A bottom-up approach within the electroweak effective theory: constraining heavy resonances

International Workshop
on Future Linear Colliders, LCWS2021
March 17th 2021 – virtual edition

Juan José Sanz-Cillero

IPARCOS

UNIVERSIDAD COMPLUTENSE
MADRID

Pich, Rosell, SC, Phys.Rev.D 102 (2020) 3, 035012

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

Precise EW precision tests
& their impact
on BSM resonance bounds

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Outline

1.) Prospects at future Linear Colliders

2.) EW effective theory, Resonance extension & UV completion

3.) Predictions for HEFT couplings

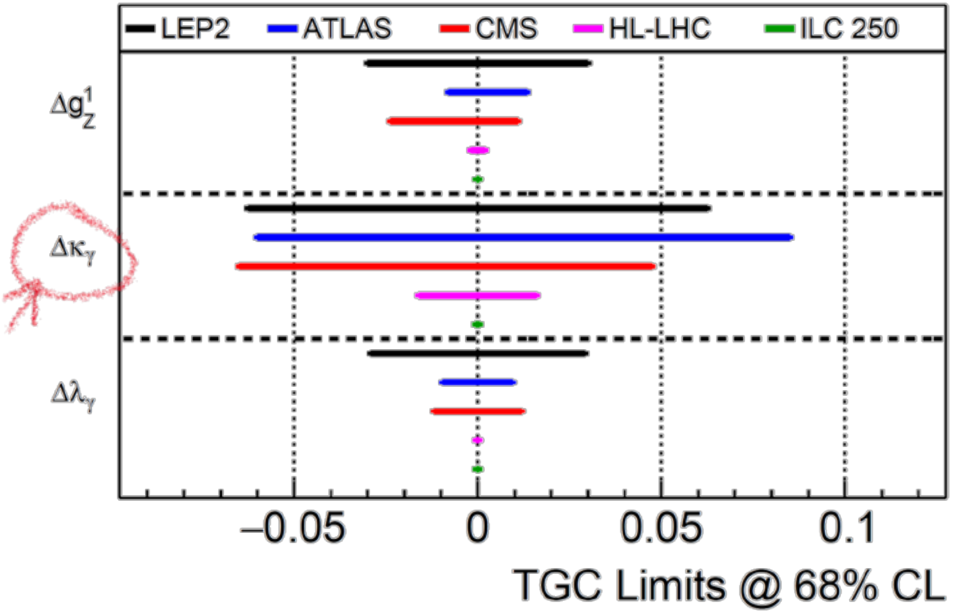
4.) Phenomenology & implications: M_R *bounds*

