EW extensions of the SM suppressing low-energy ~~4~~-fermion EFT interactions

Matter To The Deepest 2019

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Juan José Sanz-Cillero (UCM-IPARCOS)

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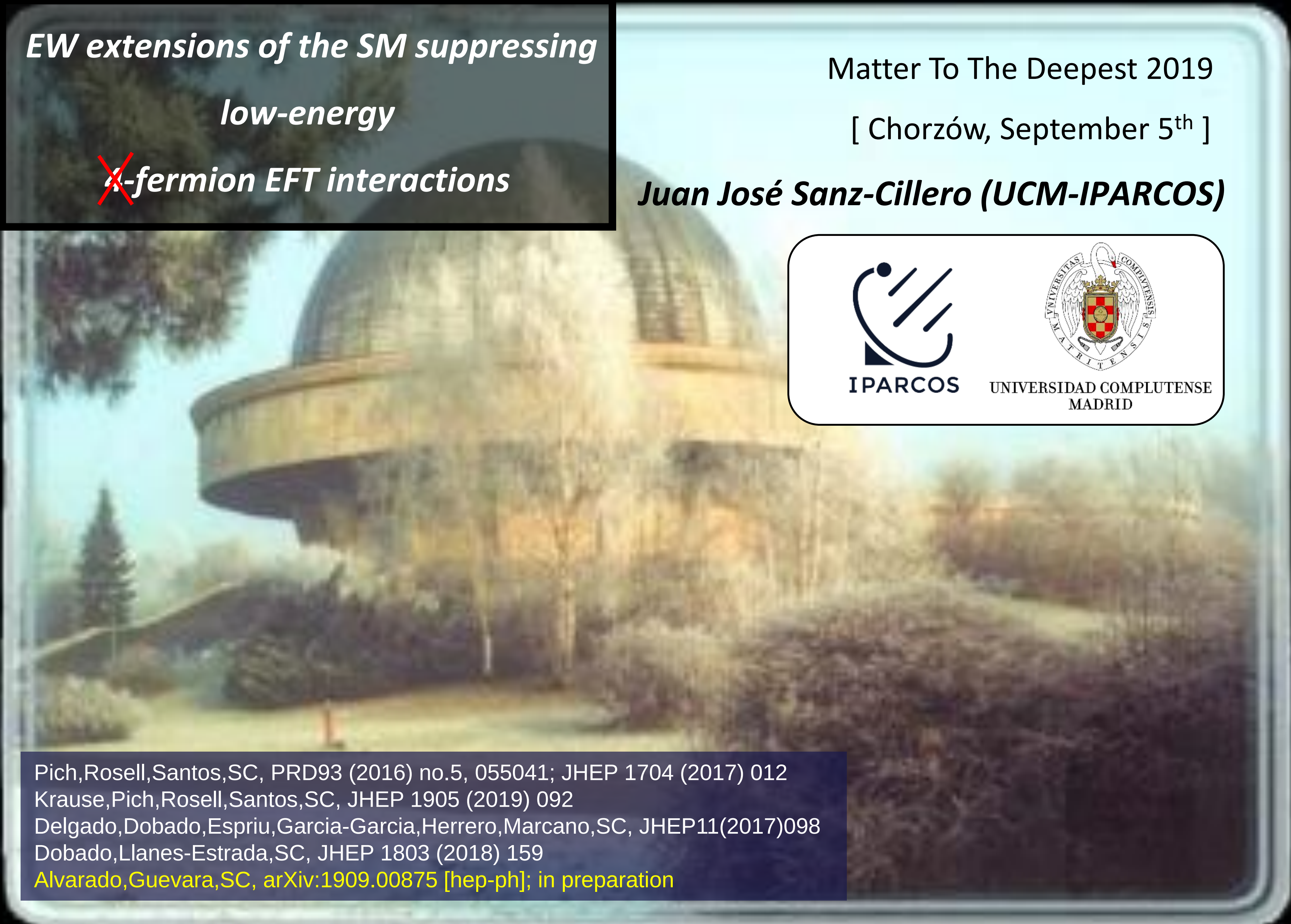


Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012
Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092
Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP11(2017)098
Dobado,Llanes-Estrada,SC, JHEP 1803 (2018) 159
Alvarado,Guevara,SC, arXiv:1909.00875 [hep-ph]; in preparation

