Resonance Lagrangians and HEFT: phenomenology

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Pich, Rosell, Sanz-Cillero, arXiv:2004.02827 [hep-ph]

A follow up on
Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012
Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

Outline

1.) (Non-linear) EW effective theory and Resonance extension

2.) Ultraviolet completion and high E constraints

3.) Predictions for Low-Energy Constants (LECs)

4.) Phenomenological implications: M_R *bounds*

$$u(\varphi) = \exp\{i\vec\sigma\,\vec\varphi/(2v)\}$$
$$U(\varphi) \equiv u(\varphi)^2$$

- (Non-linear) EW Effective Theory (*EWET = EWχL = HEFT*) based on chiral & other SM symmetries:

  - **Chiral expansión in powers of p^d:** $$\mathcal{L}_{\rm EWET} = \sum_{\hat d\ge 2} \mathcal{L}_{\rm EWET}^{(\hat d)}$$

  - **O(p^2), LO** ($\supset$ SM) : $$\mathcal{L}_{\rm EWET}^{(2)} = \sum_\xi \left[i\,\bar\xi\gamma^\mu d_\mu\xi - v\left(\,\bar\xi_L\,\mathcal{Y}\,\xi_R + \text{h.c.}\right)\right] - \frac{1}{2g^2}\langle \hat W_{\mu\nu}\hat W^{\mu\nu}\rangle_2 - \frac{1}{2g'^2}\langle \hat B_{\mu\nu}\hat B^{\mu\nu}\rangle_2 - \frac{1}{2g_s^2}\langle \hat G_{\mu\nu}\hat G^{\mu\nu}\rangle_3 + \frac12 \partial_\mu h\,\partial^\mu h - \frac12\, m_h^2\, h^2 - V(h/v) + \frac{v^2}{4}\mathcal{F}_u(h/v)\,\langle u_\mu u^\mu\rangle_2$$

    with $\mathcal{F}_{\rm u} = 1 + \frac{2\kappa_{\rm W}{\rm h}}{\rm v} + \frac{{\rm c}_{\rm 2V}{\rm h}^2}{{\rm v}^2} + \mathcal{O}({\rm h}^3)$, *being* $\kappa_{\rm W}^{\rm SM} = {\rm c}_{\rm 2V}^{\rm SM} = 1$

  - **O(p^4), NLO** (pure BSM):

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

(x) Buchalla, Cata, JHEP 1207 (2012) 101; Buchalla,Catà,Krause, NPB 880 (2014) 552-573
(x) Alonso,Gavela,Merlo,Rigolin,Yepes, PLB 722 (2013) 330-335; Brivio et al, JHEP 1403 (2014) 024
(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

- Here, study of the bosonic sector ➔ bosonic operators only

- List of CP even operators:

i	$\mathcal{O}_i$ [P-even]
1	$\frac{1}{4}\langle\, f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\,\rangle_2$
2	$\frac{1}{2}\langle\, f_+^{\mu\nu} f_{+\,\mu\nu} + f_-^{\mu\nu} f_{-\,\mu\nu}\,\rangle_2$
3	$\frac{i}{2}\langle\, f_+^{\mu\nu}[u_\mu, u_\nu]\,\rangle_2$
4	$\langle\, u_\mu u_\nu\,\rangle_2\,\langle\, u^\mu u^\nu\,\rangle_2$
5	$\langle\, u_\mu u^\mu\,\rangle_2\,\langle\, u_\nu u^\nu\,\rangle_2$
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	$\langle\, \mathcal{T} u_\mu\,\rangle_2\,\langle\, \mathcal{T} u^\mu\,\rangle_2$
11	$\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$
12	$\langle\, \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\,\rangle_3$

i	$\widetilde{\mathcal{O}}_i$ [P-odd]
1	$\frac{i}{2}\langle\, f_-^{\mu\nu}[u_\mu, u_\nu]\,\rangle_2$
2	$\langle\, f_+^{\mu\nu} f_{-\,\mu\nu}\,\rangle_2$
3	$\frac{(\partial_\mu h)}{v}\langle\, f_+^{\mu\nu} u_\nu\,\rangle_2$

Correspondence with Longhitano [x, +]:

$$a_i = \mathcal{F}_i(0)\,, \quad i = 1,4,5$$
$$a_2 = (\mathcal{F}_3(0) - \widetilde{\mathcal{F}}_1(0))/2$$
$$a_3 = -(\mathcal{F}_3(0) + \widetilde{\mathcal{F}}_1(0))/2$$

(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092
(+) Longhitano, PRD 22 (1980) 1166; NPB 188 (1981) 118; Herrero,Ruiz Morales, NPB 418 (1994) 431

- Resonance Lagrangian extension: 0^{++} (S), 0^{-+} (P), 1^{--} (V) and 1^{++} (A)

  (relevant terms)

$$\Delta\mathcal{L}_{\rm RT} = \frac{v^2}{4}\left(1+\frac{2\,\kappa_W}{v}h+c_{2V}\,h^2\right)\langle\, u_\mu u^\mu\,\rangle_2 + \frac{c_d}{\sqrt{2}}\,S_1^1\langle\, u_\mu u^\mu\,\rangle_2 + d_P\frac{(\partial_\mu h)}{v}\langle\, P_3^1\, u^\mu\,\rangle_2 + \widetilde{c}_{\mathcal{T}}\,\hat{V}^1_{1\,\mu}\langle\, u^\mu\mathcal{T}\,\rangle_2 + c_{\mathcal{T}}\,\hat{A}^1_{1\,\mu}\langle\, u^\mu\mathcal{T}\,\rangle_2$$
$$+\langle\, V^1_{3\,\mu\nu}\left(\frac{F_V}{2\sqrt{2}}f_+^{\mu\nu}+\frac{iG_V}{2\sqrt{2}}[u^\mu,u^\nu]+\frac{\widetilde{F}_V}{2\sqrt{2}}f_-^{\mu\nu}+\sqrt{2}\,\widetilde{\lambda}_1^{hV}(\partial^\mu h)u^\nu\right)\rangle_2 + F_X V^1_{1\,\mu\nu}\hat{X}^{\mu\nu} + C_G V^8_{1\,\mu\nu}\hat{G}^{\mu\nu}$$
$$+\langle\, A^1_{3\,\mu\nu}\left(\frac{F_A}{2\sqrt{2}}f_-^{\mu\nu}+\sqrt{2}\,\lambda_1^{hA}(\partial^\mu h)u^\nu+\frac{\widetilde{F}_A}{2\sqrt{2}}f_+^{\mu\nu}+\frac{i\widetilde{G}_A}{2\sqrt{2}}[u^\mu,u^\nu]\right)\rangle_2 + \widetilde{F}_X A^1_{1\,\mu\nu}\hat{X}^{\mu\nu} + \widetilde{C}_G A^8_{1\,\mu\nu}\hat{G}^{\mu\nu}\,.$$

(we denote couplings of P-odd ops. w/ a tilde: e.g., $\widetilde{F}_V$)

(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

• R contribution to the O(p^4) EFT:

i	$\mathcal{O}_i$	$\mathcal{F}_i$	i	$\mathcal{O}_i$	$\mathcal{F}_i$
1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\rangle_2$	$-\frac{F_V^2-\widetilde{F}_V^2}{4M_{V_3^1}^2}+\frac{F_A^2-\widetilde{F}_A^2}{4M_{A_3^1}^2}$	7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle_2$	$\frac{d_P^2}{2M_{P_3^1}^2}+\frac{\lambda_1^{hA\,2}v^2}{M_{A_3^1}^2}+\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_{V_3^1}^2}$
2	$\frac{1}{2}\langle f_+^{\mu\nu} f_{+\,\mu\nu} + f_-^{\mu\nu} f_{-\,\mu\nu}\rangle_2$	$-\frac{F_V^2+\widetilde{F}_V^2}{8M_{V_3^1}^2}-\frac{F_A^2+\widetilde{F}_A^2}{8M_{A_3^1}^2}$	8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	0
3	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu,u_\nu]\rangle_2$	$-\frac{F_V G_V}{2M_{V_3^1}^2}-\frac{\widetilde{F}_A\widetilde{G}_A}{2M_{A_3^1}^2}$	9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu} u_\nu\rangle_2$	$-\frac{F_A\lambda_1^{hA}v}{M_{A_3^1}^2}-\frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M_{V_3^1}^2}$
4	$\langle u_\mu u_\nu\rangle_2\langle u^\mu u^\nu\rangle_2$	$\frac{G_V^2}{4M_{V_3^1}^2}+\frac{\widetilde{G}_A^2}{4M_{A_3^1}^2}$	10	$\langle \mathcal{T} u_\mu\rangle_2\langle \mathcal{T} u^\mu\rangle_2$	$-\frac{\widetilde{c}_{\mathcal{T}}^2}{2M_{V_1^1}^2}-\frac{c_{\mathcal{T}}^2}{2M_{A_1^1}^2}$
5	$\langle u_\mu u^\mu\rangle_2\langle u_\nu u^\nu\rangle_2$	$\frac{c_d^2}{4M_{S_1^1}^2}-\frac{G_V^2}{4M_{V_3^1}^2}-\frac{\widetilde{G}_A^2}{4M_{A_3^1}^2}$	11	$\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$	$-\frac{F_X^2}{M_{V_1^1}^2}-\frac{\widetilde{F}_X^2}{M_{A_1^1}^2}$
6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle_2$	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M_{V_3^1}^2}-\frac{\lambda_1^{hA\,2}v^2}{M_{A_3^1}^2}$	12	$\langle \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\rangle_3$	$-\frac{(C_G)^2}{2M_{V_1^8}^2}-\frac{(\widetilde{C}_G)^2}{2M_{A_1^8}^2}$

i	$\widetilde{\mathcal{O}}_i$	$\widetilde{\mathcal{F}}_i$	i	$\widetilde{\mathcal{O}}_i$	$\widetilde{\mathcal{F}}_i$
1	$\frac{i}{2}\langle f_-^{\mu\nu}[u_\mu,u_\nu]\rangle_2$	$-\frac{\widetilde{F}_V G_V}{2M_{V_3^1}^2}-\frac{F_A\widetilde{G}_A}{2M_{A_3^1}^2}$	3	$\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu} u_\nu\rangle_2$	$-\frac{F_V\widetilde{\lambda}_1^{hV}v}{M_{V_3^1}^2}-\frac{\widetilde{F}_A\lambda_1^{hA}v}{M_{A_3^1}^2}$
2	$\langle f_+^{\mu\nu} f_{-\,\mu\nu}\rangle_2$	$-\frac{F_V\widetilde{F}_V}{4M_{V_3^1}^2}-\frac{F_A\widetilde{F}_A}{4M_{A_3^1}^2}$			

(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

• **UV completion assumptions:** high energy constraints

- VFF to two EW Goldstones ($\varphi\varphi$) : $$v^2 - F_V\, G_V - \widetilde{F}_A\, \widetilde{G}_A = 0$$

- AFF to Higgs + EW Goldstone ($h\varphi$) : $$\kappa_W\, v - F_A\, \lambda_1^{hA} - \widetilde{F}_V\, \widetilde{\lambda}_1^{hV} = 0$$

- VFF to Higgs + EW Goldstone ($h\varphi$) : $$\widetilde{F}_A\, \lambda_1^{hA} + F_V\, \widetilde{\lambda}_1^{hV} = 0$$

- AFF to two EW Goldstones ($\varphi\varphi$): $$\widetilde{F}_V\, G_V + F_A\, \widetilde{G}_A = 0$$

- W_3B correlator 1st & 2nd WSRs:

(a) 1st WSR (vanishing of the $1/s$ term):

$$F_V^2 + \widetilde{F}_A^2 - F_A^2 - \widetilde{F}_V^2 = v^2\,.$$

(b) 2nd WSR (vanishing of the $1/s^2$ term):

$$F_V^2 M_V^2 + \widetilde{F}_A^2 M_A^2 - F_A^2 M_A^2 - \widetilde{F}_V^2 M_V^2 = 0.$$

⇒

$$F_V^2 - \widetilde{F}_V^2 = \frac{v^2 M_A^2}{M_A^2 - M_V^2}$$

$$F_A^2 - \widetilde{F}_A^2 = \frac{v^2 M_V^2}{M_A^2 - M_V^2}$$

$$M_A > M_V$$

* Pich, Rosell, Sanz-Cillero, arXiv:2004.02827 [hep-ph]

- O(p^4) LEC predictions from Resonance Theories w/ just P-even ops.:

	$\mathcal{F}_i$	
i	with 2nd WSR	without 2nd WSR
1	$-\frac{v^2}{4}\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)$	$-\frac{v^2}{4M_V^2}-\frac{F_A^2}{4}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right) < \frac{-v^2}{4M_V^2}$
3	$-\frac{v^2}{2M_V^2}$	
4	$\frac{v^2}{4}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)$	$\dots$
5	$\frac{c_d^2}{4M_{S_1^1}^2}-\mathcal{F}_4$	
6	$-\kappa_W^2 v^2\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)$	$\dots$
7	$\frac{d_P^2}{2M_P^2}-\mathcal{F}_6$	
9	$-\frac{\kappa_W v^2}{M_A^2}$	

* Pich, Rosell, Sanz-Cillero, arXiv:2004.02827 [hep-ph]