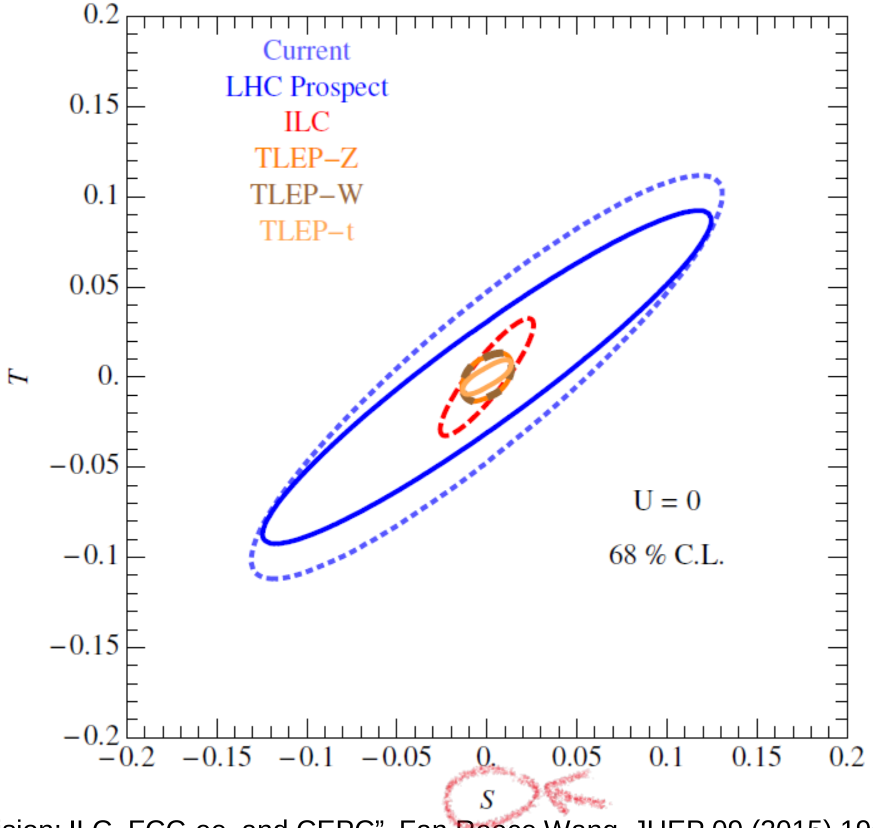
5.) Conclusions

1. Prospects at future LC

- Significant presition improvement: TGC, oblique parameters, etc

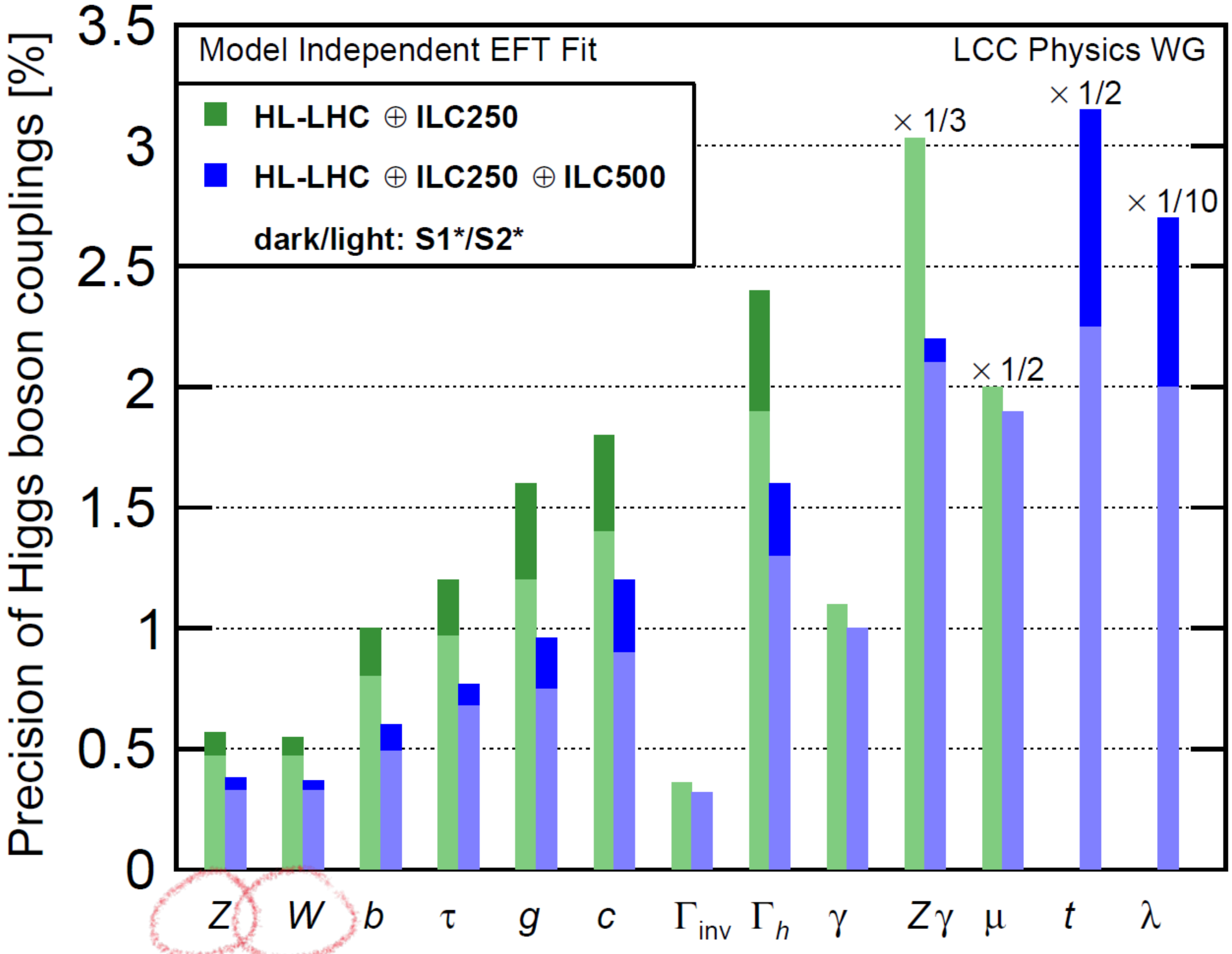
* "The International Linear Collider: A Global Project", Bambade et al., [1903.01629 [hep-ex]]





** "Possible Futures of Electroweak Precision: ILC, FCC-ee, and CEPC", Fan,Reece,Wang, JHEP 09 (2015) 196

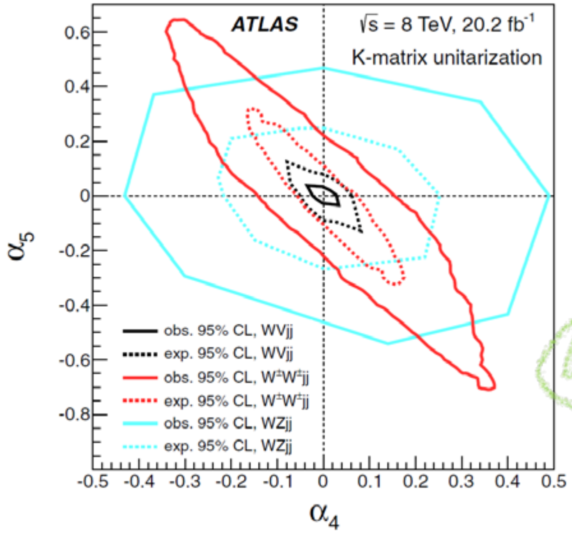
- Important presicion improvement in $\kappa_Z, \kappa_W, etc.$



* "The International Linear Collider: A Global Project", Bambade et al., [1903.01629 [hep-ex]]

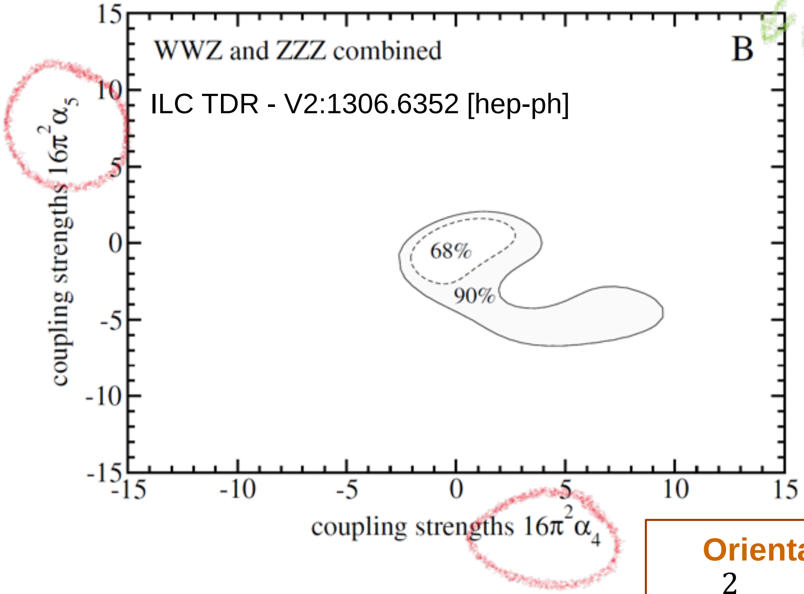
• Also improvement wrt LHC in VV→VV gauge boson scat.

* ATLAS, PRD 95 (2017) 3, 032001



** "ILC TDR - V2: Physics", Baer et al., [1306.6352 [hep-ph]]

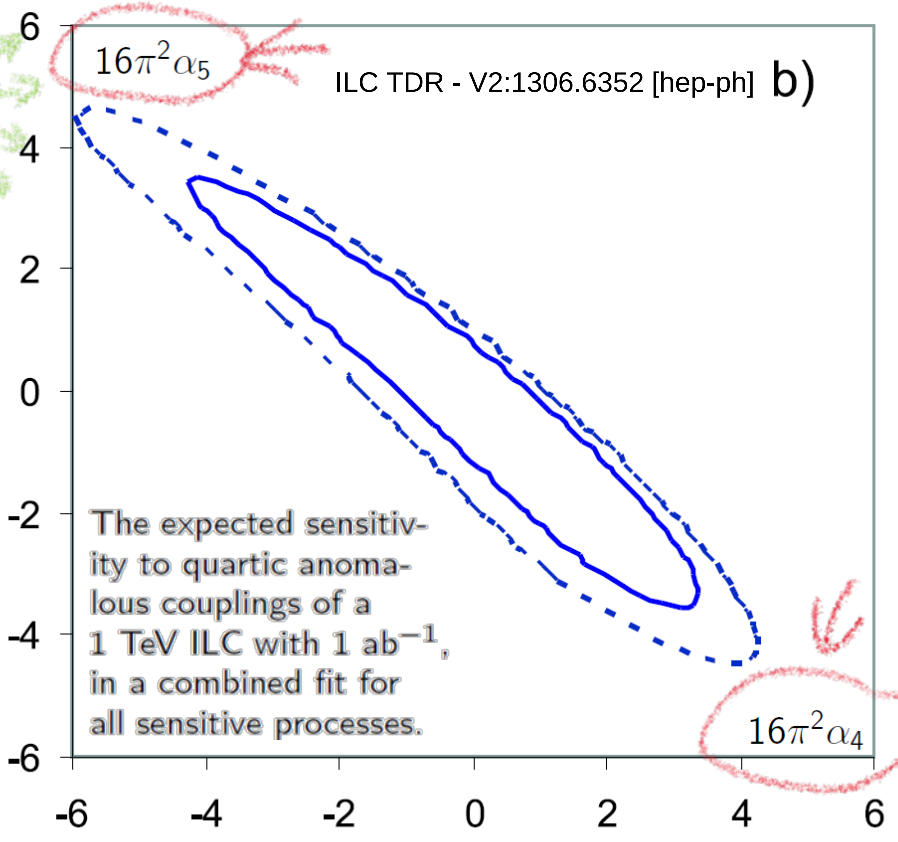
- Vector boson pair production:
  - $e+e- \rightarrow W+W-$
  - $e+e- \rightarrow ZZ$
  - $\gamma\gamma \rightarrow W+W-$
- WW, ZZ scattering at high energy