Outline

1.) BSM searches: currents NP scale *bounds (?)*

2.) (Low-energy) *HEFT* (= $EW\chi L$ = *EWET*)

3.) EWET + Resonances: *what might we expect?*

4.) a) Resonant VBS diboson production: *WZ, evading current M_R bounds*

b) Resonant DY diboson production: *Wh, evading current M_R bounds*

5.) A simple scenario: naturally suppressing SM fermion interactions

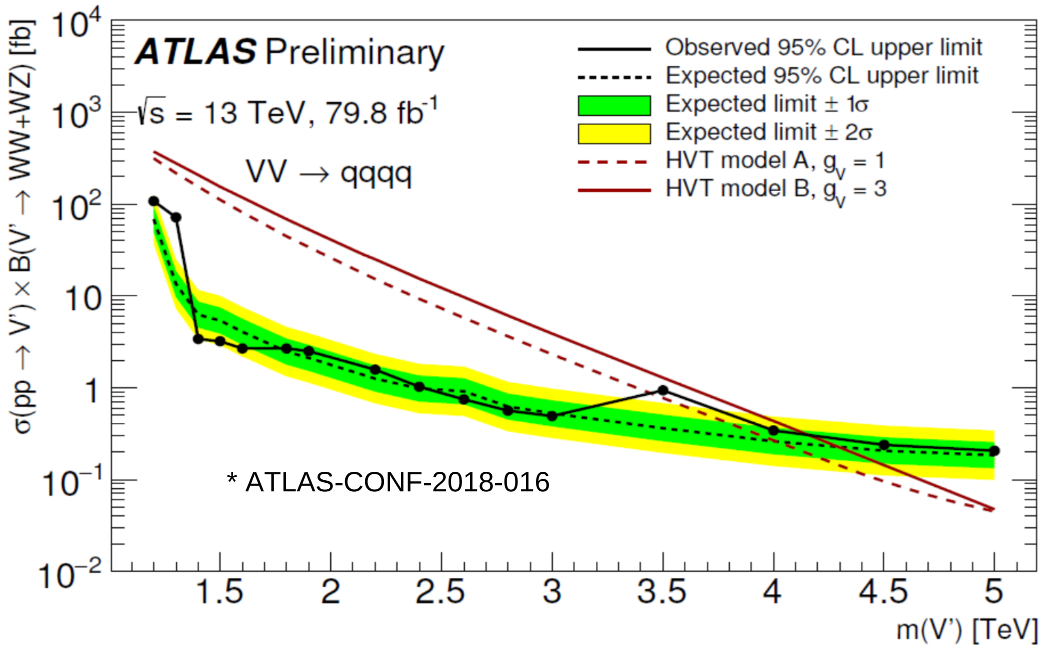
1.) BSM searches:

current NP scale bounds (?)

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

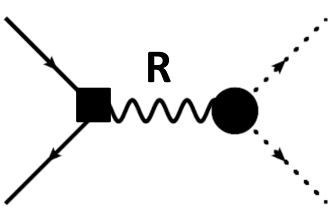
- Analyses heavily rely on specific models, HVT model[(x)] in particular