- $O(p^4)$ LEC predictions w/ P-even & P-odd ops. in the Resonance Theories:

i	$\mathcal{F}_i$ with 2nd WSR	$\mathcal{F}_i$ without 2nd WSR
1	$-\frac{v^2}{4}\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)$	$-\frac{v^2}{4M_V^2}-\frac{F_A^2-\widetilde{F}_A^2}{4}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)$ $^\dagger < -\frac{v^2}{4M_V^2}$
3	$-\frac{v^2}{2M_A^2}-\frac{F_V G_V}{2}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)$ $^\ddagger <$ $-\frac{v^2}{2M_A^2}$	
5	$\frac{c_d^2}{4M_{S_1^1}^2}-\mathcal{F}_4$	
7	$\frac{d_P^2}{2M_P^2}-\mathcal{F}_6$	
9	$-\frac{\kappa_W v^2}{M_V^2}+F_A\lambda_1^{hA}v\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)$ $^\S >$ $-\frac{\kappa_W v^2}{M_V^2}$	

$F_A^2 > \widetilde{F}_A^2$

$|\widetilde{F}_A\,\widetilde{G}_A| < |F_V G_V|$ ⇒ $F_V G_V > 0$

$|\widetilde{F}_V\,\widetilde{\lambda}_1^{hV}| < |F_A\,\lambda_1^{hA}|$ ⇒ $F_A\lambda_1^{hA} > 0$

* Pich, Rosell, Sanz-Cillero, arXiv:2004.02827 [hep-ph]

Phenomenology

- **EXPERIMENTAL INPUTS:**

1. **κ_W (h→WW):** CMS+ATLAS analysis within HEFT [21]
2. **c_{2V} (hh→WW):** ATLAS bounds [22]
3. **$\mathcal{F}_1$ (W_3B):** LEP S-parameter [24]
4. **$\mathcal{F}_3$ (γWW):** Anomalous TGC $\delta\kappa_\gamma$ [26]
5. **$\mathcal{F}_4$, $\mathcal{F}_5$ (WW→WW):** CMS VBS analysis [27]
   [Caveats:
   - very stringent bounds
   - x 100 precision improvement *
   - unitarity not incorporated (x)
   - unitarity could make bound looser (x)]

Nevertheless, considered for illustration

[95%CL] LEC	Ref.	Data
$0.89 < \kappa_W < 1.13$	[21]	LHC
$-1.02 < c_{2V} < 2.71$	[22]	LHC
$-0.004 < \mathcal{F}_1 < 0.004$	[24]	LEP via S
$-0.06 < \mathcal{F}_3 < 0.20$	[26]	LEP & LHC
$-0.0006 < \mathcal{F}_4 < 0.0006$	[27]	LHC
$-0.0010 < \mathcal{F}_4 + \mathcal{F}_5 < 0.0010$	[27]	LHC

[21] J. de Blas, O. Eberhardt and C. Krause, "Current and Future Constraints on Higgs Couplings in the Nonlinear Effective Theory," JHEP **1807** (2018) 048 [arXiv:1803.00939 [hep-ph]].

[22] The ATLAS collaboration [ATLAS Collaboration], "Search for the $HH \to b\bar{b}b\bar{b}$ process via vector boson fusion production using proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector," ATLAS-CONF-2019-030.

[24] M. Tanabashi *et al.* [Particle Data Group], "Review of Particle Physics," Phys. Rev. D **98** (2018) no.3, 030001.

[26] E. da Silva Almeida, A. Alves, N. Rosa Agostinho, O. J. P. boli and M. C. González-García, "Electroweak Sector Under Scrutiny: A Combined Analysis of LHC and Electroweak Precision Data," Phys. Rev. D **99** (2019) no.3, 033001 [arXiv:1812.01009 [hep-ph]].

[27] A. M. Sirunyan *et al.* [CMS Collaboration], "Search for anomalous electroweak production of vector boson pairs in association with two jets in proton-proton collisions at 13 TeV," Phys. Lett. B **798** (2019) 134985 [arXiv:1905.07445 [hep-ex]].

* Aaboud et al., [ATLAS Collaboration], PRD 95, 032001 (2017) 429
(x) García-García,Herrero,Morales, PRD 100 (2019) no.9, 096003
(x) Fabbrichesi,Pinamonti,Tonero,Urbano, PRD 93 (2016) no.1, 015004

• **1-loop uncertainties**:

LEC running [(x)]

$$\frac{\partial \mathcal{F}_i}{\partial \ln\mu} = -\frac{\Gamma_i}{16\pi^2}$$

$$\frac{\partial \widetilde{\mathcal{F}}_i}{\partial \ln\mu} = -\frac{\widetilde{\Gamma}_i}{16\pi^2}$$

$$\Gamma_1 = \Gamma_3 = -\frac{1}{6}\left(1-\kappa_W^2\right), \qquad \Gamma_2 = -\frac{1}{12}\left(1+\kappa_W^2\right),$$
$$\Gamma_4 = \frac{1}{6}\left(1-\kappa_W^2\right)^2, \quad \Gamma_5 = \frac{1}{8}\left(\kappa_W^2 - c_{2V}\right)^2 + \frac{1}{12}\left(1-\kappa_W^2\right)^2,$$
$$\Gamma_6 = -\frac{1}{6}\left(\kappa_W^2 - c_{2V}\right)\left(7\kappa_W^2 - c_{2V} - 6\right),$$
$$\Gamma_7 = \frac{4}{9}\Gamma_8 = \frac{2}{3}\left(\kappa_W^2 - c_{2V}\right)^2, \quad \Gamma_9 = -\frac{1}{3}\kappa_W\left(\kappa_W^2 - c_{2V}\right).$$

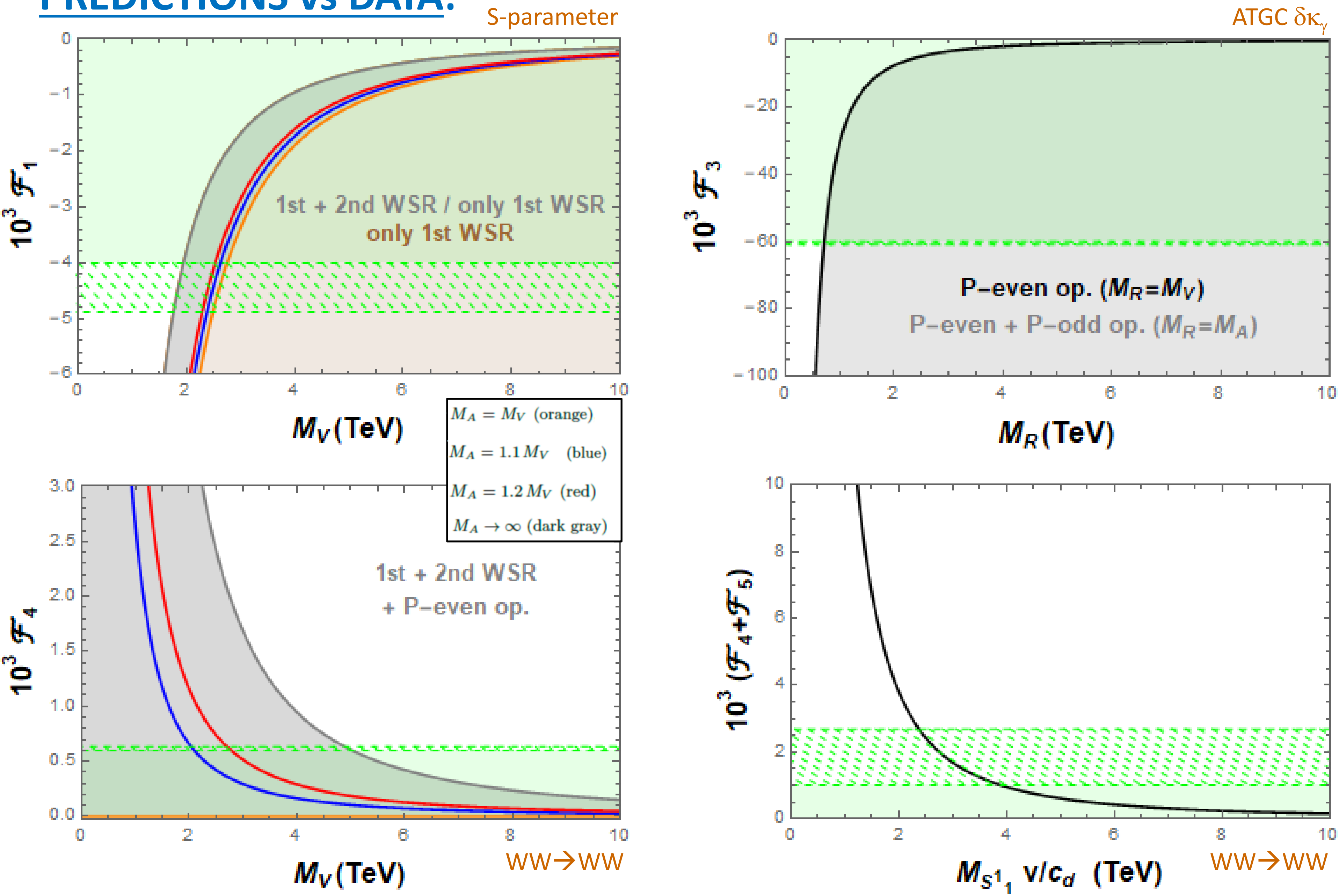
1-loop estimate from running *

$$\Delta\mathcal{F}_i = |\mathcal{F}_i(\mu = m_h) - \mathcal{F}_i(\mu = 3\text{ TeV})|$$

$$\Delta\mathcal{F}_1 = \Delta\mathcal{F}_3 = 0.9\cdot 10^{-3}, \qquad \Delta\mathcal{F}_4 = 3\cdot 10^{-5},$$
$$\Delta(\mathcal{F}_4 + \mathcal{F}_5) = 1.7\cdot 10^{-3}, \qquad \Delta\mathcal{F}_6 = 3\cdot 10^{-3},$$
$$\Delta(\mathcal{F}_6 + \mathcal{F}_7) = 0.6\cdot 10^{-2}, \qquad \Delta\mathcal{F}_9 = 1.4\cdot 10^{-2}.$$

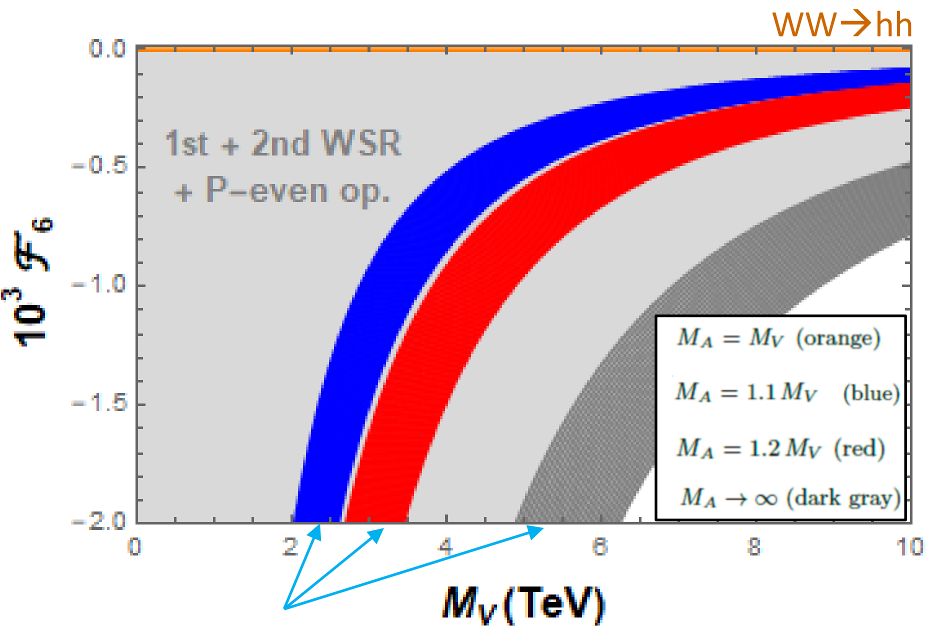
(x) Guo,Ruiz-Femenia,SC, PRD92 (2015) 074005. See also: Alonso,Jenkins,Manohar, PLB 754 (2016) 335-342
Full theory running: Alonso,Kanshin,Saa, PRD 97 (2018) no.3, 035010; Buchalla,Cata,Celis,Knecht,Krause, NPB 928 (2018) 93-106
* Pich, Rosell, Sanz-Cillero, arXiv:2004.02827 [hep-ph]

• PREDICTIONS vs DATA:

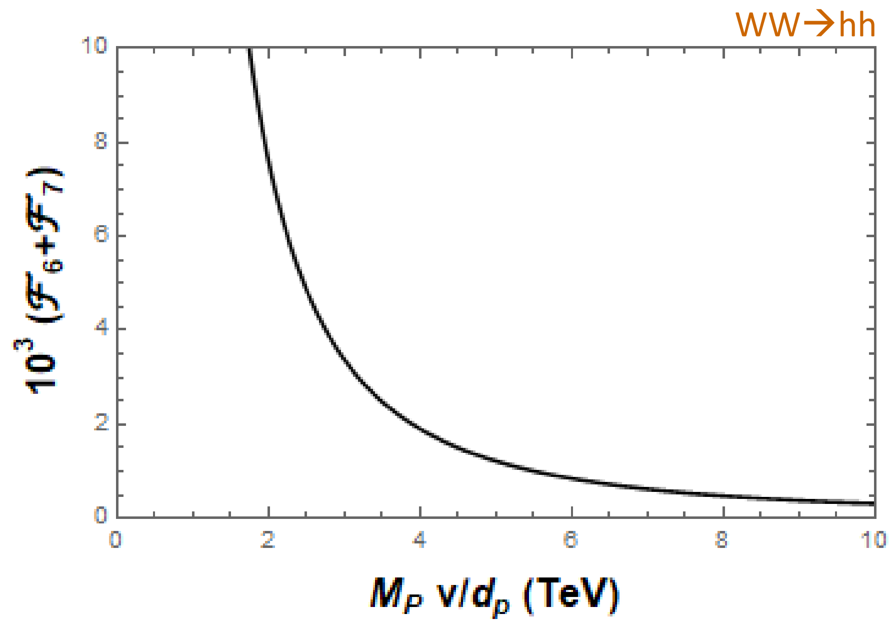


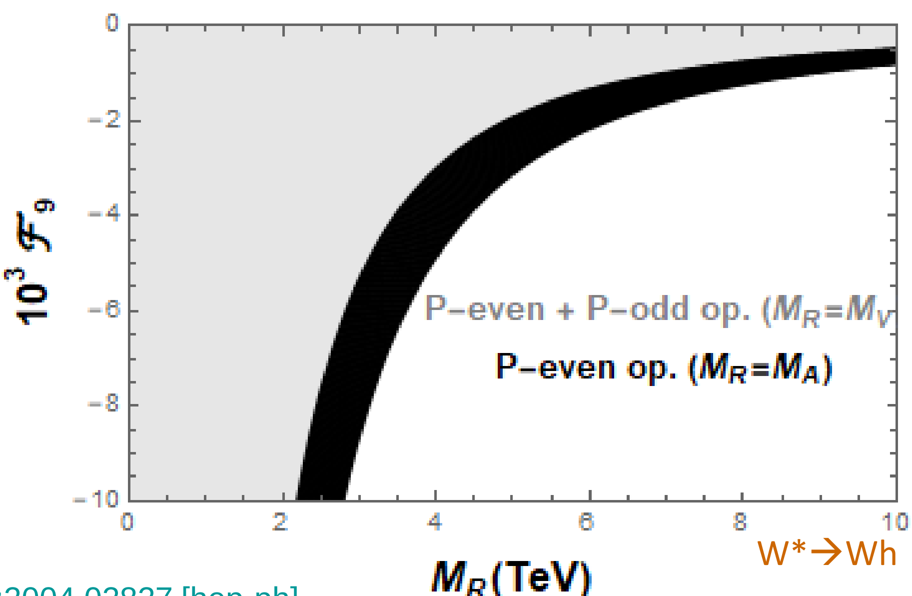
* Pich, Rosell, Sanz-Cillero, arXiv:2004.02827 [hep-ph]

• **PREDICTIONS** *(no DATA + $O(10^{-2})$ 1-loop errors -due to c_{2V}-):*



$\Delta\kappa_W^{exp}$ ➔ thick lines





* Pich, Rosell, Sanz-Cillero, arXiv:2004.02827 [hep-ph]

Conclusions

✓ **LECs with exp. data:**

- *S-parameter:* $\mathscr{F}_1$ ⇨ $M_{V,A} \gtrsim 2$ TeV
- *Anomalous TGC:* $\mathscr{F}_3$ ⇨ $M_{V,A} \gtrsim 0.5$ TeV
- *VBS:* $\mathscr{F}_4$ ⇨ $M_{V,A} \gtrsim 2$ TeV for $M_A/M_V > 1.1$

$\mathscr{F}_4 + \mathscr{F}_5$ ⇨ $M_{S_1^1} \gtrsim 2$ TeV for $c_d \sim v$

✓ **LECs with NO data:**

- WW→hh: $M_V \sim 2$ TeV ⇨ $|\mathcal{F}_6| \gtrsim 2 \cdot 10^{-3}$ (*negative*)

$M_P \lesssim 2$ TeV ⇨ $\mathcal{F}_6 + \mathcal{F}_7 \gtrsim 5 \cdot 10^{-3}$

- W*→Wh: $M_{V,A} \sim 2$ TeV ⇨ $|\mathcal{F}_9| \sim \mathcal{O}(10^{-2})$ (*negative*)

BACKUP

$$\mathcal{G} \equiv SU(2)_L \otimes SU(2)_R \quad \longrightarrow \quad \mathcal{H} \equiv SU(2)_{L+R}$$

$\mathcal{G}/\mathcal{H}$ coset

$$u(\varphi) = \exp\{i\vec{\sigma}\,\vec{\varphi}/(2v)\}$$

$$u(\varphi) \to g_L\, u(\varphi)\, g_h^\dagger = g_h\, u(\varphi)\, g_R^\dagger\,,$$
$$U(\varphi) \equiv u(\varphi)^2 \to g_L\, U(\varphi)\, g_R^\dagger\,, \qquad g_h \equiv g_h(\varphi, g) \in \mathcal{H}$$

$$D_\mu U = \partial_\mu U - i\,\hat{W}_\mu U + i\,U\hat{B}_\mu \to g_L\,(D_\mu U)\,g_R^\dagger\,,$$
$$u_\mu = i\,u\,(D_\mu U)^\dagger u = -i\,u^\dagger D_\mu U\,u^\dagger = u_\mu^\dagger \to g_h\,u_\mu\,g_h^\dagger,$$

$$\mathcal{T}_R \to g_R\,\mathcal{T}_R\,g_R^\dagger\,, \qquad \mathcal{T} = u\,\mathcal{T}_R\,u^\dagger \to g_h\,\mathcal{T}\,g_h^\dagger \qquad \mathcal{T}_R = -g'\,\frac{\sigma_3}{2}$$

The power counting of chiral dimensions adopted to organize the operators of the EWET can be summarized as: $h \sim \mathcal{O}(p^0)$, $u_\mu, \partial_\mu, \mathcal{T} \sim \mathcal{O}(p^1)$ and $f_{\pm\,\mu\nu}, \hat{G}_{\mu\nu}, \hat{X}_{\mu\nu} \sim \mathcal{O}(p^2)$ [8, 9].

$$\begin{aligned}
\hat{W}^\mu &\to g_L\,\hat{W}^\mu g_L^\dagger + i\,g_L\,\partial^\mu g_L^\dagger\,,\\
\hat{B}^\mu &\to g_R\,\hat{B}^\mu g_R^\dagger + i\,g_R\,\partial^\mu g_R^\dagger\,,\\
\hat{W}_{\mu\nu} &= \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu - i\,[\hat{W}_\mu, \hat{W}_\nu] \to g_L\,\hat{W}_{\mu\nu}\,g_L^\dagger\,,\\
\hat{B}_{\mu\nu} &= \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu - i\,[\hat{B}_\mu, \hat{B}_\nu] \to g_R\,\hat{B}_{\mu\nu}\,g_R^\dagger\,,\\
f_\pm^{\mu\nu} &= u^\dagger \hat{W}^{\mu\nu} u \pm u\,\hat{B}^{\mu\nu} u^\dagger \to g_h\, f_\pm^{\mu\nu}\, g_h^\dagger\,.
\end{aligned} \tag{A3}$$

$$\hat{W}^\mu = -g\,\frac{\vec{\sigma}}{2}\,\vec{W}^\mu\,, \qquad \hat{B}^\mu = -g'\,\frac{\sigma_3}{2}\,B^\mu$$

$$\frac{\partial \mathcal{F}_i}{\partial \ln\mu} = -\frac{\Gamma_i}{16\pi^2}\,, \qquad \frac{\partial \widetilde{\mathcal{F}}_i}{\partial \ln\mu} = -\frac{\widetilde{\Gamma}_i}{16\pi^2}$$

$$\begin{aligned}
&\Gamma_1 = \Gamma_3 = -\frac{1}{6}\,(1-\kappa_W^2)\,, \qquad \Gamma_2 = -\frac{1}{12}\,(1+\kappa_W^2)\,,\\
&\Gamma_4 = \frac{1}{6}\,(1-\kappa_W^2)^2, \quad \Gamma_5 = \frac{1}{8}\,(\kappa_W^2 - c_{2V})^2 + \frac{1}{12}\,(1-\kappa_W^2)^2,\\
&\Gamma_6 = -\frac{1}{6}\,(\kappa_W^2 - c_{2V})\,(7\kappa_W^2 - c_{2V} - 6)\,,\\
&\Gamma_7 = \frac{4}{9}\,\Gamma_8 = \frac{2}{3}\,(\kappa_W^2 - c_{2V})^2, \quad \Gamma_9 = -\frac{1}{3}\kappa_W\,(\kappa_W^2 - c_{2V})\,.
\end{aligned} \tag{A9}$$

where only the first term in the expansion of Γ_i in powers of h/v is given, *i.e.*, $\Gamma_i(h=0)$. Note that $\Gamma_1 = \Gamma_{3-9} = 0$ and $\Gamma_2 \neq 0$ for the SM values, $\kappa_W = c_{2V} = 1$, as it should be.

$$\mathcal{F}_u = 1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \mathcal{O}(h^3) \qquad a_{SM} = b_{SM} = 1$$

$$\mathcal{L}_{\rm EWET} = \sum_{\hat{d}\geq 2} \mathcal{L}_{\rm EWET}^{(\hat{d})}$$

$$\Delta\mathcal{L}_{\rm EWET}^{(2)} = \frac{v^2}{4}\left(1 + \frac{2\,\kappa_W}{v} h + \frac{c_{2V}}{v^2}\, h^2\right) \langle\, u_\mu u^\mu \,\rangle_2$$

$$\Delta\mathcal{L}_{\rm EWET}^{(4)} = \sum_{i=1}^{12} \mathcal{F}_i(h/v)\, \mathcal{O}_i \,+\, \sum_{i=1}^{3} \widetilde{\mathcal{F}}_i(h/v)\, \widetilde{\mathcal{O}}_i$$

$$R_3^n \;=\; \frac{1}{\sqrt{2}} \sum_{i=1}^{3} \sigma_i\, R_{3,i}^n\,, \qquad R_n^8 \;=\; \sum_{a=1}^{8} T^a\, R_n^{8,a}$$

with $\langle\, \sigma_i \sigma_j \,\rangle_2 = 2\delta_{ij}$ and $\langle\, T^a T^b \,\rangle_3 = \delta^{ab}/2$, where $\langle \cdots \rangle_3$ indicates an $SU(3)_C$ trace.

The spin-1 resonances V and A can be described with either a four-vector Proca field $\hat{R}^\mu$ or with an antisymmetric tensor $R^{\mu\nu}$. Here we keep both formalisms because, at it was demonstrated in Ref. [9], the sum of tree-level resonance-exchange contributions from the $\mathcal{O}(p^2)$ resonance Lagrangian with Proca and antisymmetric spin-1 resonances gives the complete (non-redundant and correct) set of predictions for the $\mathcal{O}(p^4)$ EWET LECs, without any additional contributions from local operators without resonance fields.

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

(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	$(\sim p^1)$
weak SM fermion coupling $[\psi\psi]$	⇔	order 2	$(\sim p^2)$

* See, e.g., rev: HXSWG Yellow Report (non-linear EFT Sec.), arXiv:1610.07922 [hep-ph]

* Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

Low-energy EFT (SM + …): representations

- Higgs field representation: a matter of taste? (+)

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

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

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

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

? ? ?

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

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

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

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

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

(+) SC, arXiv:1710.07611 [hep-ph]
* 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 :***

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

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

(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), (+), *]

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

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

- 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).

$$\mathcal{L}_V = -\frac{1}{4}\mathrm{Tr}(\hat{V}_{\mu\nu}\hat{V}^{\mu\nu}) + \frac{1}{2}M_V^2\,\mathrm{Tr}(\hat{V}_\mu\hat{V}^\mu) + \frac{f_V}{2\sqrt{2}}\mathrm{Tr}(\hat{V}_{\mu\nu}f_+^{\mu\nu}) + \frac{ig_V}{2\sqrt{2}}\mathrm{Tr}(\hat{V}_{\mu\nu}[u^\mu, u^\nu])\,,$$

$$\hat{V}_\mu = \frac{\tau^a V_\mu^a}{\sqrt{2}} = \begin{pmatrix} \frac{V_\mu^0}{\sqrt{2}} & V_\mu^+ \\ V_\mu^- & -\frac{V_\mu^0}{\sqrt{2}} \end{pmatrix},$$

$$\hat{V}_{\mu\nu} = \nabla_\mu\hat{V}_\nu - \nabla_\nu\hat{V}_\mu\,,$$

$$u_\mu = i\,u\left(D_\mu U\right)^\dagger u\,, \qquad \text{with} \qquad u^2 = U$$

$$f_+^{\mu\nu} = -\left(u^\dagger\hat{W}^{\mu\nu}u + u\hat{B}^{\mu\nu}u^\dagger\right),$$

$$\nabla_\mu\mathcal{X} = \partial_\mu\mathcal{X} + [\Gamma_\mu, \mathcal{X}]\,, \qquad \text{with} \qquad \Gamma_\mu = \frac{1}{2}\left(\Gamma_\mu^L + \Gamma_\mu^R\right),$$

$$\Gamma_\mu^L = u^\dagger\left(\partial_\mu + i\,\frac{g}{2}\vec{\tau}\vec{W}_\mu\right)u\,, \qquad \Gamma_\mu^R = u\left(\partial_\mu + i\,\frac{g'}{2}\tau^3 B_\mu\right)u^\dagger\,.$$

SUMMARY: NAÏVE `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, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012
* Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

• List of CP even operators : *[Caveat: no flavour]*

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

i	$\widetilde{\mathcal{O}}_i$	$\widetilde{\mathcal{O}}_i^{\psi^2}$	$\widetilde{\mathcal{O}}_i^{\psi^4}$
1	$\frac{i}{2}\langle f_-^{\mu\nu}[u_\mu, u_\nu]\rangle_2$	$\langle J_T^{\mu\nu} f_{-\,\mu\nu}\rangle_2$	$\langle J_V^\mu J_{A,\mu}\rangle_2$
2	$\langle f_+^{\mu\nu} f_{-\,\mu\nu}\rangle_2$	$\frac{\partial_\mu h}{v}\langle u_\nu J_T^{\mu\nu}\rangle_2$	$\langle J_V^\mu\rangle_2 \langle J_{A,\mu}\rangle_2$
3	$\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu} u_\nu\rangle_2$	$\langle J_V^\mu\rangle_2 \langle u_\mu \mathcal{T}\rangle_2$	—