ILC TDR - V2:1306.6352 [hep-ph]

Orientative:

$$\frac{2}{16\pi^2} \approx 10^{-2}$$



ILC TDR - V2:1306.6352 [hep-ph]

The expected sensitivity to quartic anomalous couplings of a 1 TeV ILC with 1 ab^{-1}, in a combined fit for all sensitive processes.

2. HEFT, Resonances & UV completion

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

- EW Effective Theory (*EWET = EWχL = HEFT*) based on chiral & other SM symmetries:
  - **Chiral expansión in powers of p^d:**

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

  - **O(p^2), LO** ($\supset$ SM) :

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

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

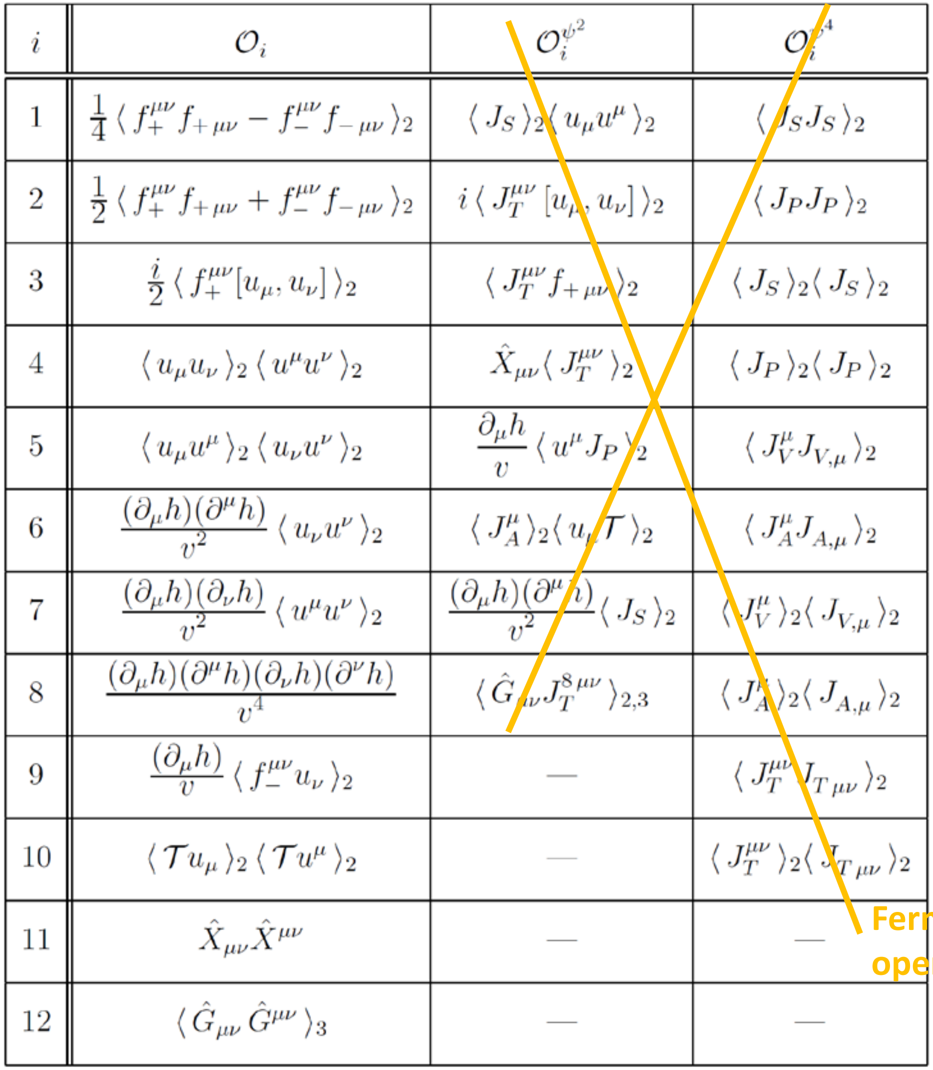
(x) Alonso,Gavela,Merlo,Rigolin,Yepes, PLB 722 (2013) 330-335; Brivio et al, JHEP 1403 (2014) 024

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

(*) Examples of other works on EWχL: Delgado,Dobado,Llanes-Estrada, PRL114 (2015) 22, 221803; Espriu,Mescia,Yencho, PRD88 (2013) 055002; Delgado,Garcia-Garcia,Herrero, JHEP 11 (2019) 065; Fabbrichesi,Pinamonti(,Tonero,Urbano, PRD93 (2016) 1, 015004; Corbett,Éboli,Gonzalez-Garcia, PRD 93 (2016) 1, 015005; Quezada,Dobado,SC, in preparation.

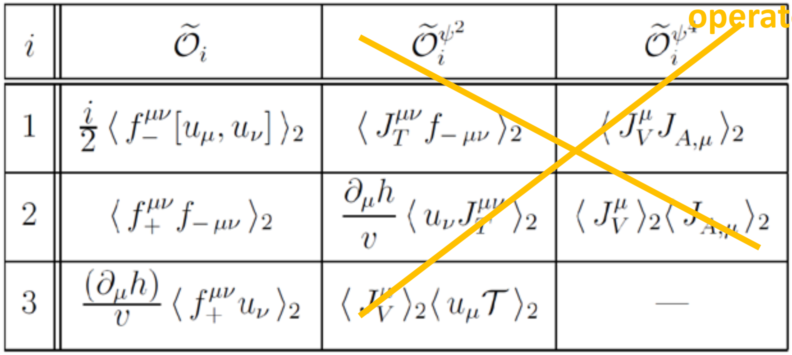
- Here, study of the SM bosonic sector ➔ EFT bosonic operators only

- List of CP even operators:



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

Fermion operators



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	$\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu} u_\nu\rangle_2$	$\langle J_V^\mu\rangle_2\langle u_\mu \mathcal{T}\rangle_2$	—

Fermion operators

For $h = 0$, these $\mathcal{F}_j$ are related to the a_i couplings of the Higgsless Longhitano Lagrangian [12, 13] in the form $a_i = \mathcal{F}_i$ for $i = 1, 4, 5$, $a_2 = (\mathcal{F}_3 - \widetilde{\mathcal{F}}_1)/2$ and $a_3 = -(\mathcal{F}_3 + \widetilde{\mathcal{F}}_1)/2$.

