Resonances and loops: scale interplay in the Higgs effective theory

(aka EWχL)

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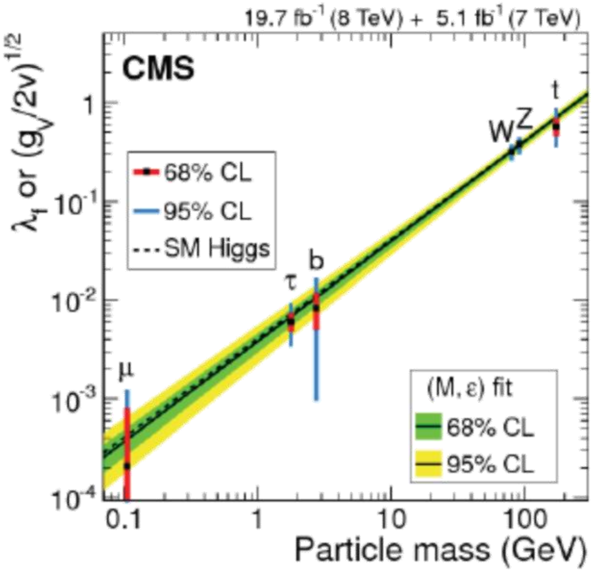
Guo,Ruiz-Femenía,SC, PRD92 (2015) 074005
Du,Guo,Ruiz-Femenía,SC, in preparation.

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

See also the talk by I. Rosell

Motivation



1) "We are so close to SM, so why not simply using SMEFT with the ϕ Higgs doublet? Isn't this enough?"

2) "Aren't BSM loops essentially negligible?

In general NO, only true if "tiny" << "tiny"

OUTLINE:
1) LIN. vs NON-LIN.
2) Loops in EWχL
3) Resonances and NLO couplings in EWχL

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

- Higgs field representation: a matter of taste?

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

$$\mathcal{L}^{\rm L}_{\rm EFT} = (D_\mu\phi)^\dagger D_\mu\phi - \frac{1}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \dots$$
$$= \frac{(v+h)^2}{4}\langle (D_\mu U)^\dagger D_\mu U\rangle + \frac{1}{2}(1+P(h))\,(\partial_\mu h)^2 + \dots$$

$$\frac{dh^{\rm NL}}{dh^{\rm L}} = \sqrt{1+P(h^{\rm L})}$$

$$h^{\rm NL} = \int_0^{h^{\rm L}} \sqrt{1+P(h)}\, dh$$

? ? ?

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

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

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

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

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

* Jenkins,Manohar,Trott, JHEP 1310 (2013) 087
* LHCHXSWG Yellow Report [1610.07922]

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

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

- **SMEFT → EWχL :***

$$\mathcal{L}^{\mathrm{L}}_{\mathrm{EFT}} = (D_\mu\phi)^\dagger D_\mu\phi - \frac{1}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \ldots$$
$$= \frac{(v+h)^2}{4}\langle (D_\mu U)^\dagger D_\mu U\rangle + \frac{1}{2}(1+P(h))\,(\partial_\mu h)^2 + \ldots$$

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

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

(D≥8 operators: corrections v^4/Λ^4, v^6/Λ^6...)

- **Non-linear scenarios:** e.g., dilaton models [(x)] ⟶ $\Delta(a^2) = \Delta b$

if you want to write it in the SMEFT form, large "..." needed (D ≥ 8 operators!!) ➔ SMEFT exp. breakdown

* Jenkins,Manohar,Trott, [1308.2627]
* LHCHXSWG Yellow Report [1610.07922]
* Buchalla,Catà,Celis,Krause,NPB917 (2017) 209-233
(x) Goldberger,Grinstein,Skiba, PRL100 (2008) 111802

EWχL

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

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_4 + \quad \ldots$$

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

- Amplitudes organized according to chiral exp.: (x), *

  - **Dominant corrections:** Deviations from SM in $O(p^2)$ operators
  - **Subdominant corrections:** $O(p^4)$ operators + $O(p^2)$ loops
    - $O(p^4)$ operators: *(heavier states)*
    - $O(p^2)$ loops: *(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
(+) LHCHXSWG 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: *

Finite pieces from loops (amplitude dependent) (+)

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

LO (tree)

NLO (tree)

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

NLO (1-loop)

Typical loop suppression
$\sim R_{ijmn} / (16\pi^2)$
(non-linearity)

** 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]

- Indeed, the SM has this arrangement but with $\frac{\mathbf{p}^2}{16\pi^2\mathbf{v}^2} \sim \frac{\mathbf{g}^{(\prime)\,2}}{(4\pi)^2},\ \frac{\lambda}{(4\pi)^2},\ \frac{\lambda_{\mathbf{f}}^2}{(4\pi)^2} \ll 1$, **always**

Scale suppression in the loops

- Observables at 1 loop: previous computations (-)
- 1 loop of h & ω^a in path integral: *, (x) **Heat kernel**

$$\mathcal{L}_2 = \mathcal{L}_2^{\mathcal{O}(\eta^0)} + \mathcal{L}_2^{\mathcal{O}(\eta^1)} + \mathcal{L}_2^{\mathcal{O}(\eta^2)} + \mathcal{O}(\eta^3)$$

Tree-level ↑ EoM ↑ 1-loop ↑ Higher loops ↑

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

➔ 1 loop UV-div: (+)

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

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

➔ O(p^4) renormalization: *,(x) $\delta\mathcal{L}_2 + \delta\mathcal{L}_4^{\text{Fer}} + \delta\mathcal{L}_4^{\text{Bos}}$

- Espriu,Yencho, PRD 87 (2013) 055017
- Espriu,Mescia, Yencho, 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-Femenía,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^4) operators (purely bosonic) *,(x)

c_k	Operator $\mathcal{O}_k$	Γ_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) $\mathcal{L}_2 + \mathcal{L}_4^{\rm Fer}$ corrected by fermions & gauge boson loops: Du,Guo,Ruiz-Femenía,SC, in preparation.