Current most stringent bound on EW triplet-V



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

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

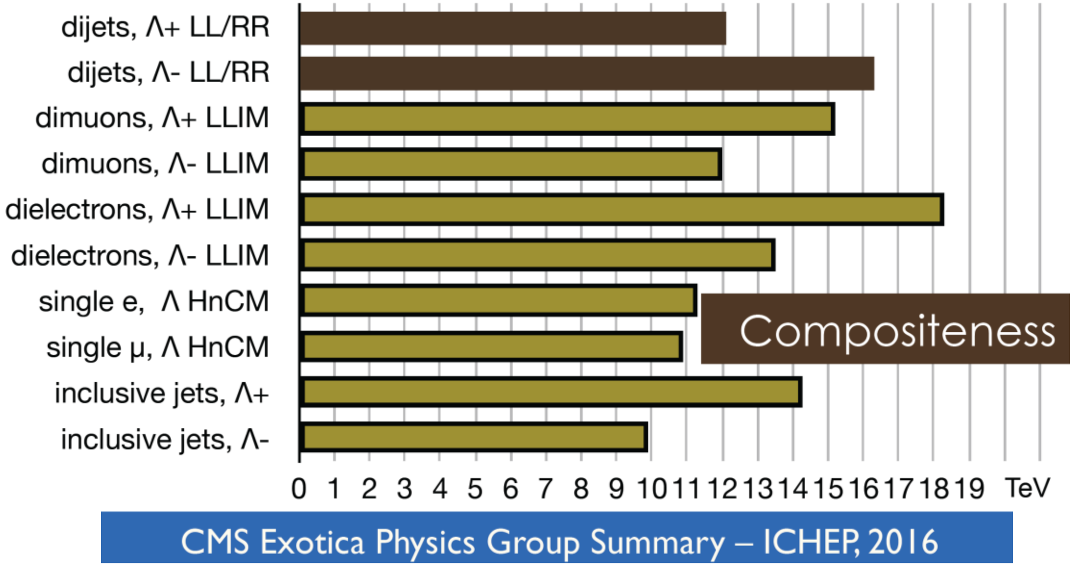


(x) Pappadopulo,Thamm,Torre,Wulzer, JHEP 1409 (2014) 060

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

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

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



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

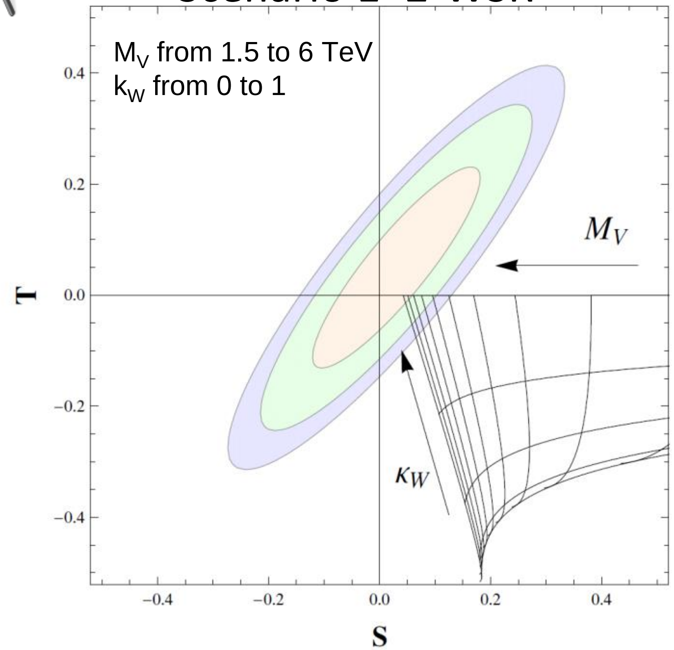
- Also bounds from low-E hadronic experiments *

(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

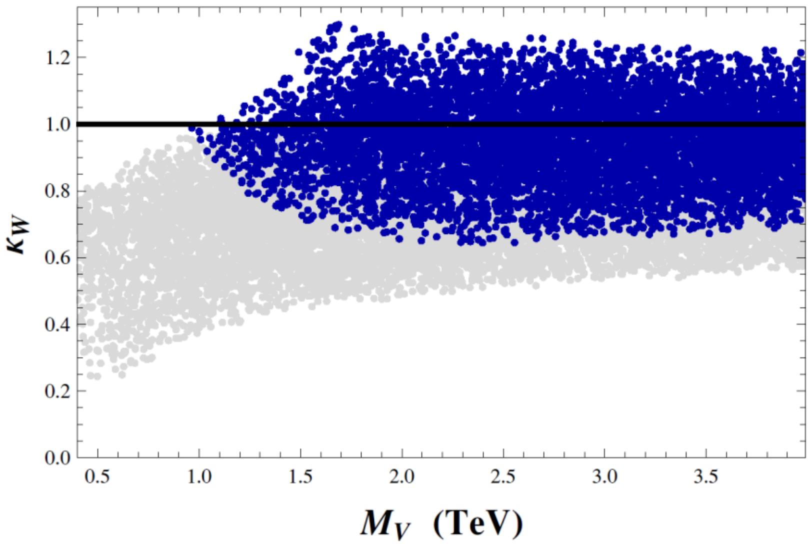
(+) Zhang, Chin. Phys. C 42 (2018) no.2, 023104
(+) Buckley et al, JHEP 1604 (2016) 015
(+) Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]
* Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]
* Isidori, arXiv:1302.0661 [hep-ph]
* Jung,Straub, arXiv:1801.01112 [hep-ph].