(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

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) (+)

$$\mathcal{M}(2\to 2) \approx \frac{\mathbf{p}^2}{\mathbf{v}^2} + \left(\frac{\mathcal{F}_{\mathbf{k}}(\mu)\,\mathbf{p}^4}{\mathbf{v}^2} - \frac{\Gamma_{\mathbf{k}}\,\mathbf{p}^4}{16\pi^2\mathbf{v}^2}\ln\frac{\mathbf{p}^2}{\mu^2} + \ldots \right) + \mathcal{O}(\mathbf{p}^6)$$

LO (tree)

NLO (tree)

suppression
~1/M^2 + ...
(heavier states)

NLO (1-loop)

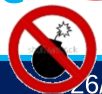
Typical loop suppression
$\sim \Gamma_k / (16\pi^2 v^2)$
(non-linearity)

** 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

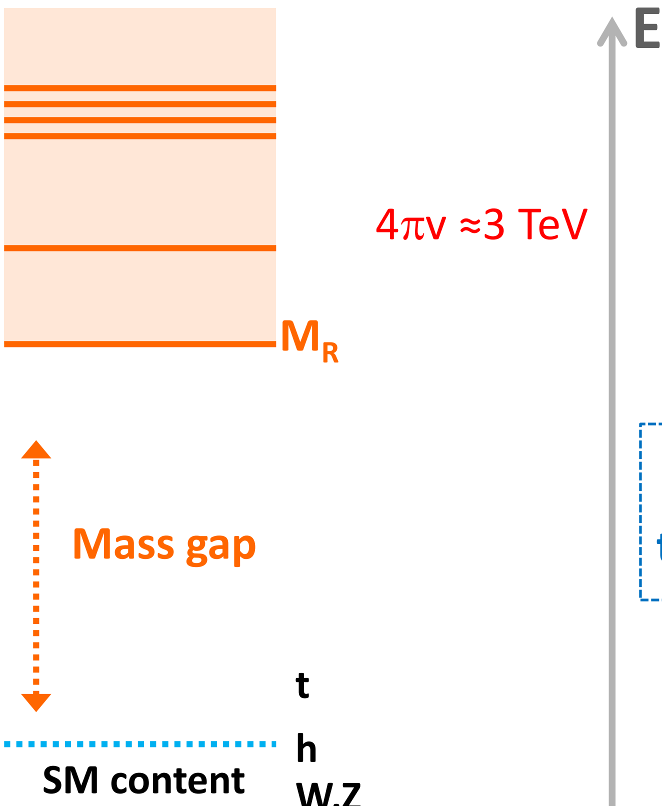
100% determined by $\mathcal{L}_2$
[Guo,Ruiz-Femenia,SC, PRD92 (2015) 074005]

*** Alonso,Jenkins,Manohar, PLB 754 (2016) 335-342
*** Alonso,Kanshin,Saa, PRD 97 (2018) no.3, 035010
*** Buchalla,Cata,Celis,Knecht,Krause, NPB 928 (2018) 93-106

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



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



Custodial symmetry

+

Resonance Lagrangian

+

UV completion hypothesis

Resonance contributions *,**

to the NLO low-energy couplings

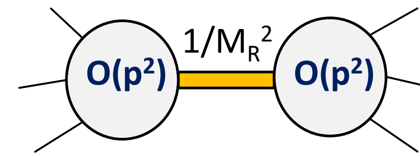
$SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$

V,A,S,P, Fermionic R

EW singlet, doublet & triplet

Colour singlet & octet

Sum-rules



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, JHEP 1905 (2019) 092

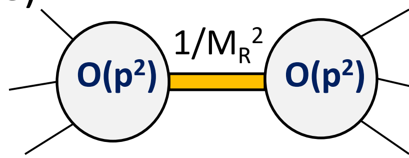
** See also: Alboteanu, Kilian, Reuter, JHEP 0811 (2008) 010; Pappadopulo, Thamm, Torre, Wulzer, JHEP 1409 (2014) 060; Corbett, Joglekar, Li, Yu, [arXiv:1705.02551 [hep-ph]]; Corbett,Éboli,Gonzalez-Garcia,PRD93 (2016) no.1, 015005; Buchalla, Cata, Celis, Krause, NPB917 (2017) 209; de Blas,Criado,Perez-Victoria,Santiago, JHEP 1803 (2018) 109

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)

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



Low-energy Lagrangian (tree-level)

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

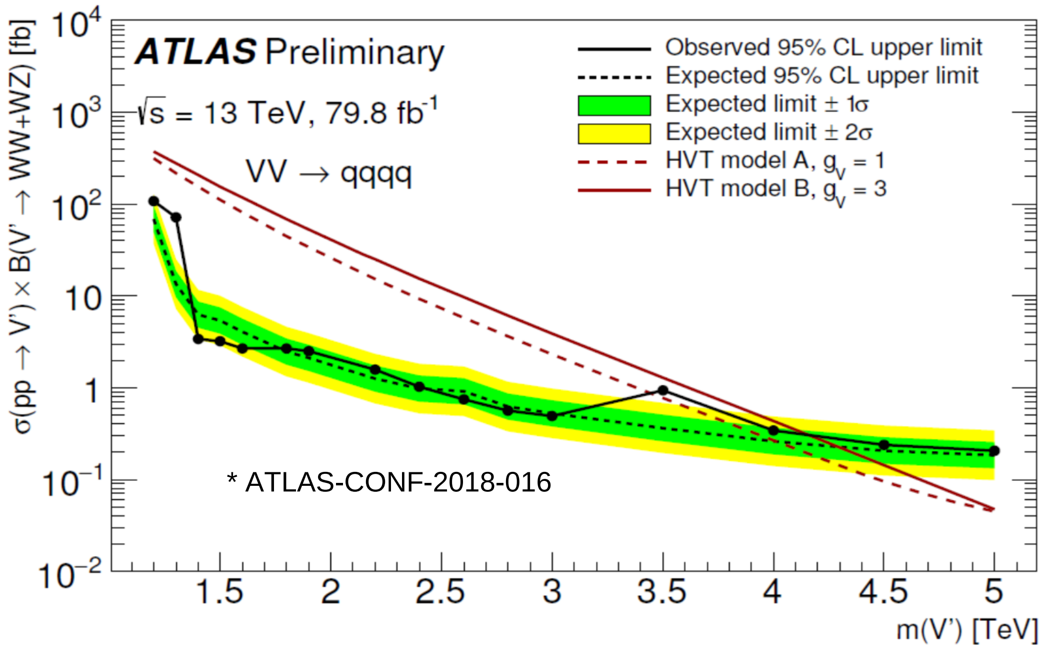
- Solve R eom at low energies: $\;{\rm R_{cl}}[\ell{\rm ight}] \sim \frac{1}{{\rm M_R^2}}\chi_{\rm R}[\ell{\rm ight}] + \mathcal{O}\left(\frac{{\rm p}^4}{{\rm M_R^4}}\right)$
- Evaluate $\;\mathcal{L}^{\rm EFT}[\ell{\rm ight}] = \mathcal{L}^{\rm HE}[{\rm R_{cl}}[\ell{\rm ight}]\,,\,\ell{\rm ight}] \sim \mathcal{L}_2[\ell{\rm ight}] + \frac{1}{{\rm M_R^2}}(\chi_{\rm R}[\ell{\rm ight}])^2 + \dots$

* Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

1.) R mass bounds: diboson resonance searches* "have established " $M_R \gtrsim 4$ TeV

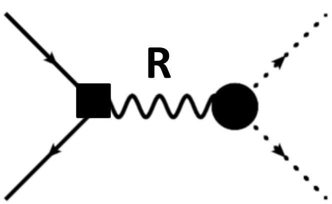
- Analyses heavily rely on specific models, HVT model(x) in particular

Current most stringent bound on EW triplet-V



(a) HVT $V' \to WW + WZ$

- We note that these analyses are **dominated by DY production**



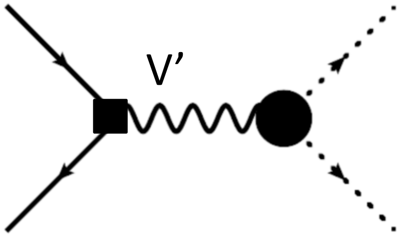
(x) Pappadopulo,Thamm,Torre,Wulzer, JHEP 1409 (2014) 060

- See review: Dorigo, Prog. Part. Nucl. Phys.100 (2018) 211

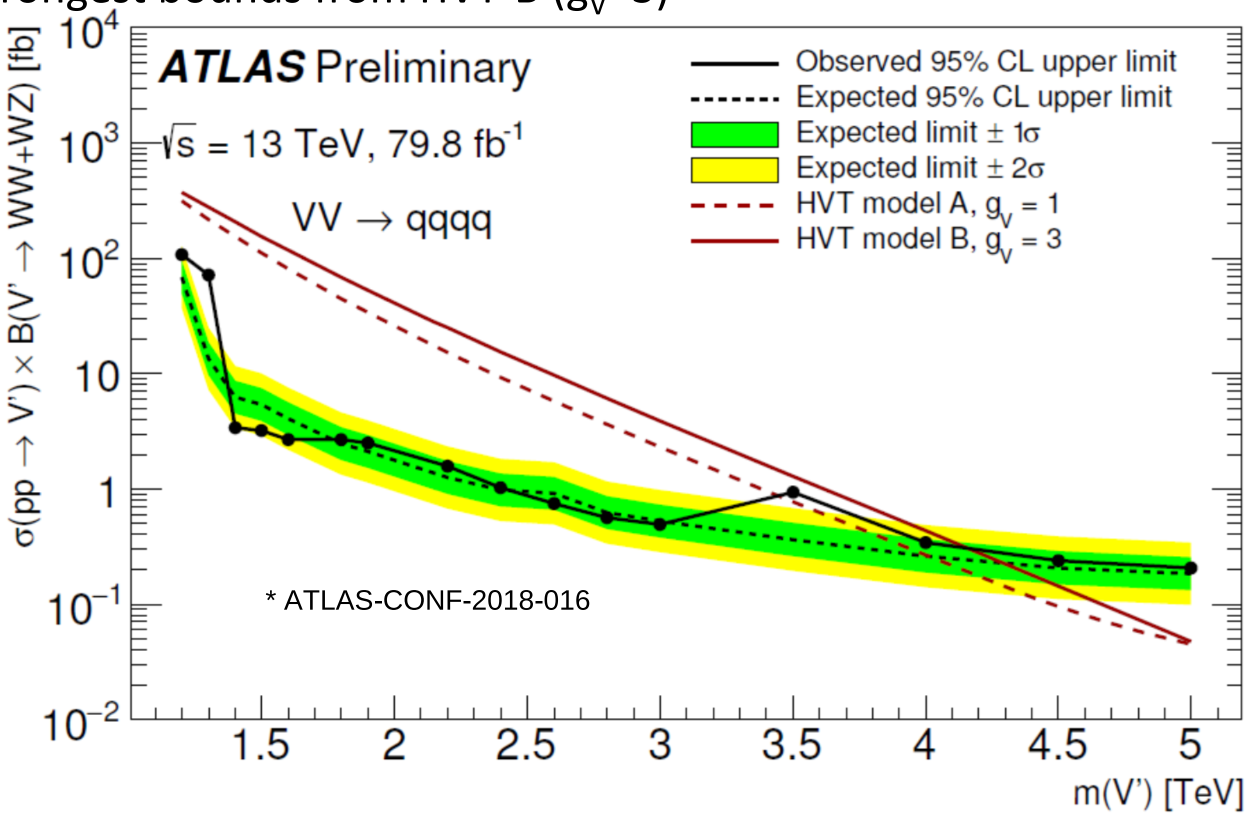
- HVT diboson searches: in practice, **DY dominated**

,

$$\sigma(pp \to V \to \text{diboson}) \simeq \sum_{q,\bar{q}'} \frac{48\pi^2 \gamma_{q\bar{q}'}}{4N_C^2} \left. \frac{dL_{q,\bar{q}'}}{d\hat{s}} \right|_{\hat{s}=M_V^2} \qquad \gamma_{ij} = \frac{\Gamma_{V\to ij}}{M_V} \times \mathcal{B}_{V\to \text{dibos}}$$



- Strongest bounds from HVT-B (g_V=3) [(x)]

