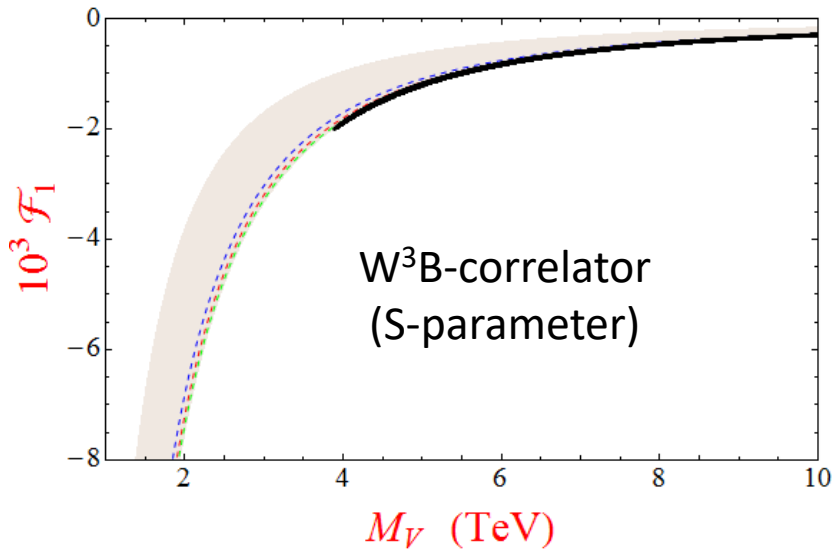
$$R_{hh} = \mathfrak{R}_{0h}(h) \widehat{R},$$

$$R = \mathfrak{R}_0(h) \widehat{R},$$

(x) Alonso, Jenkins, Manohar, PLB754 (2016) 335; PLB756 (2016) 358; JHEP 1608 (2016) 101



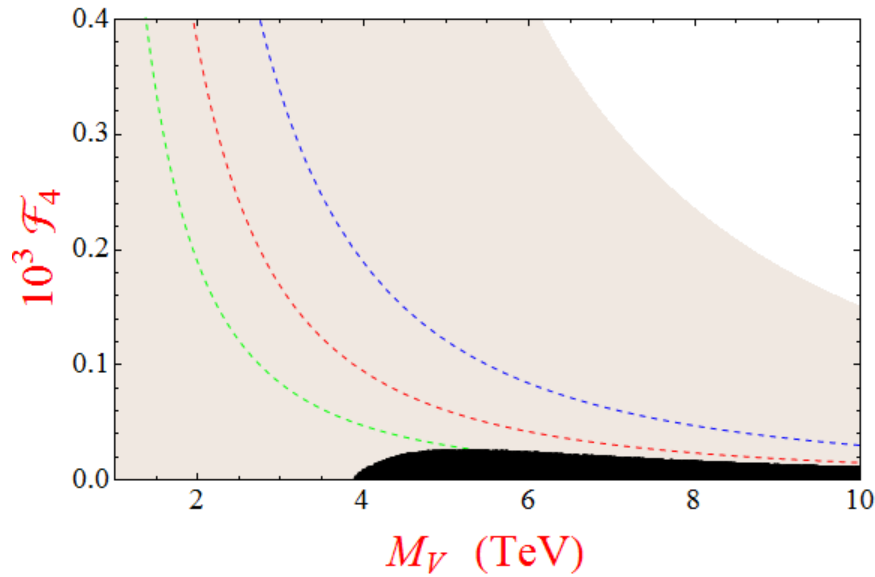
# S-parameter and form-factor couplings (affected by S+T + 2WSRs bounds)



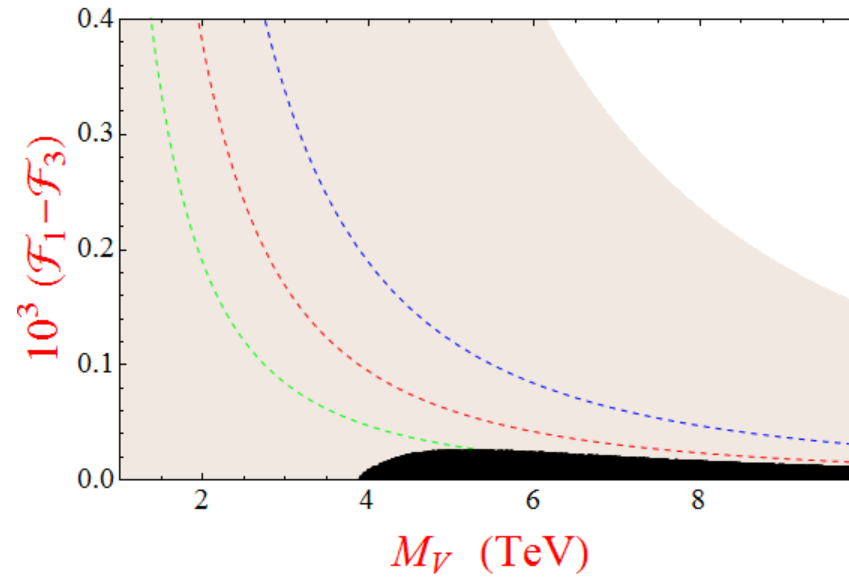
\* Pich, Rosell, Santos, SC, [arXiv:1510.03114 [hep-ph]]