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

2.) (Non-linear) HEFT

aka EWχL

aka EWET

Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092
Also see, e.g., rev: HXSWG Yellow Report (non-linear EFT Sec.), arXiv:1610.07922 [hep-ph]

(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) $G_{SM} \to H_{SM} = U(1)_{EM}$
- **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. $G \to H = SU(2)_{L+R} \times U(1)_{B-L} \supset H_{SM}$
  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

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

- EW Effective Theory (*EWET = EWχL = HEFT*):

  - **Chiral expansión:**
$$\mathcal{L}_{\rm EWET} = \sum_{\hat{d}\geq 2} \mathcal{L}_{\rm EWET}^{(\hat{d})}$$

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

with $\mathcal{F}_{\mathbf{u}} = 1 + \frac{\mathbf{2ah}}{\mathbf{v}} + \frac{\mathbf{bh^2}}{\mathbf{v^2}} + \mathcal{O}(\mathbf{h^3})$*, being* $\mathbf{a_{SM} = b_{SM} = 1}$

  - **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

• 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) (+)

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

LO (tree)

NLO (tree)

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

** 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

NLO (1-loop)

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

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 $\frac{\mathrm{p}^2}{16\pi^2\mathrm{v}^2} \sim \frac{g^{(\prime)\,2}}{(4\pi)^2}, \frac{\lambda}{(4\pi)^2}, \frac{\lambda_f^2}{(4\pi)^2} \ll 1$; **hence**

3.) HEFT + Resonances:

what might we expect?

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

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

Custodial symmetry
+
Resonance Lagrangian
+
UV completion hypothesis

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

V,A,S,P, Fermionic R
EW singlet, doublet & triplet
Colour singlet & octet

Sum-rules

E

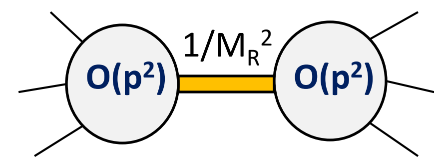
$4\pi v \approx 3$ TeV

M_R

Mass gap

t
h
W,Z

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



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

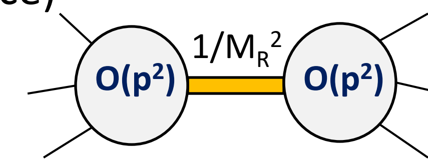
** See also: Alboteanu, Kilian, Reuter, JHEP 0811 (2008) 010; Pappadopulo, Thamm, Torre, Wulzer, JHEP 1409 (2014) 060; Corbett, Joglekar, Li, Yu, [arXiv:1705.02551 [hep-ph]]; Corbett,Éboli,Gonzalez-Garcia,PRD93 (2016) no.1, 015005; Buchalla, Cata, Celis, Krause, NPB917 (2017) 209;
de Blas,Criado,Perez-Victoria,Santiago,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

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

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

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

• The High-E Resonances leave a **specific imprint in the Low-E couplings**: (*)

- Contributions to purely bosonic operators

i	$\Delta\mathcal{F}_i$	$\Delta\widetilde{\mathcal{F}}_i$	i	$\Delta\mathcal{F}_i$
1	$-\frac{F_V^2-\widetilde{F}_V^2}{4M^2_{V^1_3}}+\frac{F_A^2-\widetilde{F}_A^2}{4M^2_{A^1_3}}$	$-\frac{\widetilde{F}_V G_V}{2M^2_{V^1_3}}-\frac{F_A\widetilde{G}_A}{2M^2_{A^1_3}}$	7	$\frac{d_P^2}{2M^2_{P^1_3}}+\frac{\lambda_1^{hA\,2}v^2}{M^2_{A^1_3}}+\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M^2_{V^1_3}}$
2	$-\frac{F_V^2+\widetilde{F}_V^2}{8M^2_{V^1_3}}-\frac{F_A^2+\widetilde{F}_A^2}{8M^2_{A^1_3}}$	$-\frac{F_V\widetilde{F}_V}{4M^2_{V^1_3}}-\frac{F_A\widetilde{F}_A}{4M^2_{A^1_3}}$	8	0
3	$-\frac{F_V G_V}{2M^2_{V^1_3}}-\frac{\widetilde{F}_A\widetilde{G}_A}{2M^2_{A^1_3}}$	$-\frac{F_V\widetilde{\lambda}_1^{hV}v}{M^2_{V^1_3}}-\frac{\widetilde{F}_A\lambda_1^{hA}v}{M^2_{A^1_3}}$	9	$-\frac{F_A\lambda_1^{hA}v}{M^2_{A^1_3}}-\frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M^2_{V^1_3}}$
4	$\frac{G_V^2}{4M^2_{V^1_3}}+\frac{\widetilde{G}_A^2}{4M^2_{A^1_3}}$	—	10	$-\frac{\widetilde{c}_T^2}{2M^2_{V^1_1}}-\frac{c_T^2}{2M^2_{A^1_1}}$
5	$\frac{c_d^2}{4M^2_{S^1_1}}-\frac{G_V^2}{4M^2_{V^1_3}}-\frac{\widetilde{G}_A^2}{4M^2_{A^1_3}}$	—	11	$-\frac{F_X^2}{M^2_{V^1_1}}-\frac{\widetilde{F}_X^2}{M^2_{A^1_1}}$
6	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M^2_{V^1_3}}-\frac{\lambda_1^{hA\,2}v^2}{M^2_{A^1_3}}$	—	12	$-\frac{(C_G)^2}{2M^2_{V^8_1}}-\frac{(\widetilde{C}_G)^2}{2M^2_{A^8_1}}$