- Beautiful geometric connection to this result *
  provided by the curvature [(x)] of the scalar manifold metric $g_{ij}(\phi) = \begin{bmatrix} F(h)^2 g_{ab}(\varphi) & 0 \\ 0 & 1 \end{bmatrix}$

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

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

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

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

with Λ^{-2} = the Riemann $\mathbb{R}_{ijmn} \propto \mathscr{R}_{0,2,4} / v^2$ *(loosely speaking, the curvature $\mathbb{R}$)*

- NDA gives you the suppression of individual diagrams ~ $1 / (4\pi v)^2$
  but the <u>full</u> loop suppression is ~ $g^2\mathbb{R} / (4\pi)^2$ & ~ $\mathbb{R}^2 / (4\pi)^2$

  EFT as an expansion $\mathcal{M} \sim R\, \mathbf{p}^2 + \frac{R^2\, \mathbf{p}^4}{(4\pi)^2} + \frac{R^3\, \mathbf{p}^6}{(4\pi)^4} + \ldots$ in the curvature?

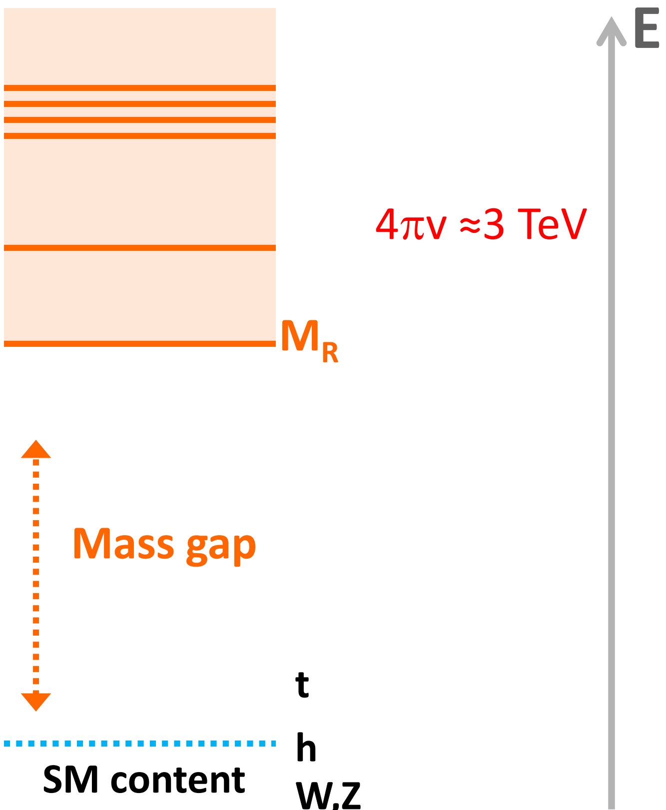
- **SM:** $\mathbb{R}_{ijmn} = 0$ ➔ No $O(p^4)$ renormalization

* 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 *

Talk by I. Rosell



SM content

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

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

+

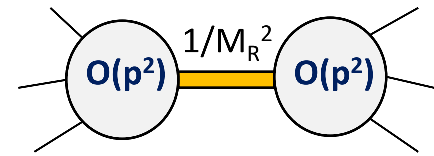
Resonance Lagrangian — V,A,S,P singlet & triplet

+

UV completion hypothesis — Sum-rules

Resonance contributions *,**

to the NLO low-energy couplings



$$e^{i\,S[\chi,\psi]_{\rm EFT}} = \int [dR]\; e^{i\,S[\chi,\psi,R]} \;\stackrel{\rm tree-level}{=}\; e^{i\,S[\chi,\psi,R_{\rm cl.}]}$$

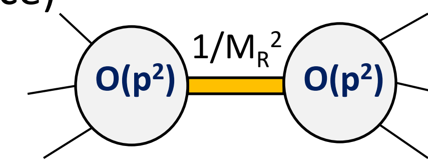
* Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012;
Krause,Pich,Rosell,Santos,SC, in preparation

** 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

$$\mathcal{L}^{\rm HE}[{\rm R},\ell{\rm ight}] = \mathcal{L}_2[\ell{\rm ight}] + \mathcal{L}_{\rm R}[{\rm R},\ell{\rm ight}] + \mathcal{L}_4^{\rm HE}[\ell{\rm ight}]$$

with the most general linear resonance O(p^2) operators (chiral + CP invariance)



$$\mathcal{L}_{\rm R} = \mathcal{L}_{\rm R}^{\rm Kin}[{\rm R}] + {\rm R}\,\chi_{\rm R}[\ell{\rm ight}] + \mathcal{O}({\rm R}^2)$$

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

Low-energy Lagrangian (tree-level)

- Solve R eom at low energies: $\quad {\rm R}_{\rm cl}[\ell{\rm ight}] \sim \frac{1}{{\rm M}_{\rm R}^2}\chi_{\rm R}[\ell{\rm ight}] + \mathcal{O}\left(\frac{{\rm p}^4}{{\rm M}_{\rm R}^4}\right)$

(e.g., for a vector triplet $\quad {\rm V}_{\rm cl}^{\mu\nu} = -\frac{2}{{\rm M}_{\rm V}^2}\left(\chi_{\rm V}^{\mu\nu} - \frac{1}{2}\langle \chi_{\rm V}^{\mu\nu}\rangle\right) + \mathcal{O}\left(\frac{{\rm p}^4}{{\rm M}_{\rm V}^4}\right)$ *)*

- Evaluate $\quad \mathcal{L}^{\rm EFT}[\ell{\rm ight}] = \mathcal{L}^{\rm HE}[{\rm R}_{\rm cl}[\ell{\rm ight}]\,,\,\ell{\rm ight}] \sim \mathcal{L}_2[\ell{\rm ight}] + \frac{1}{{\rm M}_{\rm R}^2}(\chi_{\rm R}[\ell{\rm ight}])^2 + \ldots$

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

So which NLO contribution is bigger in real life?