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

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

  (relevant terms)

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

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

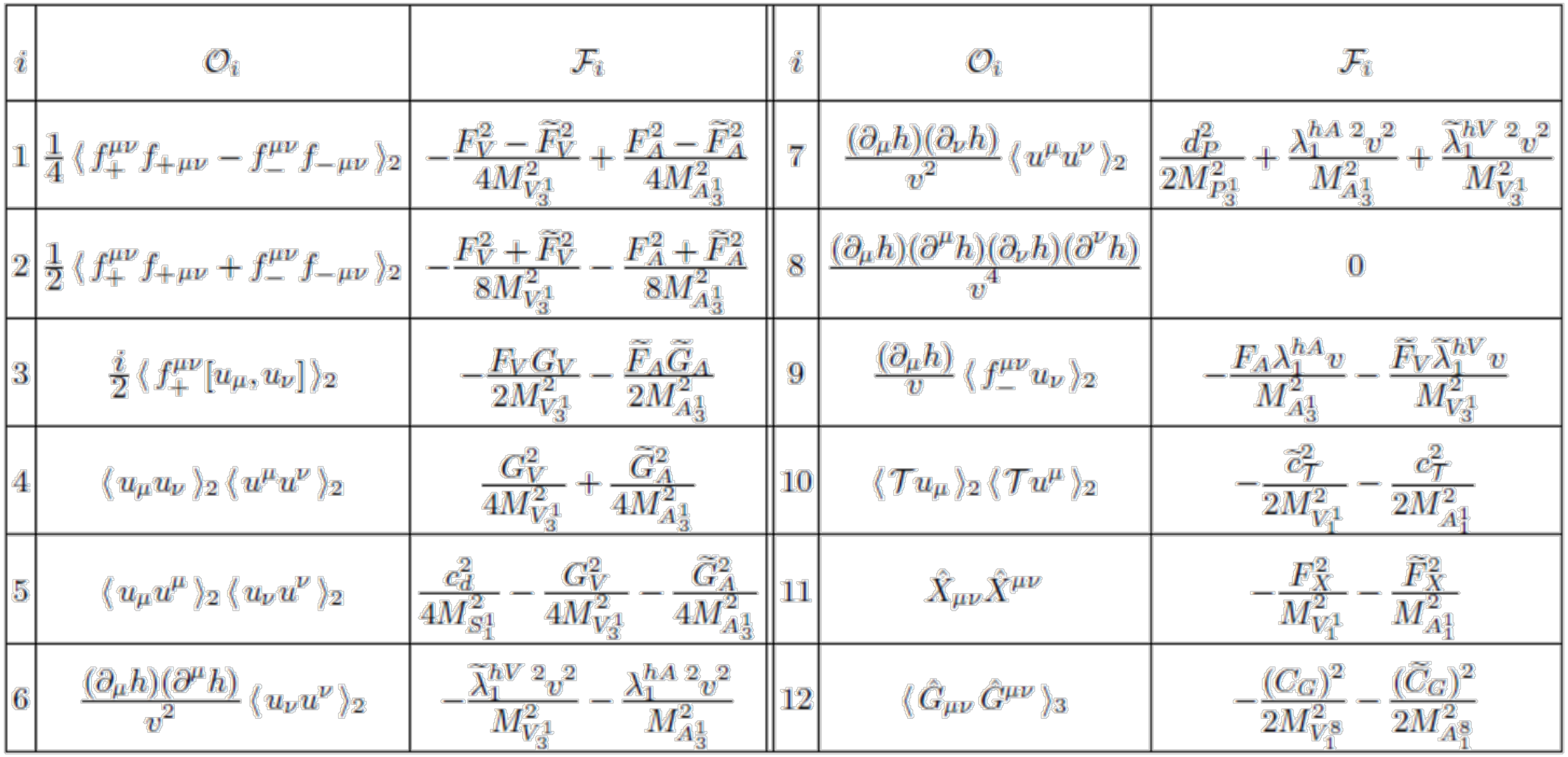
Antisymmetric tensor formalism $R_{\mu\nu}$ for Spin-1 resonance (x).

For the description of fermions+bosons a mixed Proca+Antisym. formalism needed (x) (+)

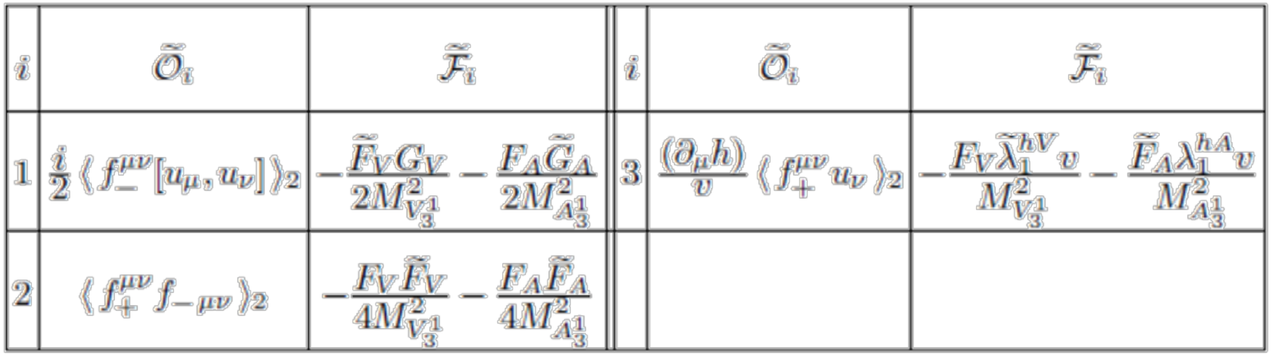
(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

(+) Kampf,Novotny,Trnka, Eur.Phys.J.C 50 (2007) 385-403

- 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 ($h\varphi$) :
$$\widetilde{F}_V\, G_V + F_A\, \widetilde{G}_A = 0$$

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

  - AFF to two EW Goldstones ($\varphi\varphi$):
$$\widetilde{F}_A\, \lambda_1^{hA} + F_V\, \widetilde{\lambda}_1^{hV} = 0$$