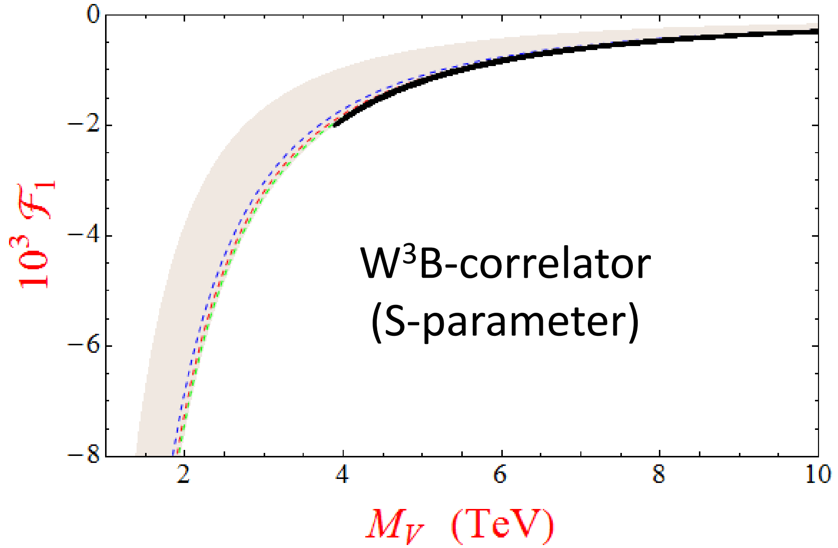
+ Contributions to ψ^2 and ψ^4 operators (more tedious) (*)

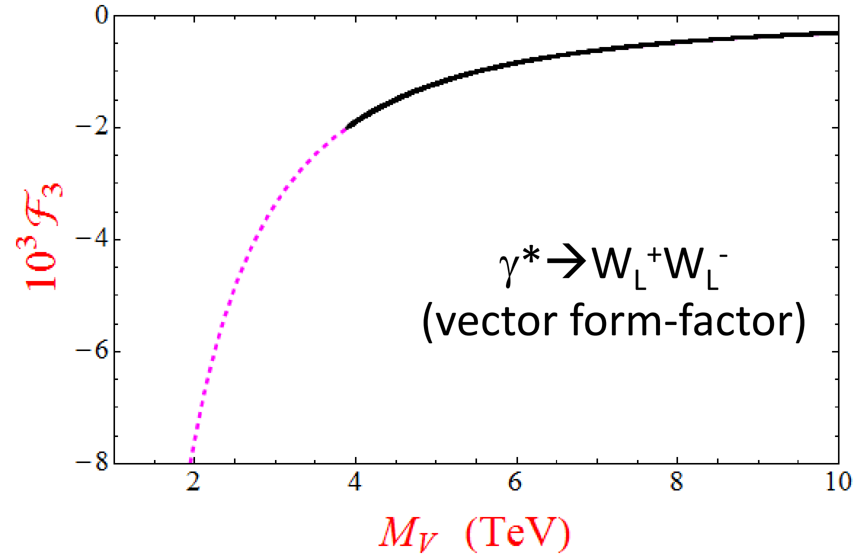
[Relation with Longhitanos's couplings $\mathcal{F}_j = a_j + O(h)$; notice: $a_{j\geq 5}$ relabelled]