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

V,A resonances + 1-loop + 2 WSRs

1st + 2nd WSRs (95%CL): **+ exp. S+T parameters**

$M_V > 4$ TeV

$0.94 < a=\kappa_W < 1$

$$S = -16\pi \Big[\underbrace{a_1^r(M_V)}_{\substack{\sim -2\times 10^{-3} \\ \Lambda^{-2}\sim (5\,\mathrm{TeV})^{-2}}} + \underbrace{\frac{a^2-1}{192\pi^2}\left(\ln\frac{M_V^2}{m_h^2}+\frac{5}{6}\right)}_{\substack{\sim -6\times 10^{-5} \\ \Lambda^{-2}\sim (30\,\mathrm{TeV})^{-2}}} \Big]$$

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

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

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

$$A_{NLO}^{\gamma\gamma\to W_L^+W_L^-} = \frac{1}{v^2}\Big[\underbrace{2ac_\gamma^r}_{\substack{\sim 6\times 10^{-3} \\ \Lambda^{-2}\sim (3\,\mathrm{TeV})^{-2}}} + \underbrace{8(a_1^r - a_2^r + a_3^r)}_{\substack{\sim 0.5\times 10^{-3} \\ \Lambda^{-2}\sim (10\,\mathrm{TeV})^{-2}}} + \underbrace{\frac{a^2-1}{8\pi^2 v^2}}_{\substack{\sim -1.5\times 10^{-3} \\ \Lambda^{-2}\sim (6\,\mathrm{TeV})^{-2}}} \Big]$$

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

$\propto \frac{R_{ijmn}}{16\pi^2}$

(x) Pich,Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801

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

(+) **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 ϕ does not always give a good expansion*

✓ **The EWχL & the chiral expansion solve this issue** *(though more tedious*

…and at the end, SMEFT might be just fine)

✓ **Two contributions potentially of the same order in the EWχL:**

- **O(p^4) 1-loop corrections:**
  - ❑ *Calculation in path integral → O(p^4) UV-div. show up*
  - ❑ *Geometric interpretation of the non-linearity:* $\mathbb{R}$ expansion
- **O(p^4) coupling corrections (tree-level):**
  - ❑ *Calculation in path integral → O(p^4) pattern from heavy states* (talk by I.Rosell)

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

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

BACKUP

- 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

(i) SM content:

- Bosons χ: Higgs h + gauge bosons W^a_μ,B_μ *(and QCD)*
  + EW Golsdtones $\omega^\pm$,z [non-linearly realized via $U(\omega^a)$ [(x)]]
- Fermions ψ: (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⇔R asymmetry of the gauge sector ($g,g'\neq 0$)
  t⇔b splitting ($\lambda_t \neq \lambda_b$)
- **Other approximate symmetries:** B, L, CP-invariance, Fermion flavour

(iii) Chiral power counting:

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

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

SUMMARY: 'CHIRAL' COUNTING

- "Chiral" counting *

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

and for the building blocks,

$$u(\varphi/v),\, U(\varphi/v),\, \frac{h}{v},\, \frac{W^a_\mu}{v},\, \frac{B_\mu}{v} \sim \mathcal{O}\left(p^0\right),$$
$$D_\mu U,\, u_\mu,\, \hat{W}_\mu,\, \hat{B}_\mu \sim \mathcal{O}\left(p\right),$$
$$\hat{W}_{\mu\nu},\, \hat{B}_{\mu\nu},\, f_{\pm\,\mu\nu} \sim \mathcal{O}\left(p^2\right),$$
$$\partial_{\mu_1}\partial_{\mu_2}...\partial_{\mu_n}\,\mathcal{F}(h/v) \sim \mathcal{O}\left(p^n\right),$$
$$\frac{\xi}{v} \sim \mathcal{O}\left(p^{\frac{1}{2}}\right)$$

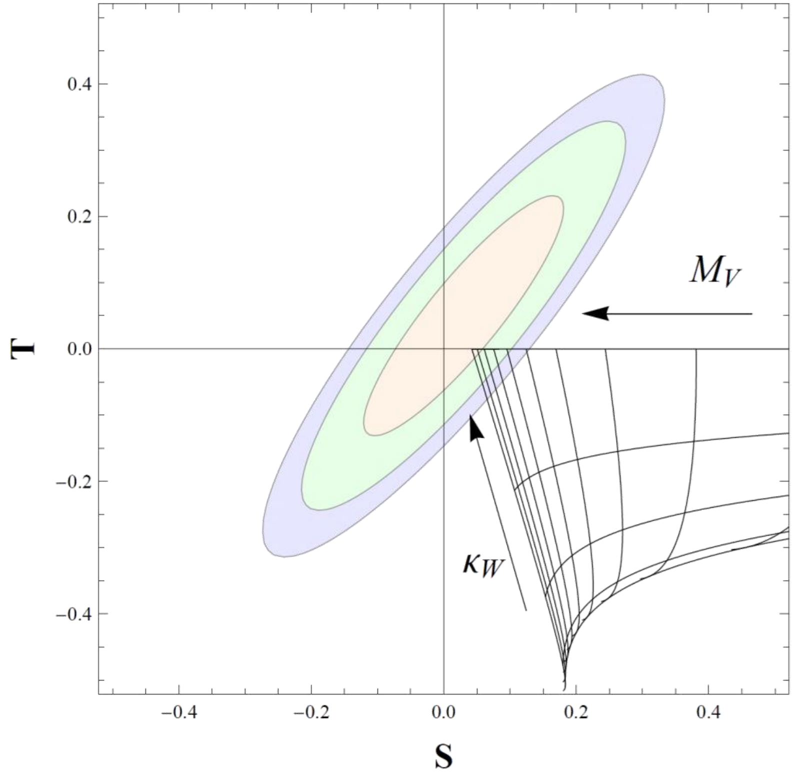
- Assignment of the 'chiral' dimension: *