  - 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):

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

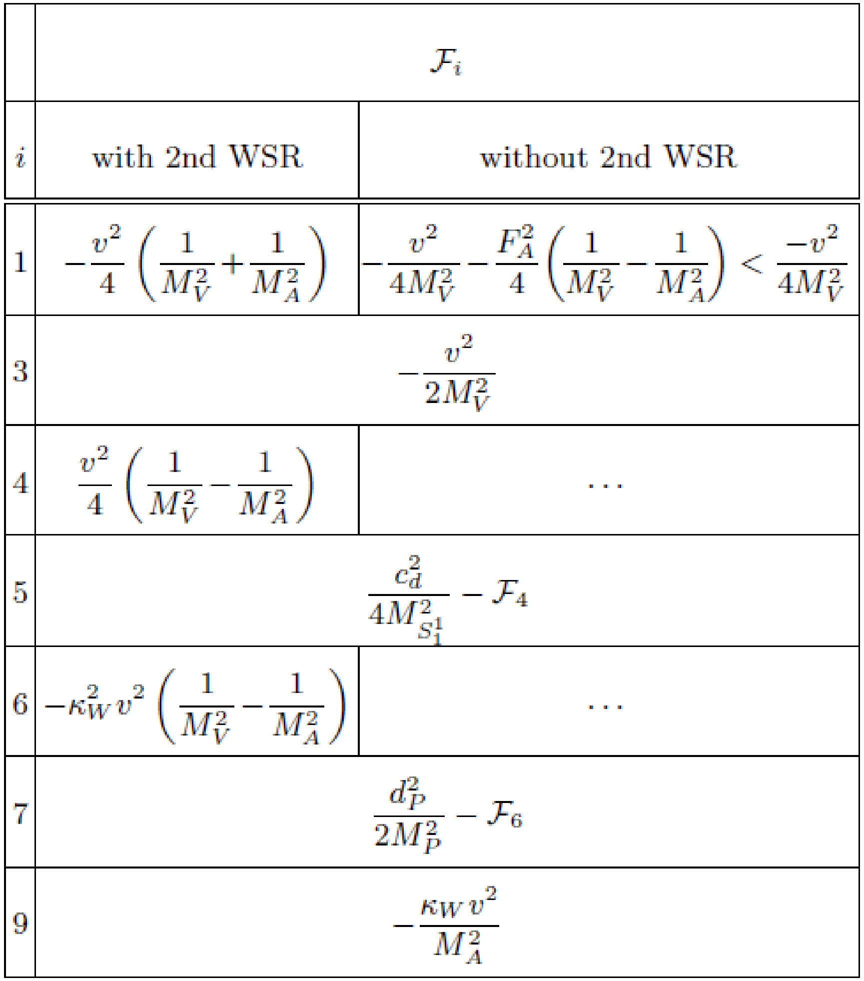
⇒

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

3. Predictions for HEFT couplings

- O(p^4) LEC predictions for

  only P-even Resonance Theories:

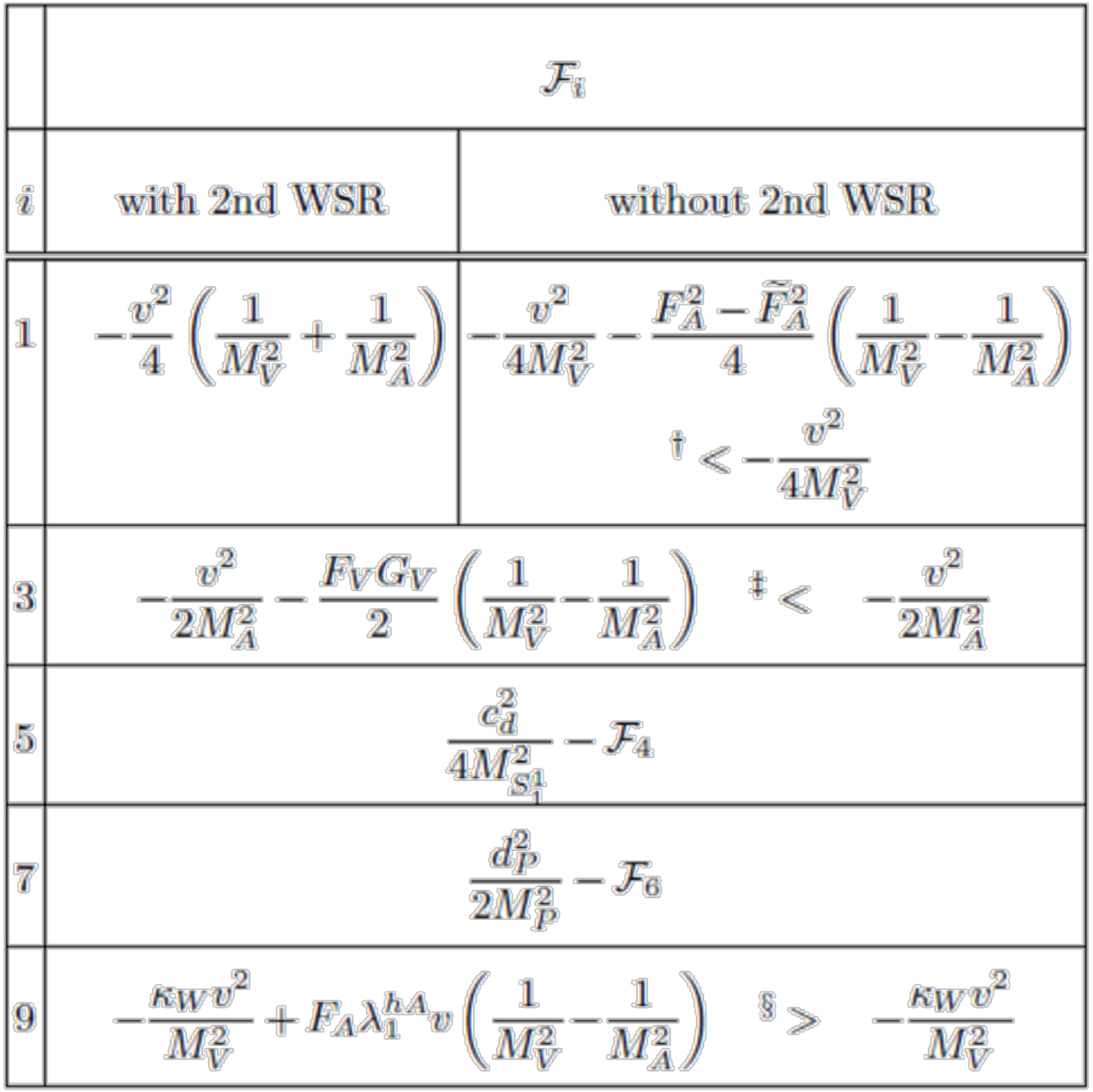


	$\mathcal{F}_i$	
i	with 2nd WSR	without 2nd WSR
1	$-\frac{v^2}{4}\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)$	$-\frac{v^2}{4M_V^2}-\frac{F_A^2}{4}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right) < \frac{-v^2}{4M_V^2}$
3	$-\frac{v^2}{2M_V^2}$	
4	$\frac{v^2}{4}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)$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

TABLE III. Resonance-exchange contributions to the P-even bosonic $\mathcal{O}(p^4)$ LECs, considering only P-even operators and the short distance constraints. Entries marked with $\cdots$ indicate that the result is the same as in Table I, without further simplification.