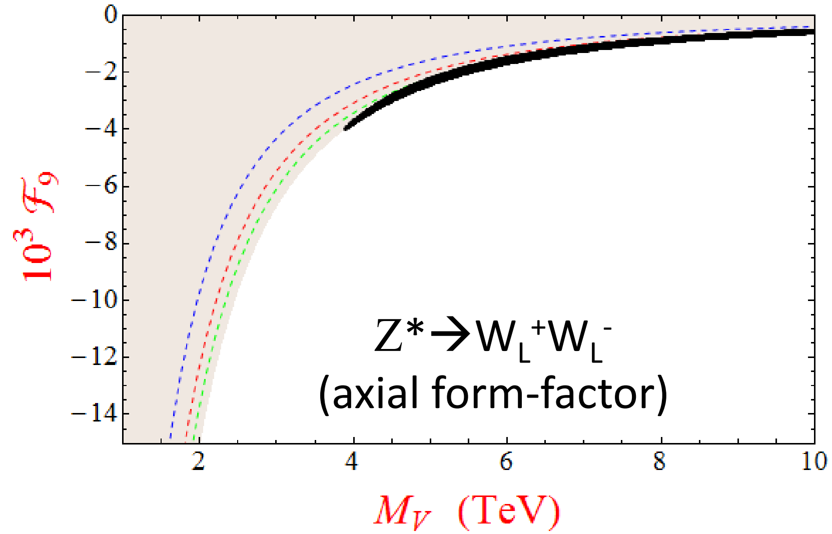
(*) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

Theory:

S-parameter and form-factor couplings
(bounds after using exp S+T in 1+2-WSR scenario)