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

* 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]

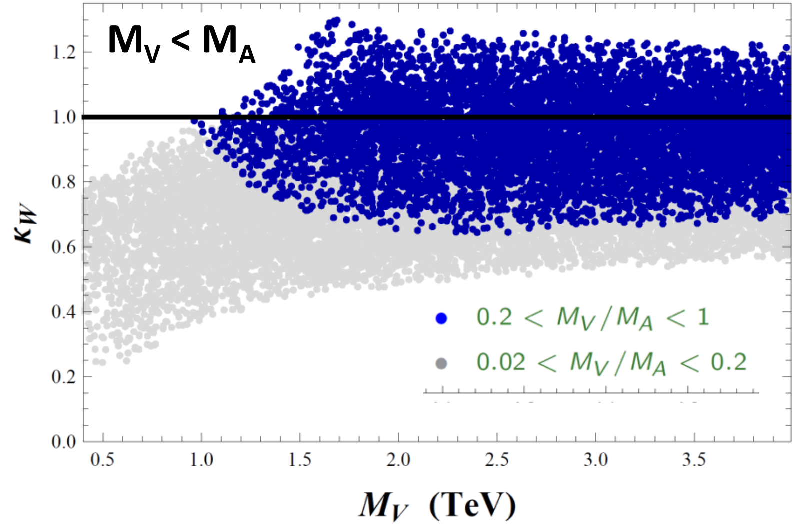
At NLO with the 1st and 2nd WSRs

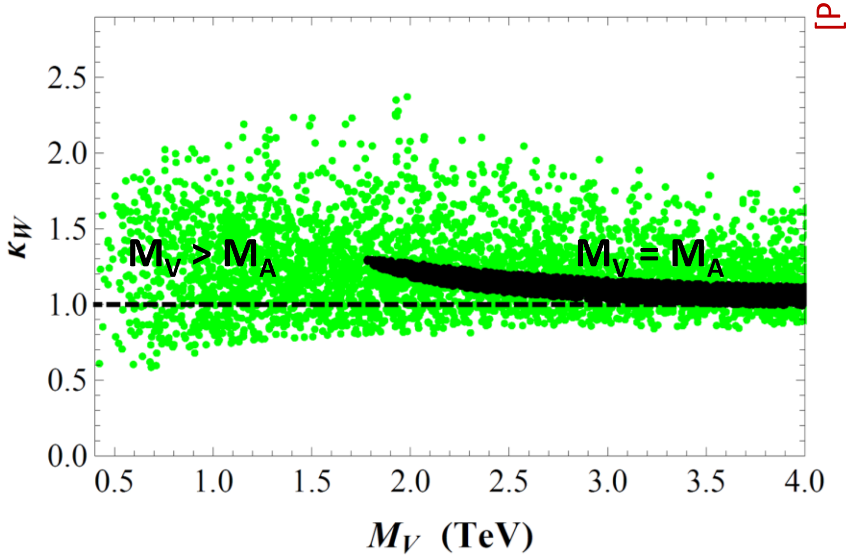
$M_V > 5.4$ TeV, $0.97 < \kappa_W < 1$ at 68% CL

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

NLO results: only 1st WSR

(*walking & conformal TC, extra dimensions,…*)





[Pich,Rosell,SC '12]

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

$$\mathcal{L}_4 = a_1 g' g\langle UT_3B_{\mu\nu}U^\dagger W^{\mu\nu}\rangle + ia_2 g'\langle UT_3B_{\mu\nu}U^\dagger[V^\mu,V^\nu]\rangle - ia_3 g\langle W_{\mu\nu}[V^\mu,V^\nu]\rangle$$
$$+a_4\langle V_\mu V_\nu\rangle\langle V^\mu V^\nu\rangle + a_5\langle V_\mu V^\mu\rangle\langle V_\nu V^\nu\rangle + \frac{e^2}{16\pi^2}c_{\gamma\gamma}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}$$
$$+\frac{g^{hh}}{v^4}(\partial_\mu h\partial^\mu h)^2 + \frac{d^{hh}}{v^2}(\partial_\mu h\partial^\mu h)\langle D_\nu U^\dagger D^\nu U\rangle + \frac{e^{hh}}{v^2}(\partial_\mu h\partial^\nu h)\langle D^\mu U^\dagger D_\nu U\rangle + \dots$$