* Pich, Rosell,SC, Phys.Rev.D 102 (2020) 3, 035012

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



	$\mathcal{F}_i$	
i	with 2nd WSR	without 2nd WSR
1	$-\frac{v^2}{4}\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)$	$-\frac{v^2}{4M_V^2}-\frac{F_A^2-\widetilde{F}_A^2}{4}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)$ $^\dagger< -\frac{v^2}{4M_V^2}$
3	$-\frac{v^2}{2M_A^2}-\frac{F_VG_V}{2}\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)\ ^\ddagger< \ -\frac{v^2}{2M_A^2}$	
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	$-\frac{\kappa_W v^2}{M_V^2}+F_A\lambda_1^{hA}v\left(\frac{1}{M_V^2}-\frac{1}{M_A^2}\right)\ ^\S> \ -\frac{\kappa_W v^2}{M_V^2}$	

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

$$|\widetilde{F}_A\widetilde{G}_A| < |F_VG_V|$$

$$\Downarrow$$

$$F_VG_V > 0$$

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

$$\Downarrow$$

$$F_A\lambda_1^{hA} > 0$$

* Pich, Rosell,SC, Phys.Rev.D 102 (2020) 3, 035012

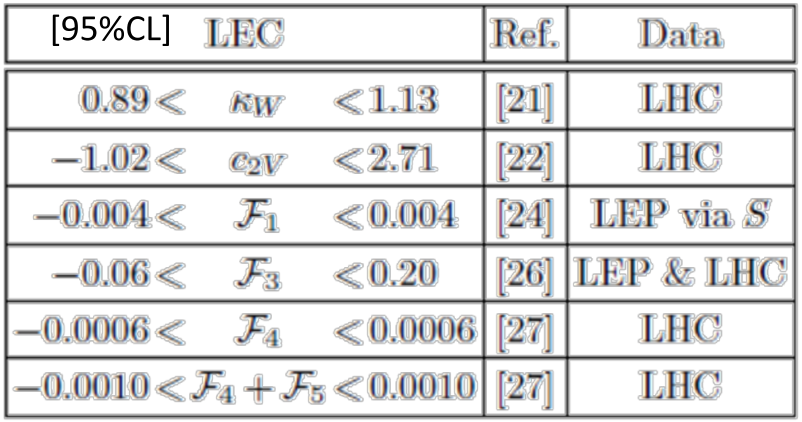
4. Phenomenology & implications: M_R bounds

- **INPUTS:**

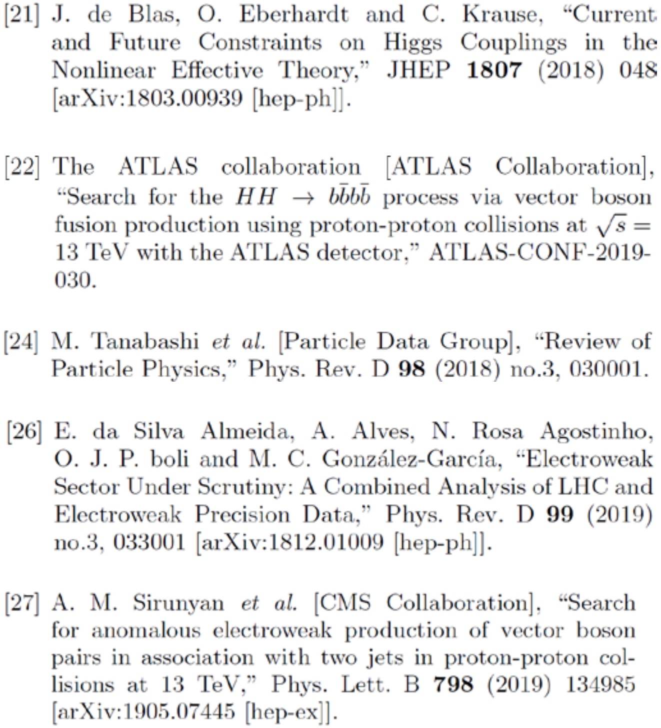
1. **k_W (h→WW):** CMS+ATLAS analysis within HEFT [21]
2. **c_{2V} (hh→WW):** ATLAS bounds [22]
3. **F_1 (W_3B):** LEP S-parameter [24]
4. **F_3 (γWW):** Anomalous TGC $\delta\kappa_\gamma$ [26]
5. **F_4, F_5 (WW→WW):** CMS VBS analysis [27]

[Caveats:
- very stringent bounds
- x 100 precision improvement *
- unitarity not incorporated $^{(x)}$
- unitarity would 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]].

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* 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 *

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

$$\Delta\mathcal{F}_1 = \Delta\mathcal{F}_3 = 0.9\cdot 10^{-3}, \qquad \Delta\mathcal{F}_4 = 3\cdot 10^{-5},$$

$$\Delta(\mathcal{F}_4+\mathcal{F}_5) = 1.7\cdot 10^{-3}, \qquad \Delta\mathcal{F}_6 = 3\cdot 10^{-3},$$

$$\Delta(\mathcal{F}_6+\mathcal{F}_7) = 0.6\cdot 10^{-2}, \qquad \Delta\mathcal{F}_9 = 1.4\cdot 10^{-2}.$$