# Scattering couplings (affected by S+T + 2WSRs bounds)

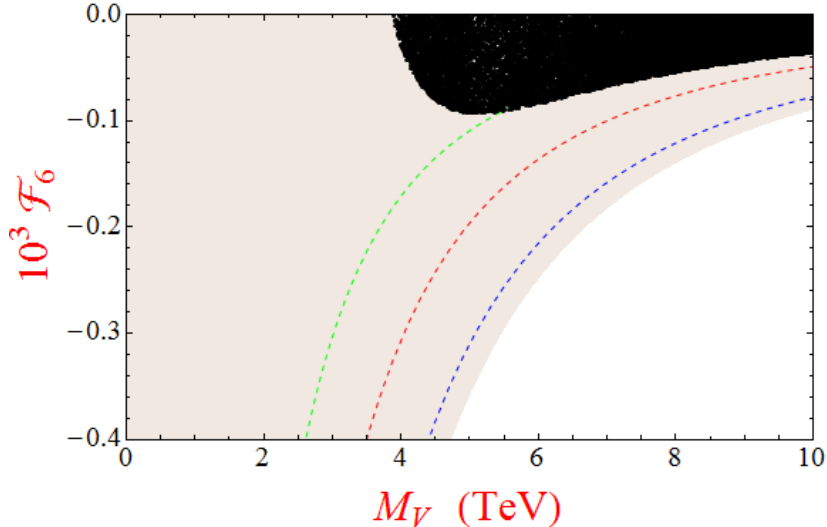
•  $w^a w^b \rightarrow w^c w^d$  scattering



•  $\gamma\gamma \rightarrow w^+ w^-$  scattering



•  $w^a w^b \rightarrow hh$  scattering



•  $hh \rightarrow hh$  scattering  $\rightarrow 0$

\* Pich, Rosell, Santos, SC, [arXiv:1510.03114 [hep-ph]]

# R contributions to the NLO EFT couplings [i.e., $O(p^4)$ ]

## High-energy theory for Resonances + $\chi$ + $\psi$

General  $\Delta\mathcal{L}_R$  'up to  $O(p^2)$ ' \*\*

R= singlet and triplet V, A, S, P [also  $J^{PC}=1^{+-}$  at (x)]

## Low-energy EFT (ECLh) \*

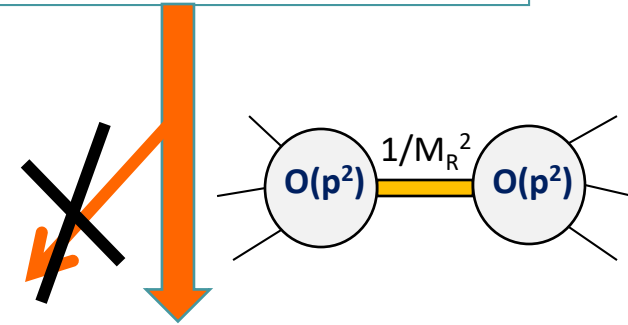
$$e^{iS[\chi,\psi]_{\text{EFT}}} = \int [dR] e^{iS[\chi,\psi,R]} \underset{\text{tree-level}}{=} e^{iS[\chi,\psi,R_{\text{cl.}}]}$$

$$\begin{aligned} \Delta\mathcal{L}_{p^4}^{\text{EFT}} &= \frac{1}{2M_R^2} \left( \langle \mathcal{O}_R \mathcal{O}_R \rangle - \frac{1}{N} \langle \mathcal{O}_R \rangle^2 \right) & (R = S, P), \\ \Delta\mathcal{L}_{p^4}^{\text{EFT}} &= -\frac{1}{M_R^2} \left( \langle \mathcal{O}_R^{\mu\nu} \mathcal{O}_{R\mu\nu} \rangle - \frac{1}{N} \langle \mathcal{O}_R^{\mu\nu} \rangle^2 \right) & (R = V, A), \\ \Delta\mathcal{L}_{p^4}^{\text{EFT}} &= \frac{1}{2M_{R_1}^2} \langle \mathcal{O}_{R_1} \rangle^2 & (R_1 = S_1, P_1), \\ \Delta\mathcal{L}_{p^4}^{\text{EFT}} &= -\frac{1}{M_{R_1}^2} \langle \mathcal{O}_{R_1}^{\mu\nu} \mathcal{O}_{R_1\mu\nu} \rangle & (R_1 = V_1, A_1). \end{aligned}$$

## Impose UV-completion assumptions on $\mathcal{L}_R$ , (sum-rules, unitarity...)

➔ EFT predictions \*\*

$$\Delta\mathcal{L}_R = \boxed{\mathbf{F}_R \mathbf{R} \mathcal{O}_{p^2}[\chi, \psi]} + \dots$$



$$\mathcal{L}_{\text{ECLh}} = \mathcal{L}_{p^2} + \boxed{\mathcal{L}_{p^4}} + \dots$$

$$\supset \mathcal{L}^{\text{SM}}$$

(classification of the operators according to 'chiral' dimension)