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

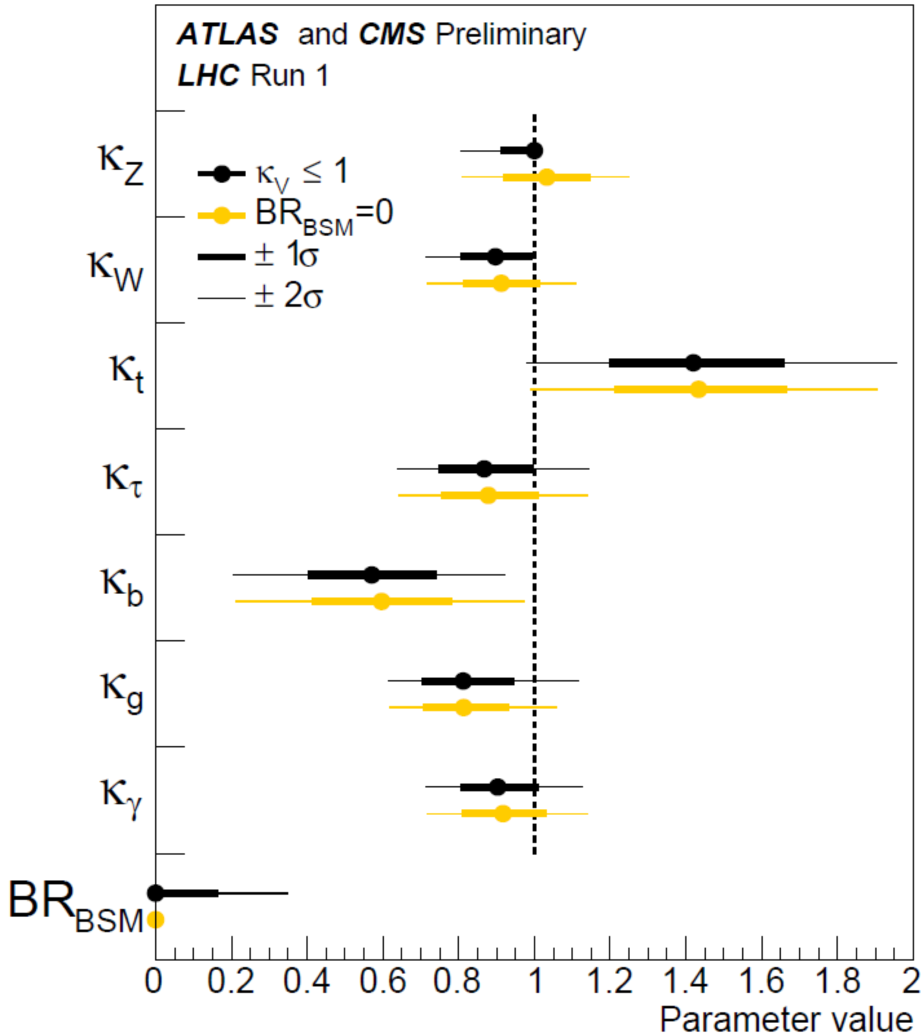
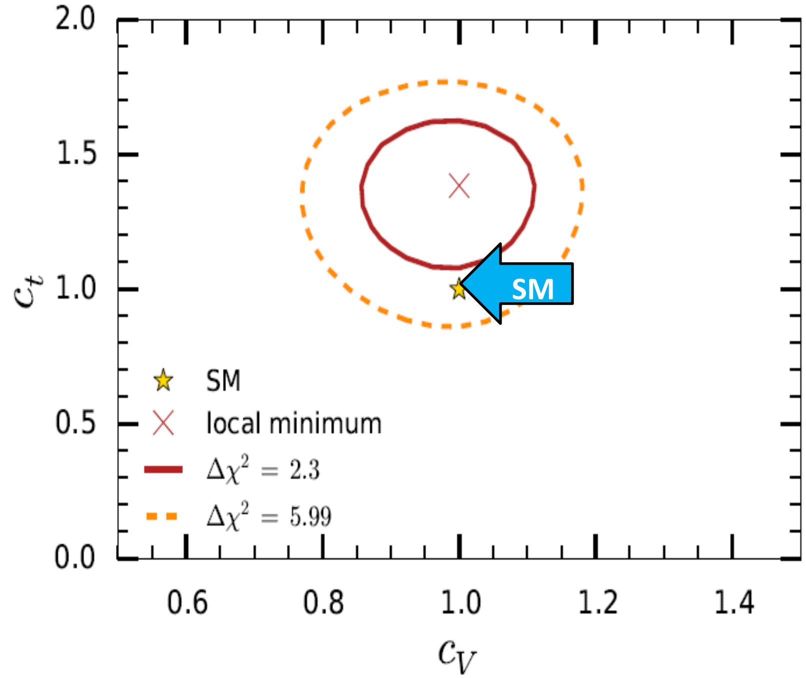


Figure 14: Fit results for the two parameterisations allowing BSM loop couplings, with $\kappa_V \leq 1$, where κ_V stands for κ_Z or κ_W, or without additional BSM contributions to the Higgs boson width, i.e. $\mathrm{BR}_{\mathrm{BSM}} = 0$. The measured results for the combination of ATLAS and CMS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



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

ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002 (September 2015)

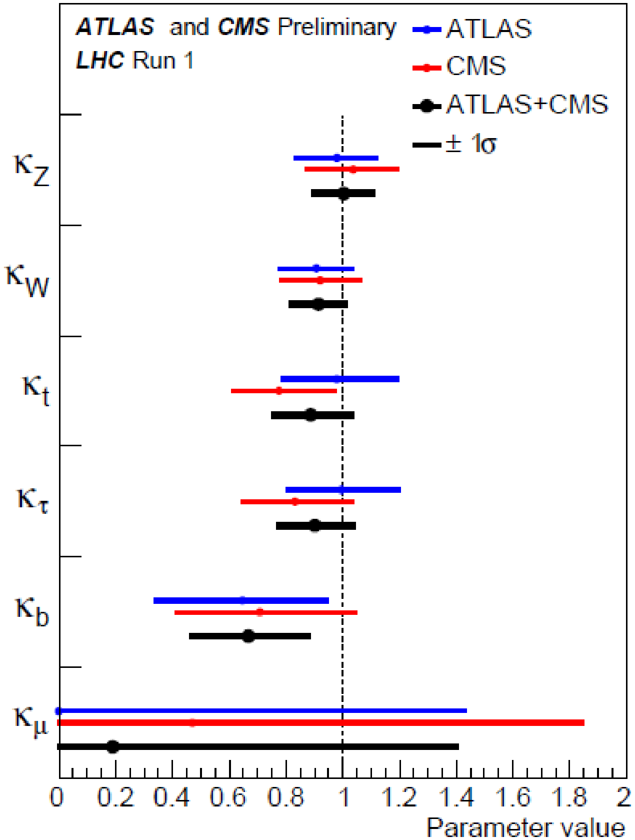


Table 15: Fit results for the parameterisation assuming the absence of BSM particles in the loops, $BR_{BSM} = 0$, and $\kappa_j \geq 0$. The measured results with their measured and expected uncertainties are reported for the combination of ATLAS and CMS, together with the measured results with their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

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

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, $BR_{BSM} = 0$, and $\kappa_j \geq 0$. The uncertainties are not indicated when the parameters are constrained and hit a boundary, namely $\kappa_j = 0$.