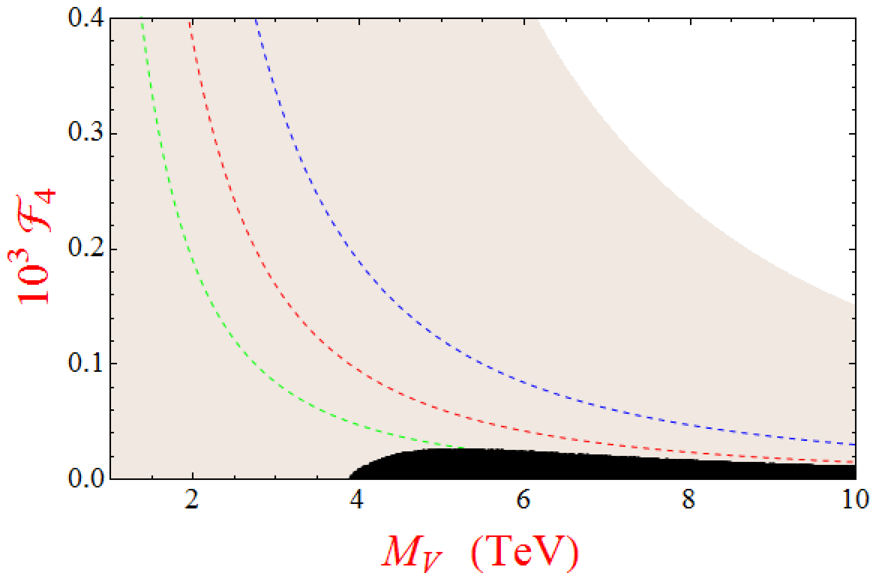




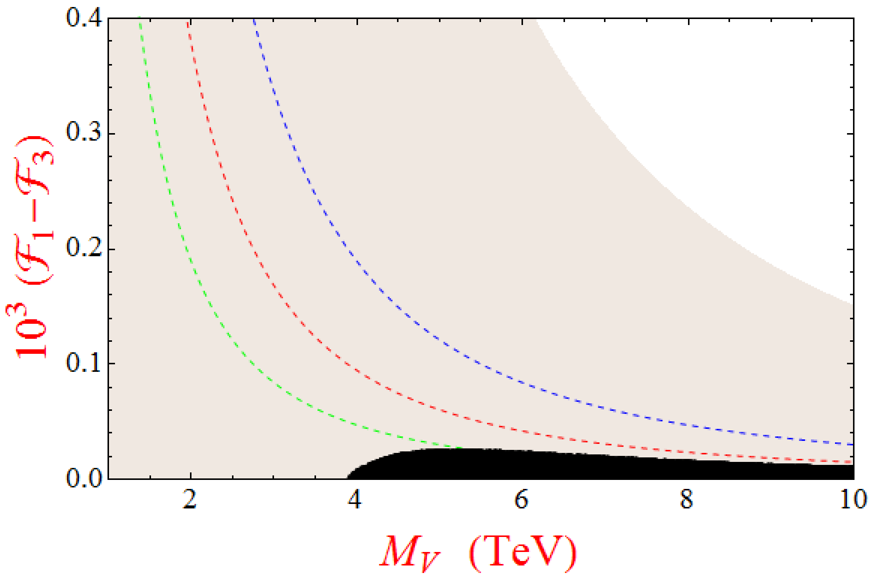
* Pich,Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801
* Pich,Rosell,Santos,SC, PRD 93 (2016) no.5, 055041

Theory: VBS and HBS couplings
(bounds after using exp S+T in 1+2-WSR scenario)

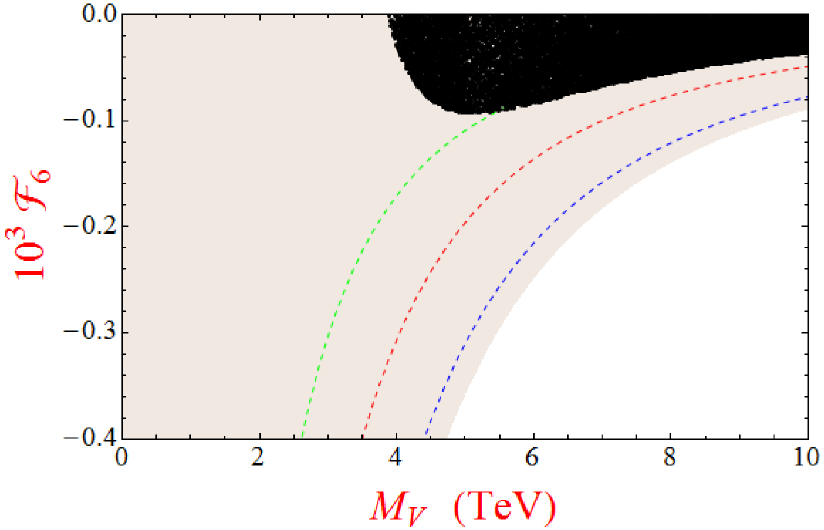
- $w^a w^b \to w^c w^d$ scattering



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



- $w^a w^b \to hh$ scattering



- $hh \to hh$ scattering $\to 0$

→ HEFT couplings in the range

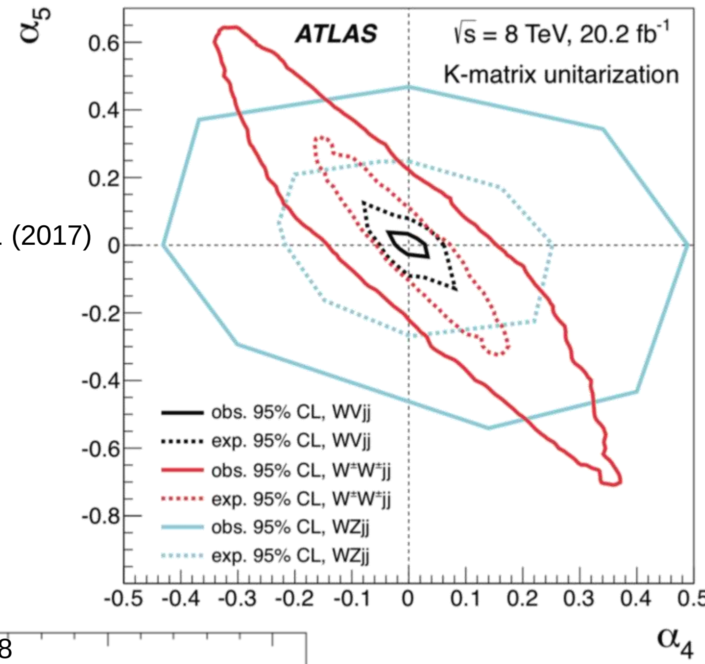
$$\mathcal{F}_j,\ a_j,\ \alpha_j \ \sim\ v^2/M_R^2 \ \sim\ 10^{-3} - 10^{-4}$$