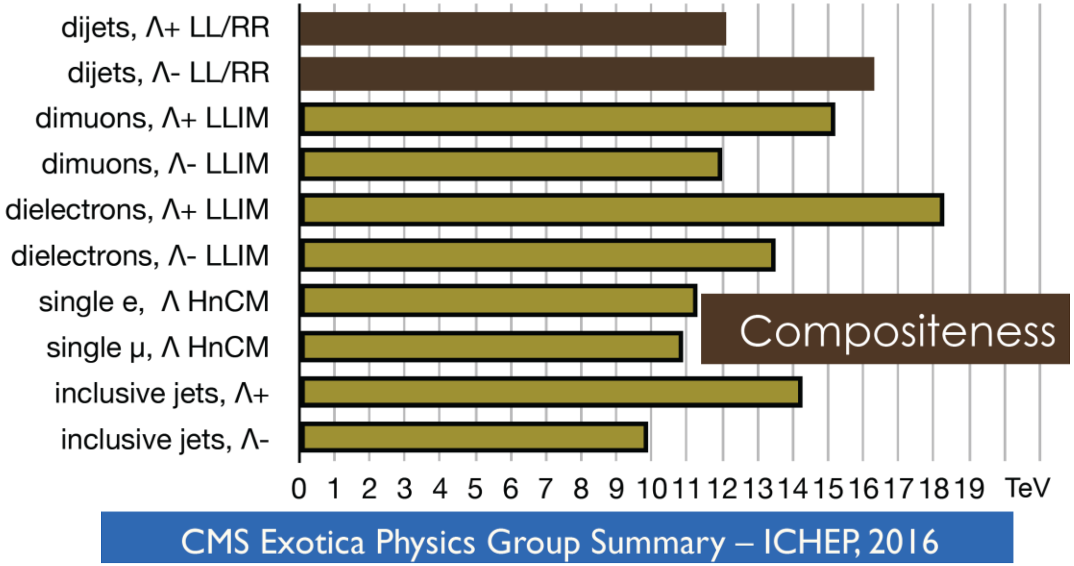


(a) HVT $V' \to WW + WZ$

(x) Pappadopulo,Thamm,Torre,Wulzer, JHEP 1409 (2014) 060

2.) Contact 4-fermion interactions: 4f-ops. searches have established $\Lambda \gtrsim 10\text{–}20$ TeV

- LHC – dijets and dileptons– yields the tightest bounds: [(x)]



- Similar strong bounds from LEP[(-)] and Tevatron+LHC [(+)]

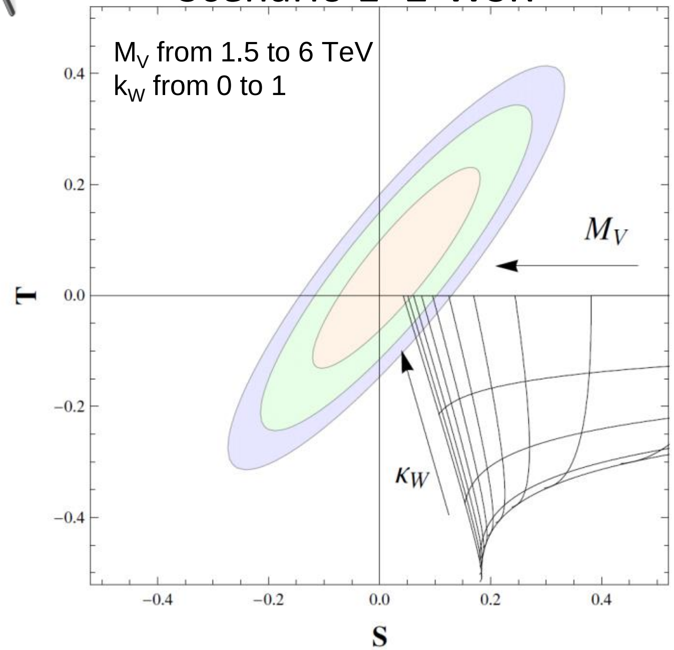
- Also bounds from low-E hadronic experiments *

(x) Aaboud et al. [ATLAS], PRD 96 (2017) no.5, 052004
(x) Sirunyan et al. [CMS] JHEP 1707 (2017) 013
(x) [ATLAS], ATLAS-CONF-2014-030
(x) [CMS], CMS-PAS-EXO-12-020 (x) 3rd generation: Greljo,Marzocca, EPJC 77 (2017) no.8, 548
(-) Schael et al. [ALEPH and DELPHI and L3 and OPAL and LEP], Phys. Rept. 532 (2013) 119

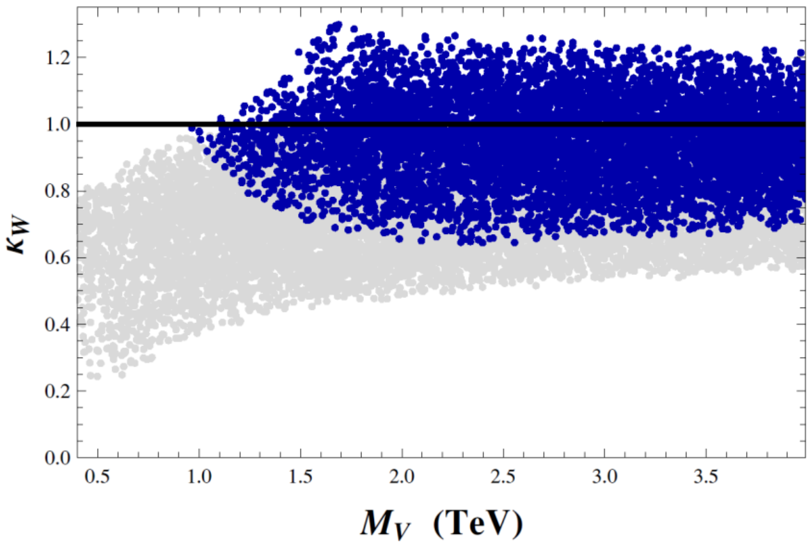
(+) Zhang, Chin. Phys. C 42 (2018) no.2, 023104
(+) Buckley et al, JHEP 1604 (2016) 015
(+) Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]
* Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]
* Isidori, arXiv:1302.0661 [hep-ph]
* Jung,Straub, arXiv:1801.01112 [hep-ph].

3.) On the other hand, EW precision tests still allow R at a few TeV

Scenario 1+2-WSR *



Scenario 1-WSR *



- **We will see that this can be easily accommodated in the HEFT framework**

  with Resonances at ~ 1 - 3 TeV

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

- **Is it possible to conciliate these results?**

Four fermion operators very suppressed

LHC exp. Searches exclude low M_V

EW precision tests (oblique,TGC,QGC…)

VBS → tiny σ even for M_R ~ 1 – 3 TeV

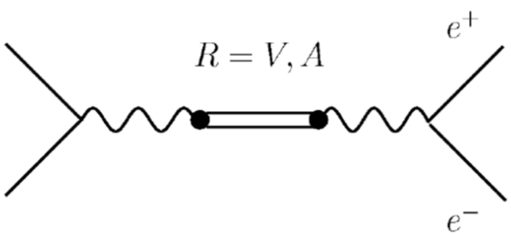
DY → tiny σ even for M_R ~ 3 TeV

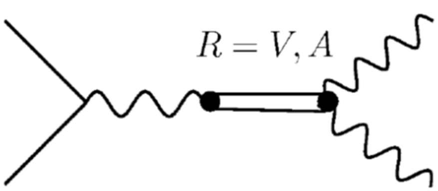
Here, R associated to EWET $a_j \sim 10^{-3}$

S+T allow M_R ~ 1 – 5 TeV

- A simple scenario solution motivated by the DY analysis [Cata,Isidori,Kamenik, NPB822 (2009) 230-244]:

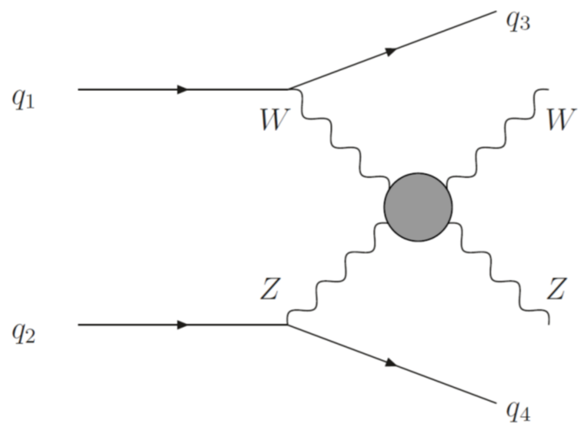
SM fermions couple to R via EW gauge bosons





$pp \to WZj_1j_2$

by $WZ \to WZ$ scattering



- Relevant HEFT Lagrangian up to NLO:

$$
\begin{aligned}
\mathcal{L}_2 = & -\frac{1}{2g^2}\mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right) - \frac{1}{2g'^2}\mathrm{Tr}\left(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right) \\
& + \frac{v^2}{4}\left[1 + 2a\frac{H}{v} + b\frac{H^2}{v^2}\right]\mathrm{Tr}\left(D^\mu U^\dagger D_\mu U\right) + \frac{1}{2}\partial^\mu H\,\partial_\mu H + \dots\,, \\
\mathcal{L}_4 = & \; a_1 \mathrm{Tr}\left(U\hat{B}_{\mu\nu}U^\dagger \hat{W}^{\mu\nu}\right) + ia_2 \mathrm{Tr}\left(U\hat{B}_{\mu\nu}U^\dagger[\mathcal{V}^\mu,\mathcal{V}^\nu]\right) - ia_3 \mathrm{Tr}\left(\hat{W}_{\mu\nu}[\mathcal{V}^\mu,\mathcal{V}^\nu]\right) \\
& + a_4\left[\mathrm{Tr}(\mathcal{V}_\mu\mathcal{V}_\nu)\right]\left[\mathrm{Tr}(\mathcal{V}^\mu\mathcal{V}^\nu)\right] + a_5\left[\mathrm{Tr}(\mathcal{V}_\mu\mathcal{V}^\mu)\right]\left[\mathrm{Tr}(\mathcal{V}_\nu\mathcal{V}^\nu)\right] \\
& - c_W\frac{H}{v}\mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right) - c_B\frac{H}{v}\mathrm{Tr}\left(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right) + \dots
\end{aligned}
$$

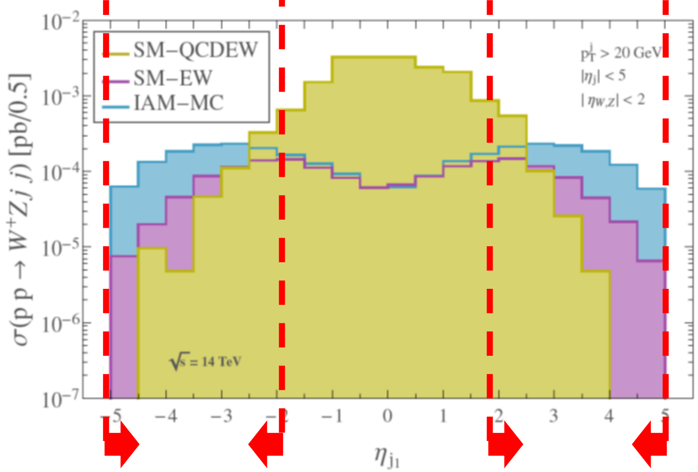
- Related to resonance parameters at higher energies

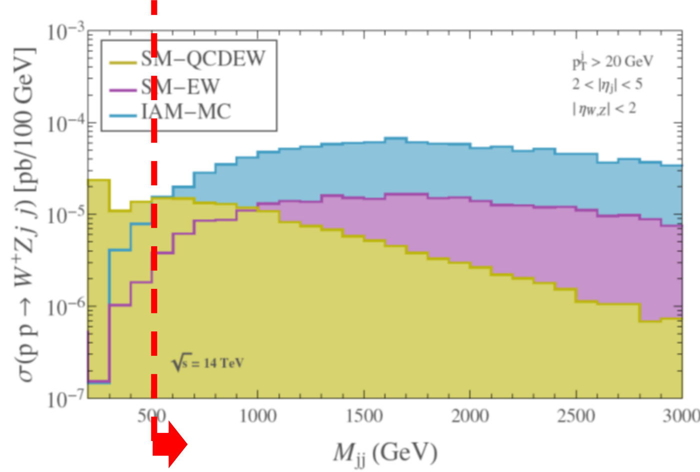
* Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP 11 (2017) 098

• Benchmark points of this study:

BP	M_V(GeV)	Γ_V(GeV)	$g_V(M_V^2)$	a	$a_4 \cdot 10^4$	$a_5 \cdot 10^4$
BP1	1476	14	0.033	1	3.5	-3
BP2	2039	21	0.018	1	1	-1
BP3	2472	27	0.013	1	0.5	-0.5
BP1'	1479	42	0.058	0.9	9.5	-6.5
BP2'	1980	97	0.042	0.9	5.5	-2.5
BP3'	2480	183	0.033	0.9	4	-1

• Backgrounds:

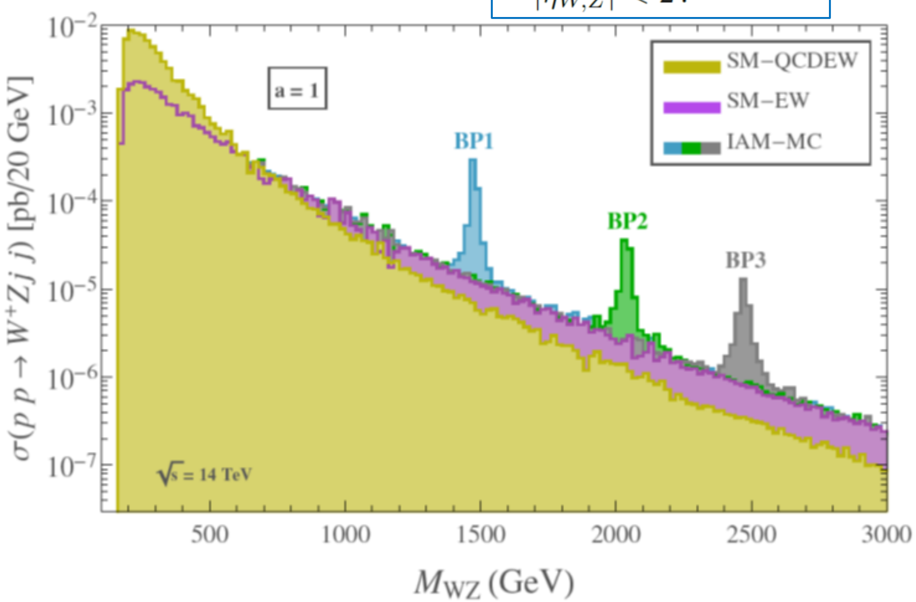


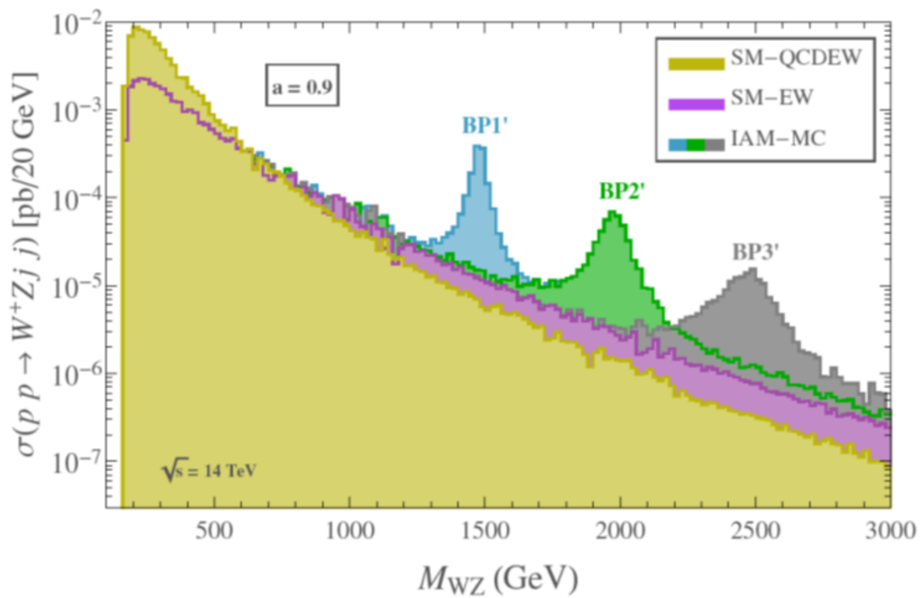


• Optimal VBS cuts: (*)

$$2 < |\eta_{j_1,j_2}| < 5\,,$$
$$\eta_{j_1}\cdot\eta_{j_2} < 0,$$
$$p_T^{j_1,j_2} > 20\,\mathrm{GeV}\,,$$
$$M_{jj} > 500\,\mathrm{GeV}\,,$$
$$|\eta_{W,Z}| < 2\,.$$

[MG5_aMC + IAM-MC UFO;
NO detector sim;
NO polarization discriminant cuts (x)]

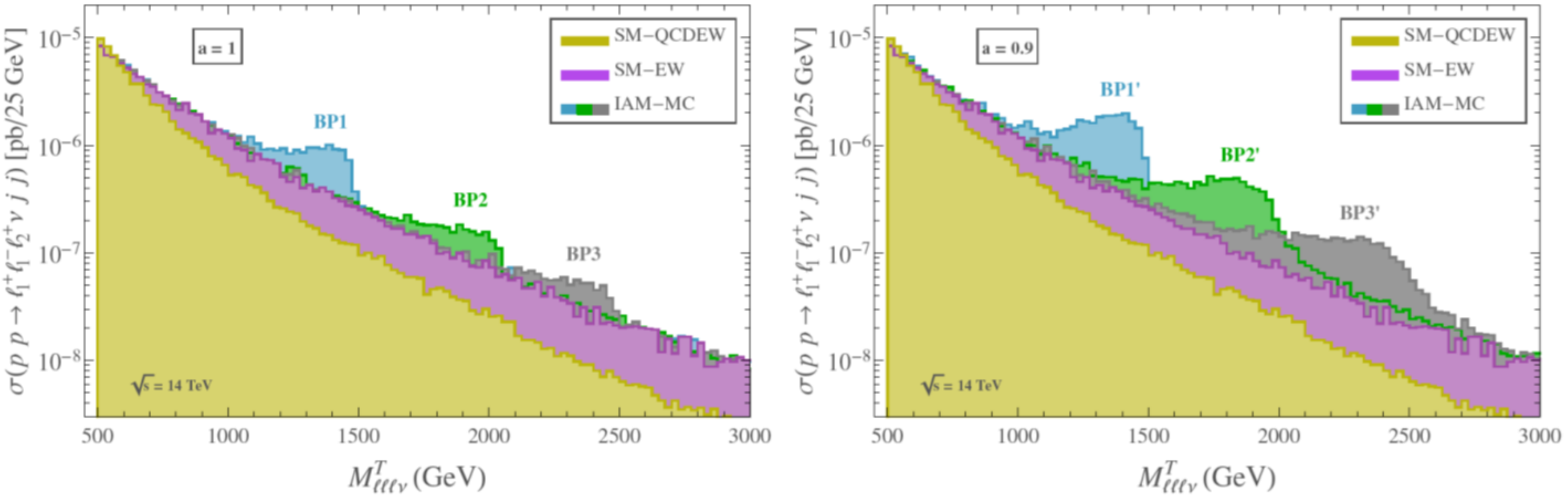




* Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP 11 (2017) 098 (x) Fabbrichesi,Pinamonti,Tonero,Urbano, PRD 93 (2016) 015004

• Fully leptonic decays:

14 TeV



These contain all the previous VBS cuts and others, and are summarized by:

$$
\begin{aligned}
2 < |\eta_{j_{1,2}}| &< 5\,,\\
\eta_{j_1}\cdot\eta_{j_2} &< 0\,,\\
p_T^{j_1,j_2} &> 20\,\mathrm{GeV}\,,\\
M_{jj} &> 500\,\mathrm{GeV}\,,\\
M_Z - 10\,\mathrm{GeV} < M_{\ell_Z^+\ell_Z^-} &< M_Z + 10\,\mathrm{GeV}\,,\\
M_{WZ}^T \equiv M_{\ell\ell\ell\nu}^T &> 500\,\mathrm{GeV}\,,\\
\not{p}_T &> 75\,\mathrm{GeV}\,,\\
p_T^{\ell} &> 100\,\mathrm{GeV}\,,
\end{aligned}
$$

$$M_{WZ}^T \equiv M_{\ell\ell\ell\nu}^T = \sqrt{\left(\sqrt{M^2(\ell\ell\ell)+p_T^2(\ell\ell\ell)}+|\not{p}_T|\right)^2 - \left(\vec{p_T}(\ell\ell\ell)+\vec{\not{p}_T}\right)^2}$$

ranges of $M_{\ell\ell\ell\nu}^T$:

BP1 : 1325–1450 GeV , BP2 : 1875–2025 GeV , BP3 : 2300–2425 GeV ,
BP1′ : 1250–1475 GeV , BP2′ : 1675–2000 GeV , BP3′ : 2050–2475 GeV .

14 TeV		BP1	BP2	BP3	BP1'	BP2'	BP3'
$\mathcal{L} = 300\ \mathrm{fb}^{-1}$	$N_\ell^{\mathrm{IAM-MC}}$	2	0.5	0.1	5	2	0.7
	N_ℓ^{SM}	1	0.4	0.1	2	0.6	0.3
	$\sigma_\ell^{\mathrm{stat}}$	0.9	–	–	2.8	1.4	–
$\mathcal{L} = 1000\ \mathrm{fb}^{-1}$	$N_\ell^{\mathrm{IAM-MC}}$	7	2	0.4	18	5	2
	N_ℓ^{SM}	4	1	0.3	6	2	1
	$\sigma_\ell^{\mathrm{stat}}$	1.6	0.3	–	5.1	2.5	1.4
$\mathcal{L} = 3000\ \mathrm{fb}^{-1}$	$N_\ell^{\mathrm{IAM-MC}}$	22	5	1	53	16	7
	N_ℓ^{SM}	12	4	1	17	6	3
	$\sigma_\ell^{\mathrm{stat}}$	2.7	0.6	0.3	8.9	4.4	2.4

- Important improvements through fat-jet reconstruction techniques

• Sensitivity with perfect WZ reconstruction efficiency:

14 TeV		BP1	BP2	BP3	BP1'	BP2'	BP3'
$\mathcal{L}=300\ \mathrm{fb}^{-1}$	$\mathrm{N}_{WZ}^{\mathrm{IAM-MC}}$	89 (147)	19 (25)	4 (9)	226 (412)	71 (151)	33 (59)
	$\mathrm{N}_{WZ}^{\mathrm{SM}}$	6 (17)	2 (4)	0.3 (2)	11 (45)	5 (27)	3 (14)
	$\sigma_{WZ}^{\mathrm{stat}}$	34.8 (31.1)	10.8 (9.7)	6 (5.4)	64.9 (54.4)	28.9 (23.8)	16.1 (12)
$\mathcal{L}=1000\ \mathrm{fb}^{-1}$	$\mathrm{N}_{WZ}^{\mathrm{IAM-MC}}$	298 (488)	64 (82)	13 (30)	752 (1374)	237 (504)	110 (196)
	$\mathrm{N}_{WZ}^{\mathrm{SM}}$	19 (57)	8 (15)	1 (6)	36 (151)	17 (90)	11 (46)
	$\sigma_{WZ}^{\mathrm{stat}}$	63.5 (56.8)	19.8 (17.7)	11 (9.9)	118.5 (99.4)	52.7 (43.5)	29.3 (22)
$\mathcal{L}=3000\ \mathrm{fb}^{-1}$	$\mathrm{N}_{WZ}^{\mathrm{IAM-MC}}$	893 (1465)	193 (246)	39 (89)	2255 (4122)	710 (1511)	331 (589)
	$\mathrm{N}_{WZ}^{\mathrm{SM}}$	58 (172)	24 (44)	3 (17)	109 (454)	52 (271)	34 (139)
	$\sigma_{WZ}^{\mathrm{stat}}$	110 (98.5)	34.3 (30.6)	19 (17.1)	205.3 (172.2)	91.3 (75.3)	50.8 (38.1)

$$\sigma_{WZ}^{\mathrm{stat}} = \frac{S_{WZ}}{\sqrt{B_{WZ}}}$$

$$\pm 0.5\,\Gamma_V \ \ (\pm 2\,\Gamma_V)$$

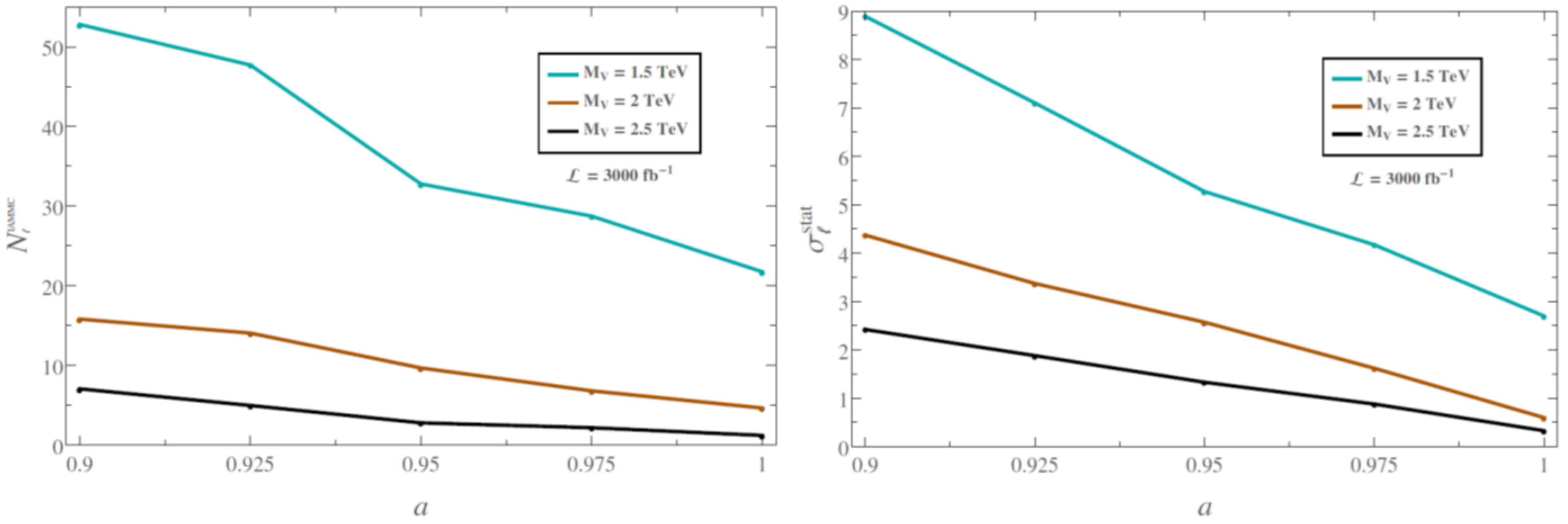
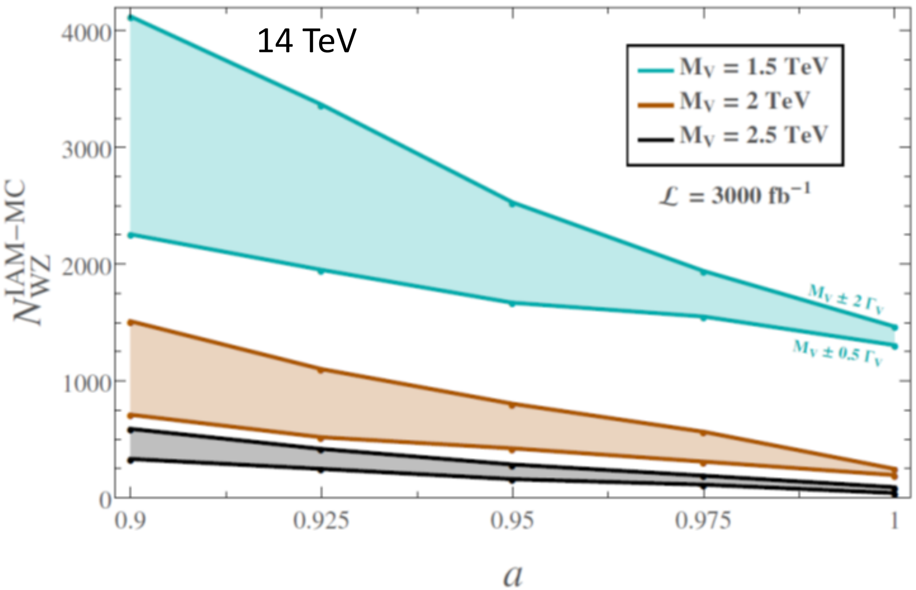
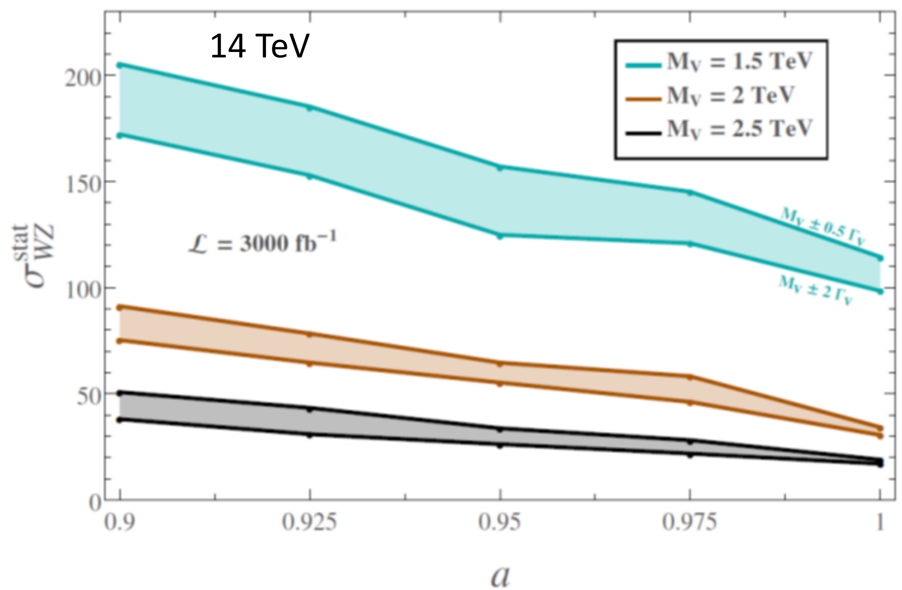