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

Geometric interpretation of the HEFT

$$\widehat{R}_{abcd}(\varphi)=\frac{1}{v^2}\left(g_{ac}(\varphi)g_{bd}(\varphi)-g_{ad}(\varphi)g_{bc}\right.$$
$$\widehat{R}_{bd}(\varphi)=\frac{1}{v^2}(N_\varphi-1)g_{bd}(\varphi)=\frac{2}{v^2}g_{bd}(\varphi$$
$$\widehat{R}=\frac{1}{v^2}N_\varphi(N_\varphi-1)=\frac{6}{v^2},$$

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

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

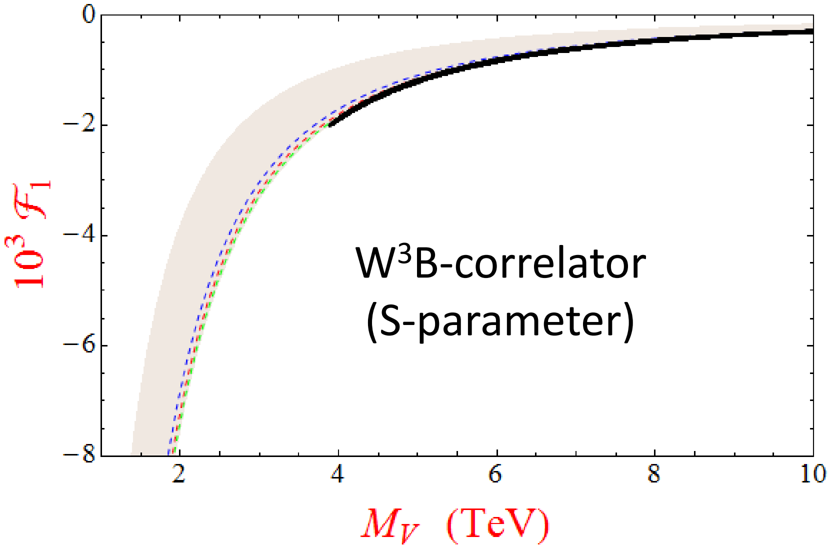
$$R(h)=\left[\frac{1}{v^2}-(F'(h))^2\right]\frac{N_\varphi(N_\varphi-1)}{F(h)^2}-\frac{2N_\varphi F''(h)}{F(h)}.$$

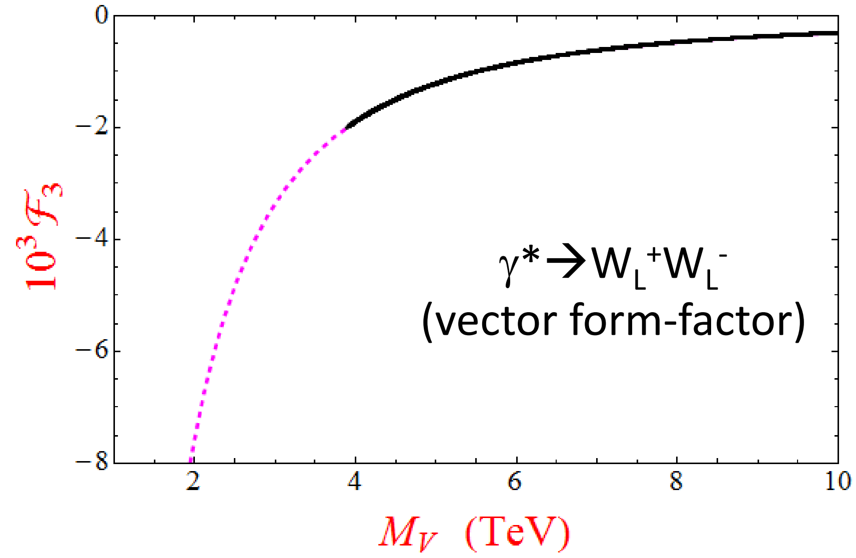
$$R_{abcd}=\mathfrak{R}_4(h)\widehat{R}_{abcd},\qquad R_{ahbh}=\mathfrak{R}_{2h}(h)\widehat{R}_{ab}$$
$$R_{bd}=\mathfrak{R}_2(h)\widehat{R}_{bd},\qquad R_{hh}=\mathfrak{R}_{0h}(h)\widehat{R},$$
$$R=\mathfrak{R}_0(h)\widehat{R},$$

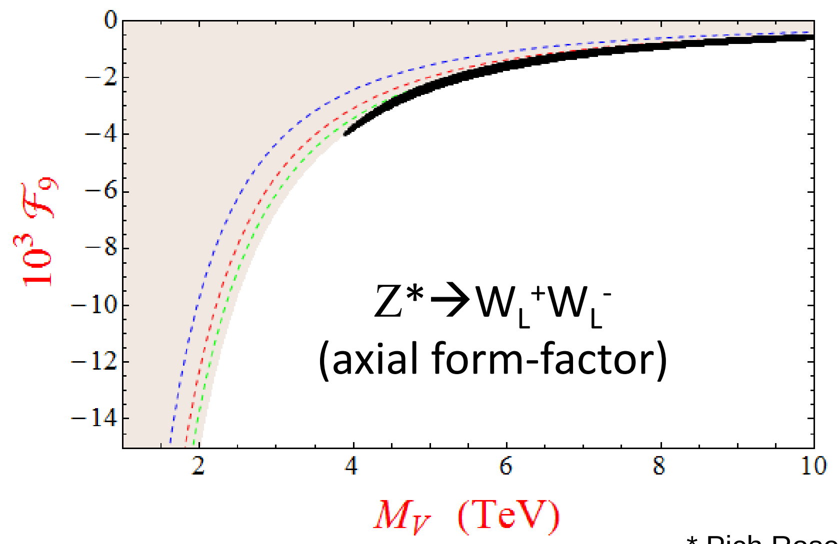
$$\mathfrak{R}_4(h)=\left[1-v^2(F'(h))^2\right]F(h)^2,$$
$$\mathfrak{R}_{2h}(h)=-\frac{v^2F(h)F''(h)}{N_\varphi-1},$$
$$\mathfrak{R}_2(h)=\frac{\mathfrak{R}_4(h)}{F(h)^2}+\mathfrak{R}_{2h}(h),$$
$$\mathfrak{R}_{0h}(h)=\frac{\mathfrak{R}_{2h}(h)}{F(h)^2},$$
$$\mathfrak{R}_0(h)=\frac{\mathfrak{R}_4(h)}{F(h)^4}+\frac{2\mathfrak{R}_{2h}(h)}{F(h)^2},$$