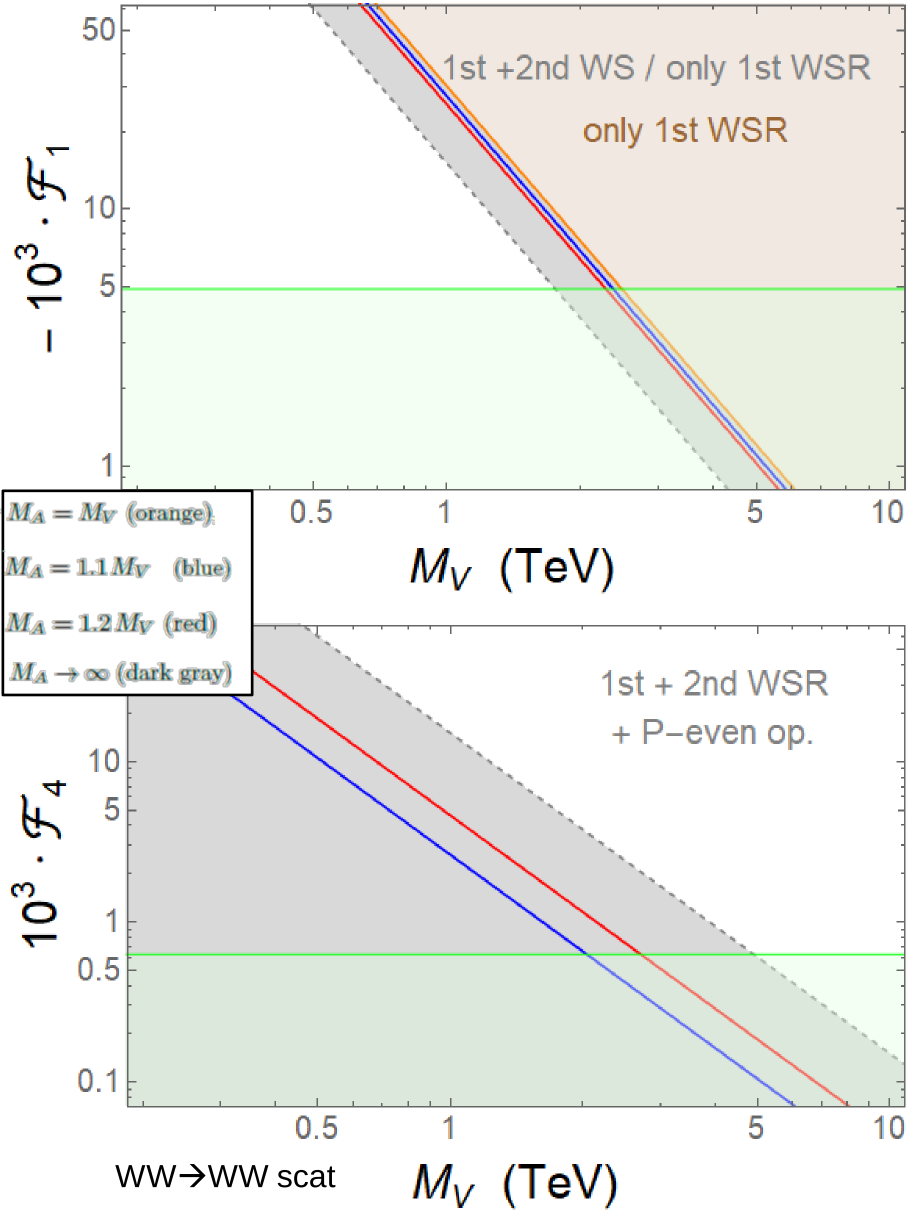
(x) Guo,Ruiz-Femenía,SC, PRD92 (2015) 074005

* Pich, Rosell,SC, Phys.Rev.D 102 (2020) 3, 035012

• PREDICTIONS vs DATA:

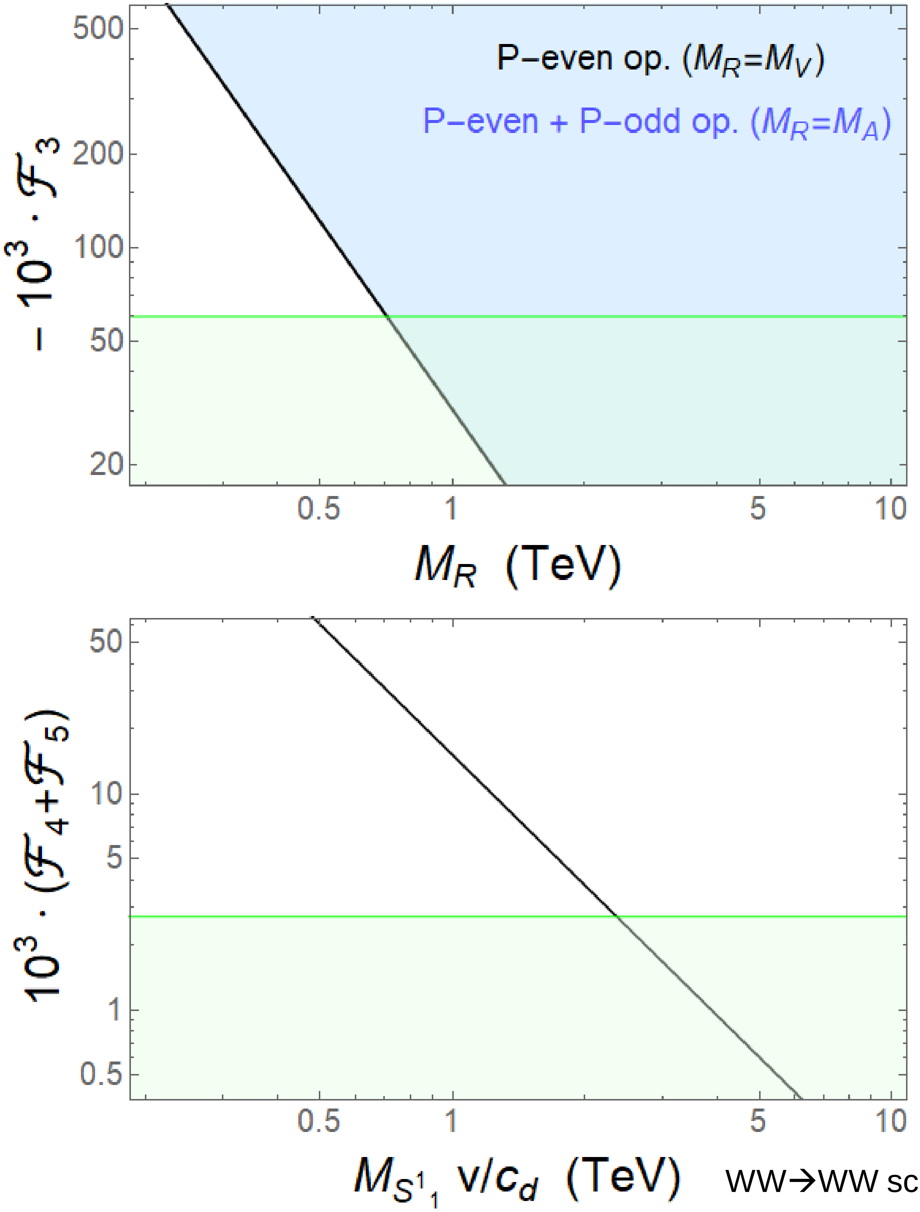
* Pich, Rosell,SC, Phys.Rev.D 102 (2020) 3, 035012