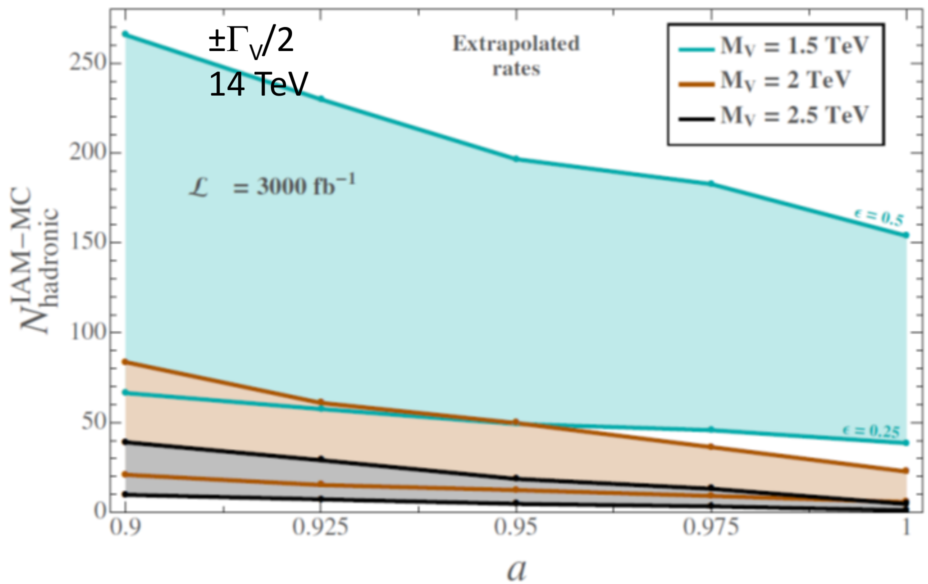
Figure 17. Predictions for the number of $pp \to \ell_1^+ \ell_1^- \ell_2^+ \nu jj$ events, N_ℓ^{IAM-MC}, (left panel) and the statistical significance, σ_ℓ^{stat}, (right panel) as a function of the parameter a for $\mathcal{L} = 3000\,\text{fb}^{-1}$. Marked points correspond to our selected benchmark points in figure 4. The cuts in eq. (5.5) have been applied.

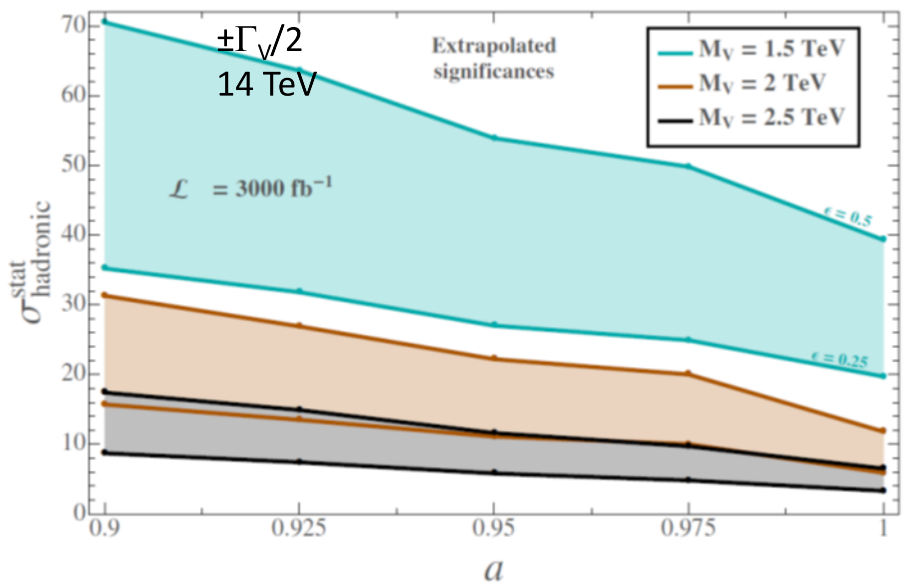
• Sensitivity with 100% WZ efficiency reconstruction:



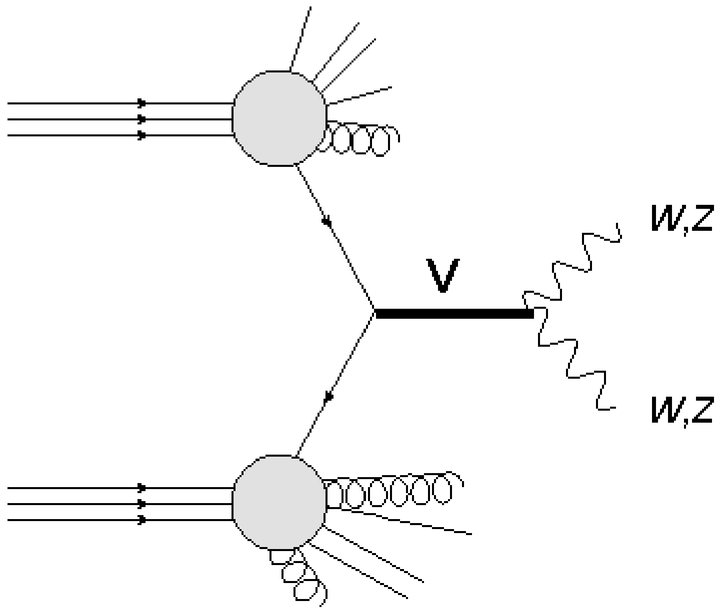


• Sensitivity estimate with "fat" jets: $\mathrm{N}_{\mathrm{hadronic}}^{\mathrm{IAM-MC}} = \mathrm{N}_{WZ}^{\mathrm{IAM-MC}} \times \mathrm{BR}(W \to \mathrm{hadrons}) \times \mathrm{BR}(Z \to \mathrm{hadrons}) \times \epsilon_W \times \epsilon_Z$



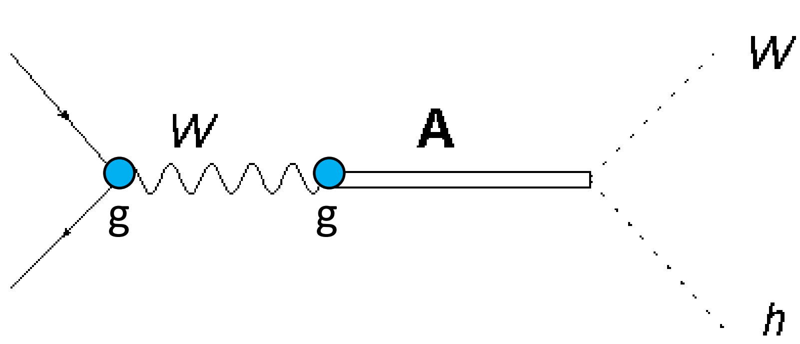


• **NOTE:** Drell-Yan production mechanism ➔ Completely dominant in all HVT search bounds



If DY removed [$\mathcal{B}(R \to q\bar{q}) \ll 10^{-4} - 10^{-6}$] ➔ No significant exp. lower bound for M_R

[Suppressed $R \to q\bar{q}$ is not enough;
huge suppression needed
to make other prod. mechanisms visible]



• **In the HEFT case,**

1) DY produces the gauge bosons
[with a weak coupling suppression]

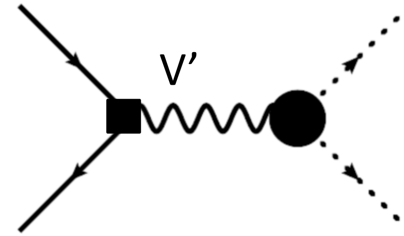
2) Then, the strong BSM interactions generate A, coupled to W
[with a weakcoupling suppression]

• **Implications**: **additional chiral suppression** ➔ Much more suppressed experimentally:

Resonances with M_R ~ 3 TeV perfectly allowed

- HVT diboson searches: in practice, **DY dominated**

$$\sigma(pp\to V\to \text{diboson}) \simeq \sum_{q,\bar q'} \frac{48\pi^2\gamma_{q\bar q'}}{4N_C^2}\, \frac{dL_{q,\bar q'}}{d\hat s}\bigg|_{\hat s = M_V^2} \qquad \gamma_{ij} = \frac{\Gamma_{V\to ij}}{M_V}\times \mathcal{B}_{V\to \text{dibos}}$$

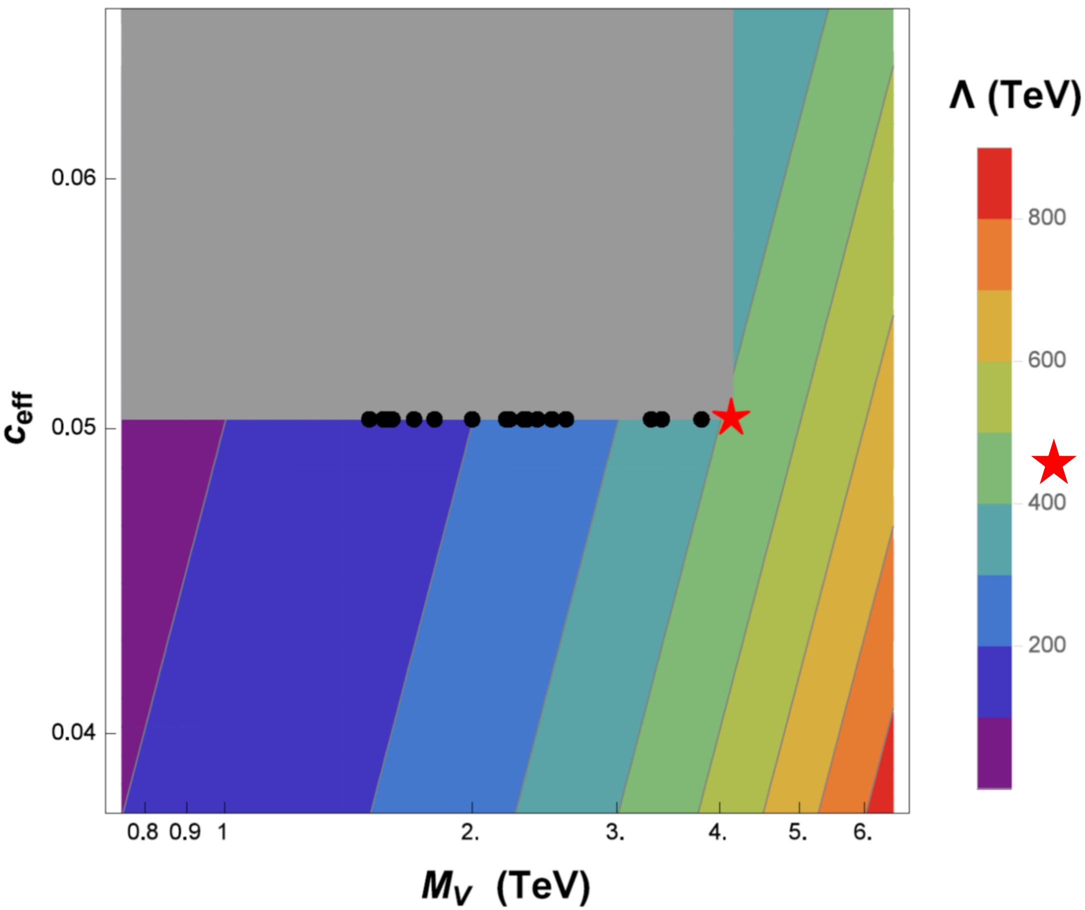


- Strongest bounds from HVT-B (g_V=3) (x)