(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)



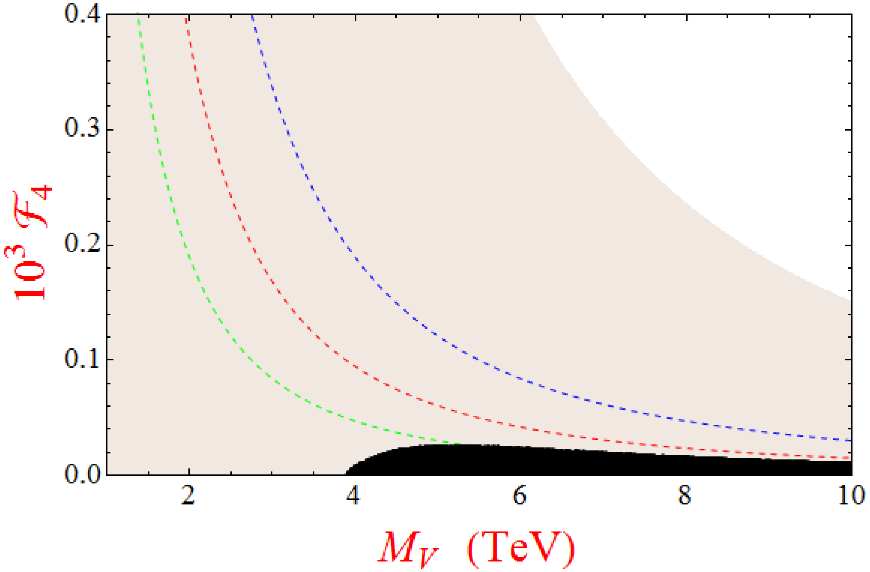




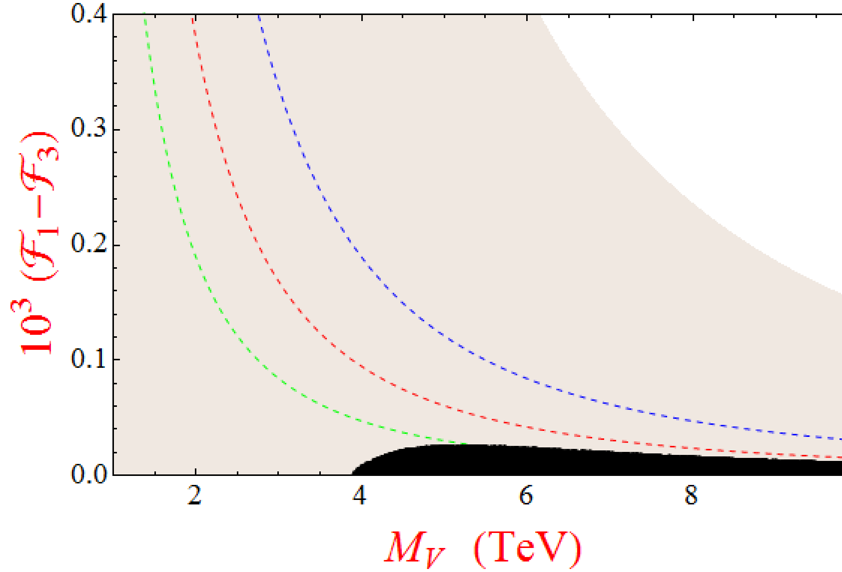
* Pich,Rosell,Santos,SC, [arXiv:1510.03114 [hep-ph]]

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

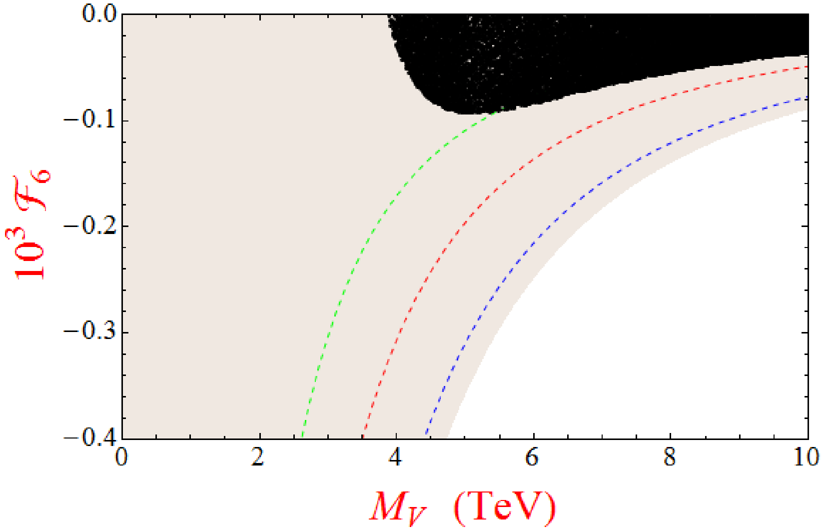
• $w^a w^b \to w^c w^d$ scattering



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



• $w^a w^b \to hh$ scattering



• $hh \to hh$ scattering $\to 0$

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

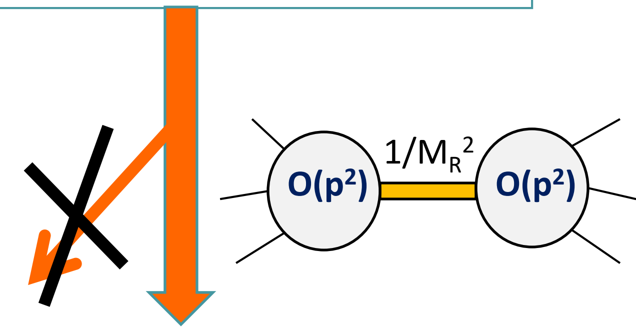
R contributions to the NLO EFT couplings *[i.e., $O(p^4)$]*