S-parameter



WW→WW scat

Anomalous TGC



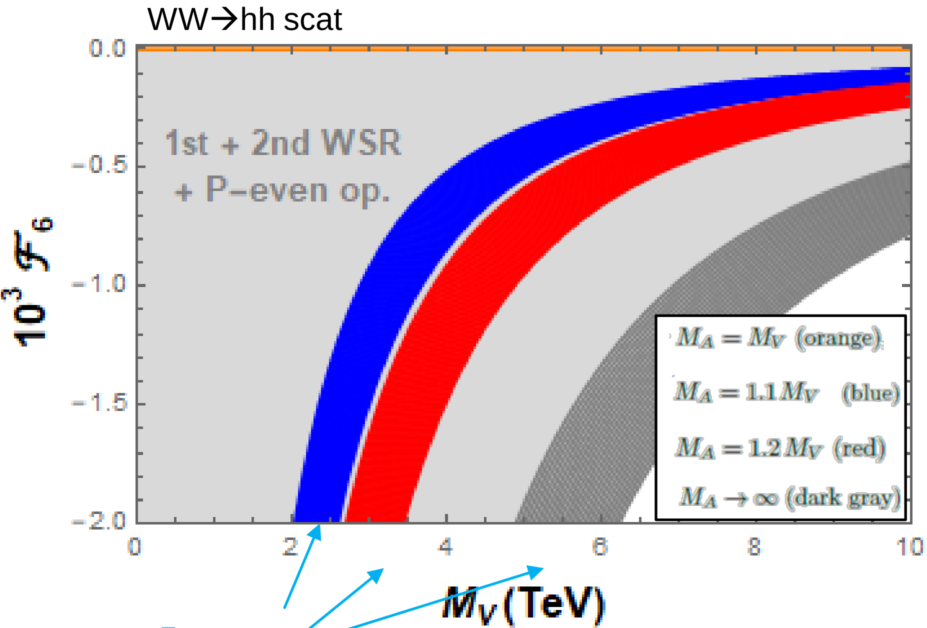
WW→WW scat

• PREDICTIONS

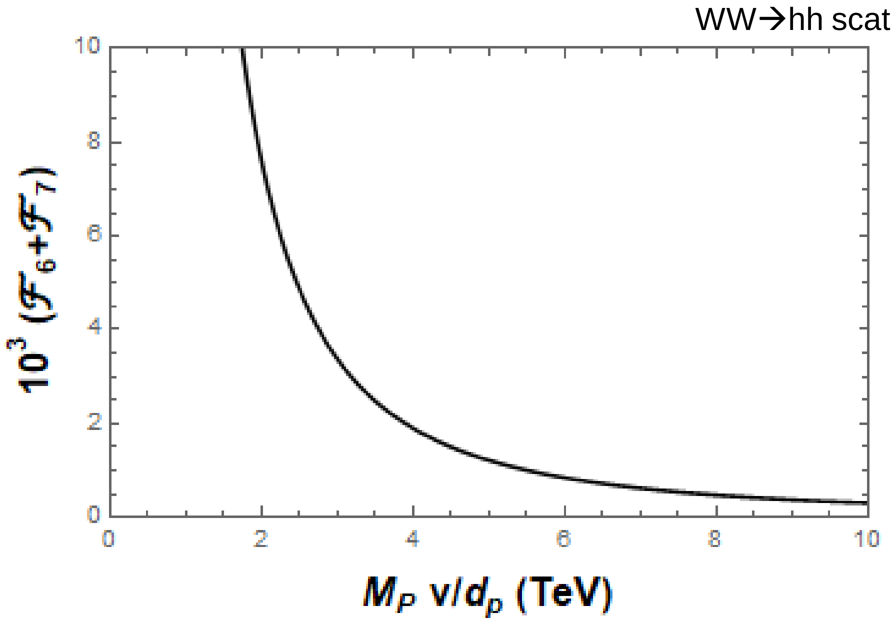
* No data currently

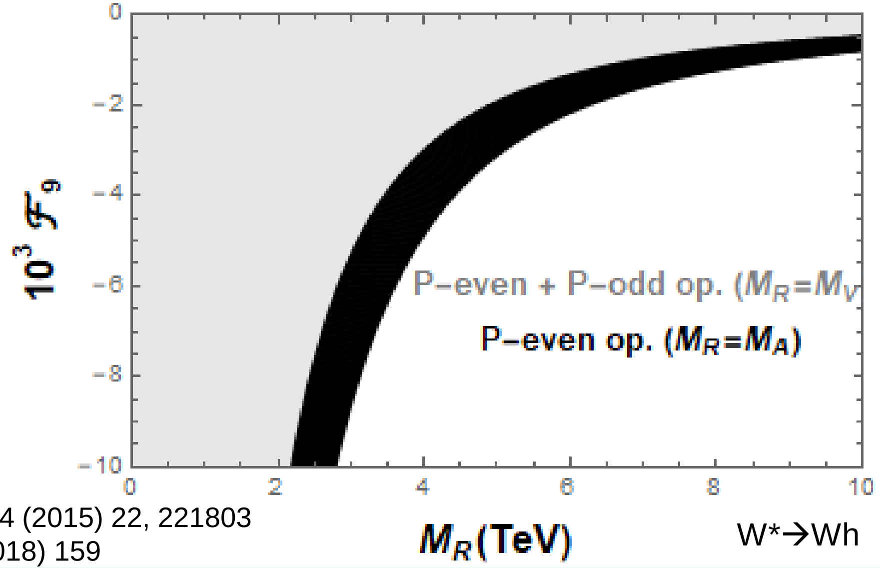
* $O(10^{-2})$ 1-loop errors [due to WW→hh coupling c_{2V}]

* Pich, Rosell,SC, Phys.Rev.D 102 (2020) 3, 035012



Δk_W^{exp} ➔ thick lines





Delgado,Dobado,Llanes-Estrada, PRL114 (2015) 22, 221803
Dobado,Llanes-Estrada,SC, JHEP 03 (2018) 159

Conclusions

✓ **LECs with exp. data:**

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

  $\mathcal{F}_4 + \mathcal{F}_5$ ⇒ $M_{S_1^1} \gtrsim 2\ \mathrm{TeV}$

✓ **LECs with NO data:**

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

  $M_P \lesssim 2\ \mathrm{TeV}$ ⇒ $\mathcal{F}_6 + \mathcal{F}_7 \gtrsim 5 \cdot 10^{-3}$
- hZγ: $M_{V,A} \sim 2\ \mathrm{TeV}$ ⇒ $|\mathcal{F}_9| \sim \mathcal{O}(10^{-2})\ (negative)$

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

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

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

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

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

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

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

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

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

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

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.

$$\mathcal{F}_{\mathbf{u}} = 1 + \frac{2\mathbf{a}\mathbf{h}}{\mathbf{v}} + \frac{\mathbf{b}\mathbf{h}^2}{\mathbf{v}^2} + \mathcal{O}(\mathbf{h}^3)$$

$$\mathbf{a}_{\mathbf{SM}} = \mathbf{b}_{\mathbf{SM}} = 1$$

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

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

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

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

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.

(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)$_L$ x 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 ($\sim p^0$)

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

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

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* 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