➔ Exclusion in the (mass_R,coupling_R) plane and the $O_j^{\psi 4}$ scale Λ (*)

$$\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2}[\eta_{LL}(\bar q_L\gamma^\mu q_L)(\bar q_L\gamma_\mu q_L) + \eta_{RR}(\bar q_R\gamma^\mu q_R)(\bar q_R\gamma_\mu q_R) + 2\eta_{RL}(\bar q_R\gamma^\mu q_R)(\bar q_L\gamma_\mu q_L)],$$

$$\frac{2\pi}{\Lambda^2} \equiv \mathcal{F}_7^{\psi^2} + \mathcal{F}_8^{\psi^2} + \frac{\mathcal{F}_{10}^{\psi^2}}{4} \overset{\text{integ. V}}{=} \frac{c_{\text{eff}}^2}{4M_V^2}$$



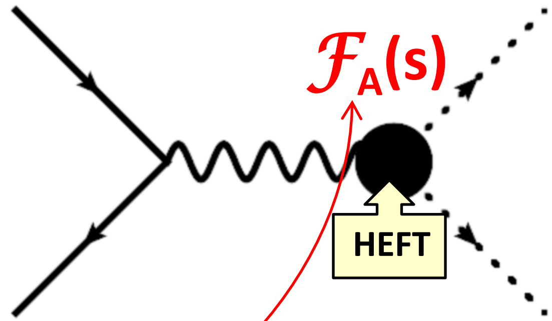
★ → Λ = 410 TeV

(x) Pappadopulo,Thamm,Torre,Wulzer, JHEP 1409 (2014) 060
(*) Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

$$c_{\rm eff}^2 \;\equiv\; (c^{\hat{V}_3^1})^2 + (\widetilde{c}^{\hat{V}_3^1})^2 + \frac{1}{2}(C_0^{V_3^1})^2 \;\;=\;\; \frac{24\pi}{N_C}\,\frac{\gamma_{q\bar{q}}}{\mathcal{B}_{V^0\to \rm dibos.}} \;\;\geq\;\; \frac{24\pi}{N_C}\,\gamma_{q\bar{q}} \;\equiv\; (c_{\rm eff}^{\rm bound})^2$$

$$\mathcal{F}_7^{\psi^4} + \mathcal{F}_8^{\psi^4} + \frac{\mathcal{F}_{10}^{\psi^4}}{4} \;=\; -\frac{1}{2}\left(\mathcal{F}_5^{\psi^4} + \mathcal{F}_6^{\psi^4} + \frac{\mathcal{F}_9^{\psi^4}}{4}\right) \;=\; \frac{c_{\rm eff}^2}{4M_V^2} \;=\; \frac{6\pi\Gamma_{V^0\to q\bar{q}}}{N_C M_V^3}$$

- Wh from DY via a gauge boson:



+ FSI via $\mathcal{M}_{11}$(s)

[elastic $W^a h$ PWA scat]

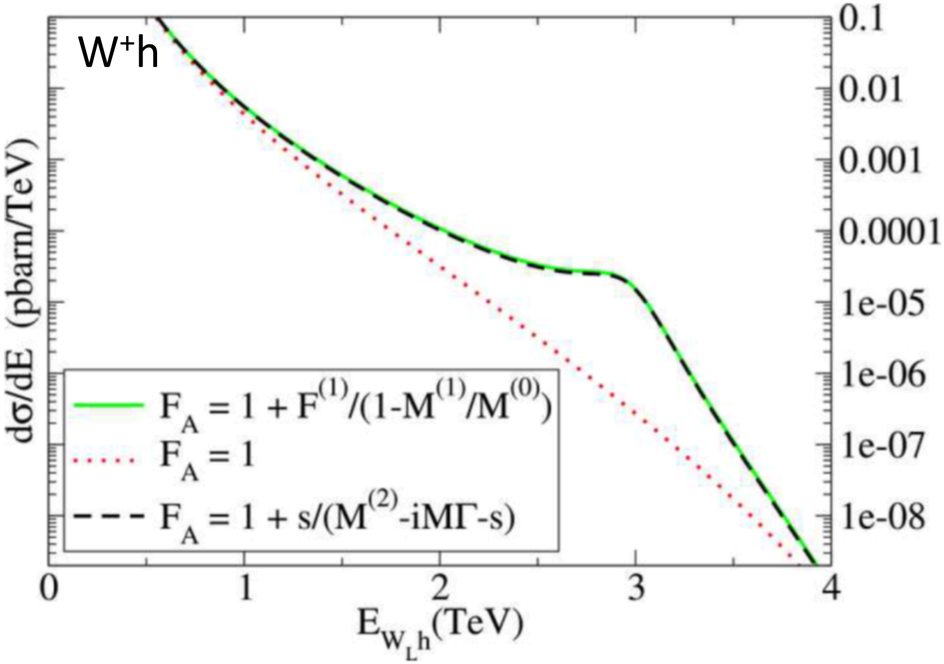
$$\tilde{T}(u_-\bar{d}_+ \to W_L^+ h) = \tilde{T}(d_-\bar{u}_+ \to W_L^- h) = \frac{g^2}{2\sqrt{2}} a \sin\theta e^{-i\varphi} \mathcal{F}_A(s) \,,$$

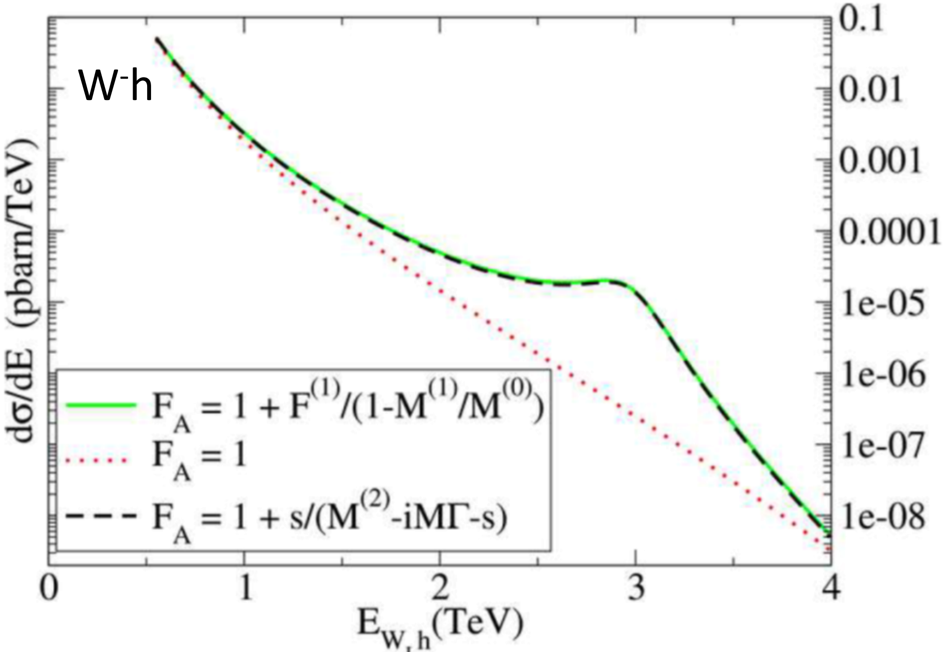
$$\tilde{T}(u_-\bar{u}_+ \to Z_L h) = -\tilde{T}(d_-\bar{d}_+ \to Z_L h) = \frac{g^2}{4} a \sin\theta e^{-i\varphi} \mathcal{F}_A(s) \,.$$

- HEFT:

$$\mathcal{L}_{\rm NLO} = d\, \frac{(\partial_\mu h \partial^\mu h)}{v^2} \mathrm{Tr}\{D_\nu U^\dagger D^\mu U\} + e\, \frac{(\partial_\mu h \partial^\nu h)}{v^2} \mathrm{Tr}\{D^\mu U^\dagger D_\nu U\}$$
$$-i f_9 \frac{(\partial_\mu h)}{v} \mathrm{Tr}\{\hat{W}^{\mu\nu}\, D_\nu U\, U^\dagger - \hat{B}^{\mu\nu}\, U^\dagger\, D_\nu U\} \,,$$

* Dobado,Llanes-Estrada,SC, JHEP 1803 (2018) 159



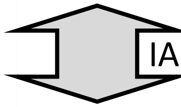


BENCHMARK point

HEFT: $a=0.95$, $b=0.7\,a^2$, $\mu = 3$ TeV

$\mathcal{M}_{11}(s)$ PWA→ $e(\mu) - 2d(\mu) = 1.64 \cdot 10^{-3}$

$\mathcal{F}_A(s)$ AFF→ $f_9(\mu) = -6 \cdot 10^{-3}$



HEFT+R: $M_A = 3$ TeV, $\Gamma_A = 0.4$ TeV

HEFT predict: BSM excess ~ 10^{-2} fb

* Dobado,Llanes-Estrada,SC, JHEP 1803 (2018) 159

• What is the impact of this "Resonance – gauge-boson mixing" in the HEFT?

$$\mathcal{L} \;=\; \mathcal{L}^{(2)}_{\rm non-R} + \sum_{R=V,A} \mathcal{L}_R\,, \qquad \mathcal{L}_R \;=\; \frac{1}{4}\langle\, R_{\mu\nu}\mathcal{D}^{\mu\nu,\rho\sigma}R_{\rho\sigma} + M_R^2 R_{\mu\nu}R^{\mu\nu}\,\rangle + \langle\, R_{\mu\nu}\chi_R^{\mu\nu}\,\rangle\,,$$

$$\chi_V^{\mu\nu} \;=\; \frac{1}{2\sqrt{2}}(F_V f_+^{\mu\nu} + \widetilde{F}_V f_-^{\mu\nu}) + i\frac{G_V}{2\sqrt{2}}[u^\mu,u^\nu] + \frac{\widetilde{\lambda}_1^{hV}}{\sqrt{2}}\left[(\partial^\mu h)\,u^\nu - (\partial^\nu h)\,u^\mu\right].$$

(similar for A)

$$\mathcal{L}^{\rm EWET} = \mathcal{L}\Big|_{R\to R^{c\ell}} \;=\; \mathcal{L}_2^{\rm EWET} + \mathcal{L}_4^{\rm EWET} + \mathcal{L}_6^{\rm EWET} + \ldots$$

- Terms from $\mathcal{L}_{\text{non-R}}$: **O(p²) →** $\mathcal{L}_2^{\rm EWET} \;=\; \mathcal{L}^{(2)}_{\rm non-R}\,,$

- Terms with 4 D_μ from $\mathcal{L}_R$ (*): **O(p⁴) →** $\mathcal{L}_4^{\rm EWET} \;=\; -\sum_{R=V,A}\frac{1}{M_R^2}\langle\,\chi_{R,\mu\nu}\chi_R^{\mu\nu}\,\rangle\,,$

• $\mathcal{L}_4$ EFT fermionic operators: **absent**
• $\mathcal{L}_4$ EFT custodial breaking ops: **absent**

(*) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

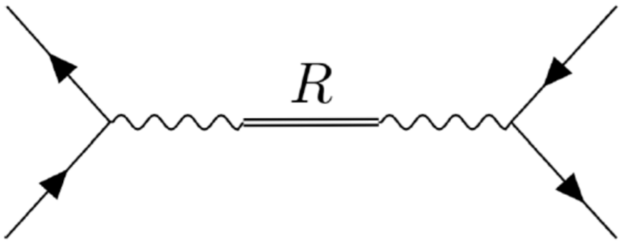
- Terms with 6 D_μ from $\mathcal{L}_R$ (x): **O(p^6) →** $\mathcal{L}_6^{\rm EWET} = -\sum_{R=V,A} 2\langle \nabla^\rho \left(\frac{\chi_{R,\rho\nu}}{M_R^2}\right) \nabla_\mu \left(\frac{\chi_R^{\mu\nu}}{M_R^2}\right) \rangle$

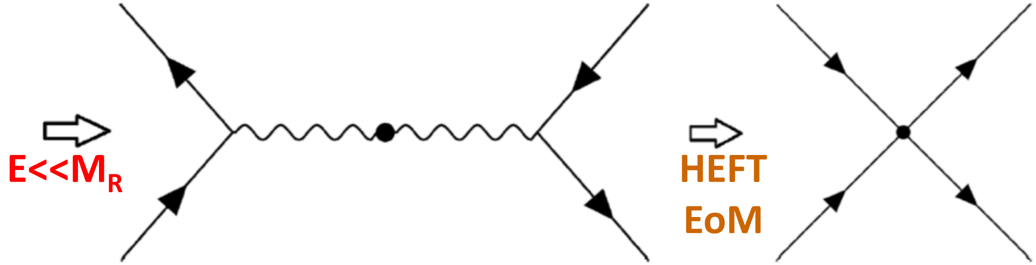
- **Resonance – gauge boson mixing:** terms in the HEFT with the structure of $\mathcal{L}_4$

  (but the suppression of $\mathcal{L}_6$)

$$\mathcal{L}_6^{\rm EWET} = -\frac{2F_V^2}{M_V^4}\langle (\nabla_\rho f_+^{\rho\nu}) (\nabla^\mu f_{+\,\mu\nu}) \rangle + \dots \quad \xrightarrow{\text{EoM}} \quad \Delta\mathcal{L}_4^{\rm EWET} \propto m_{W,Z}^2\, p^4$$

- Diagrammatically:





(x) Alvarado,Guevara,SC, arXiv:1909.00875 [hep-ph]; in preparation

(*) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041