- **High-energy theory for Resonances + χ + ψ**

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

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

$$\Delta\mathcal{L}_{\mathbf{R}} = \mathbf{F_R}\,\mathbf{R}\,\mathcal{O}_{\mathbf{p^2}}[\chi,\psi] + \ldots$$



- **Low-energy EFT (ECLh) ***

$$e^{i\,S[\chi,\psi]_{\rm EFT}} = \int [dR]\, e^{i\,S[\chi,\psi,R]} \stackrel{\rm tree-level}{=} e^{i\,S[\chi,\psi,R_{\rm cl.}]}$$

$$\mathcal{L}_{ECLh} = \mathcal{L}_{p^2} + \mathcal{L}_{p^4} + \ldots$$

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

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

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

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

  ➔ **EFT predictions ****

Then, is SMEFT enough?

Can't we drop the chiral loops?

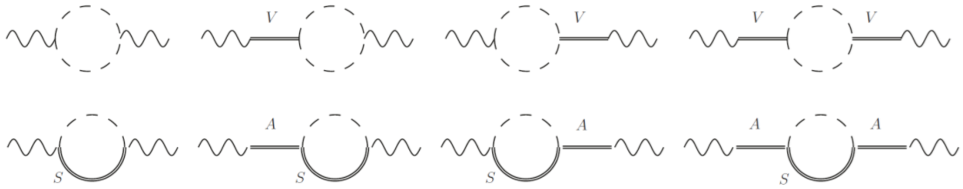
- It will depend on whether

"tiny" *[O(p^4) 1-loop]* << "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

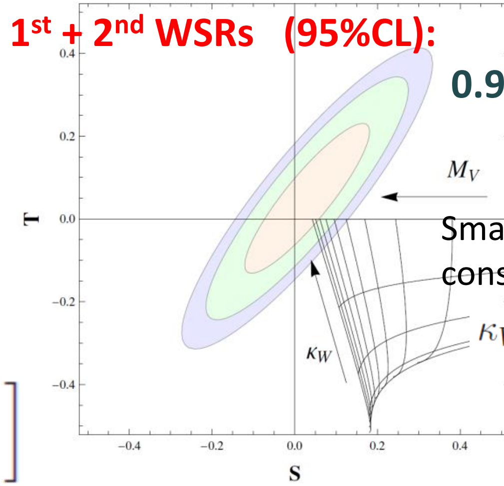
EXAMPLE 1: *, (x) S-parameter + 2 WSRs



1^{st} + 2^{nd} WSRs (95%CL):

$M_V > 4$ TeV

$0.94 < a = \kappa_W < 1$



Small splitting due to constraints from WSRs

$\kappa_W = M_V^2/M_A^2$

V,A resonances + 1-loop + 2 WSRs

$$\mathbf{S} = -16\pi\Big[\underbrace{a_1^r(M_V)}_{\substack{\sim -2\times 10^{-3} \\ \Lambda^{-2}\sim (5\,\mathrm{TeV})^{-2}}} + \underbrace{\frac{a^2-1}{192\pi^2}\left(\ln\frac{M_V^2}{m_h^2}+\frac{5}{6}\right)}_{\substack{\sim -6\times 10^{-5} \\ \Lambda^{-2}\sim (30\,\mathrm{TeV})^{-2}}}\Big]$$

$$-\frac{\mathrm{v}^2}{4\mathrm{M}_\mathrm{V}^2} - \frac{\mathrm{v}^2}{4\mathrm{M}_\mathrm{A}^2} + \dots$$

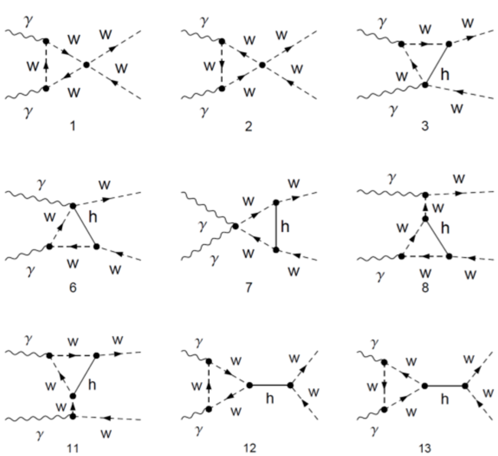
$- \mathscr{R}_4 / 192\pi^2$

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

(only charged shown here)

$$\mathrm{A}_{\mathrm{NLO}}^{\gamma\gamma\to \mathrm{W_L^+W_L^-}} = \frac{1}{\mathrm{v}^2}\Big[\underbrace{2ac_\gamma^r}_{\substack{\sim 6\times 10^{-3} \\ \Lambda^{-2}\sim (3\,\mathrm{TeV})^{-2}}} + \underbrace{8(a_1^r - a_2^r + a_3^r)}_{\substack{\sim 0.5\times 10^{-3} \\ \Lambda^{-2}\sim (10\,\mathrm{TeV})^{-2}}} + \underbrace{\frac{a^2-1}{8\pi^2 v^2}}_{\substack{\sim -1.5\times 10^{-3} \\ \Lambda^{-2}\sim (6\,\mathrm{TeV})^{-2}}}\Big]$$

$$\propto \frac{1}{\mathrm{M}^2} \qquad\qquad \propto \frac{\mathrm{R_{ijmn}}}{16\pi^2}$$



+30 more

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

(x) Pich,Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801

(+) **Inputs:** Buchalla,Catà,Celis,Krause, EPJC76 (2016) no.5, 233