* Pich,Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801
* Pich,Rosell,Santos,SC, PRD 93 (2016) no.5, 055041

- Still far from current experimental precision,

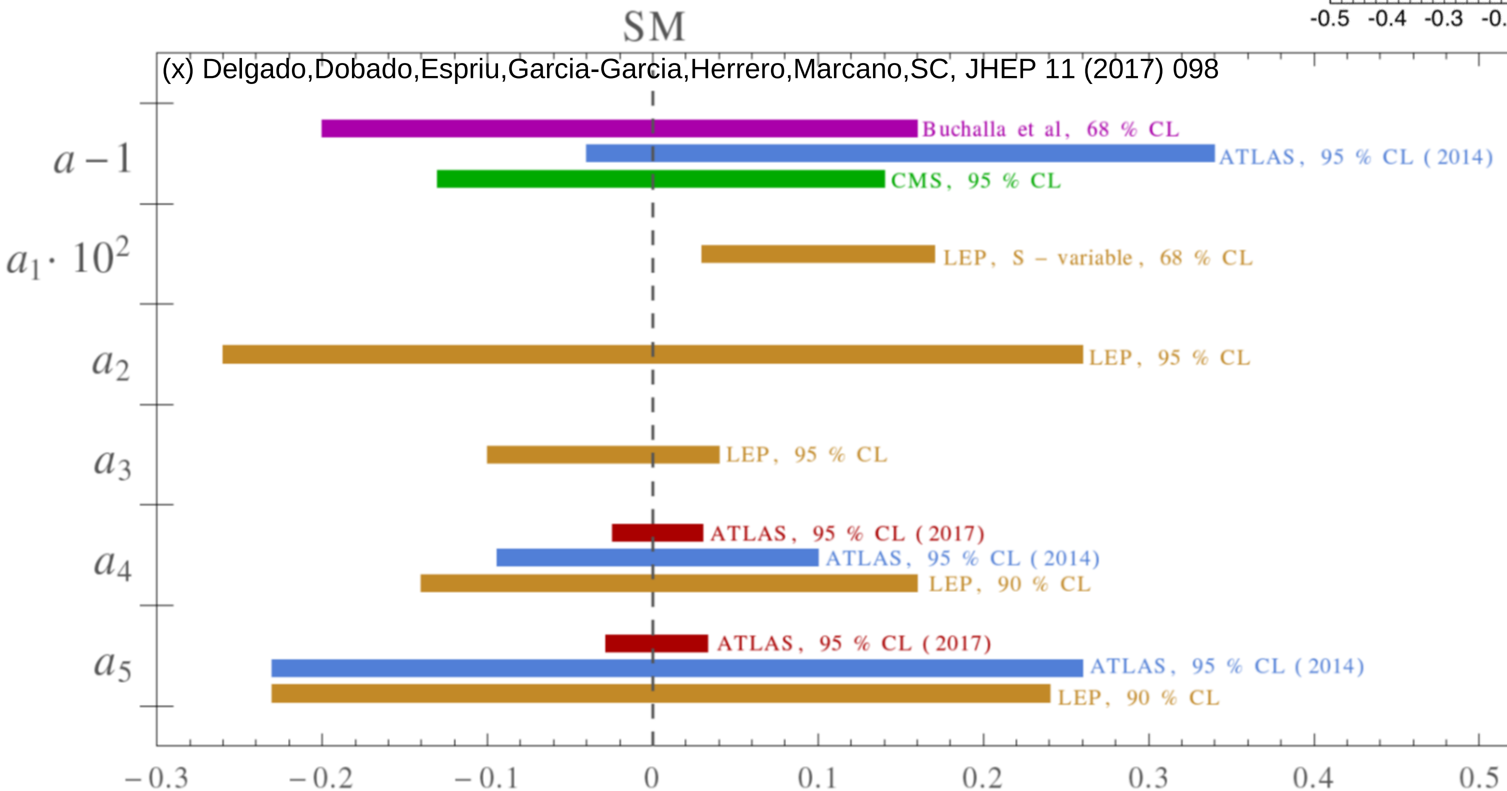
  although recent important improvements from VBS:

[ATLAS], PRD 95 032001 (2017)



- Useful to observe the summary: (x)

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



4.) Resonant diboson production at LHC

Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP11(2017)098

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

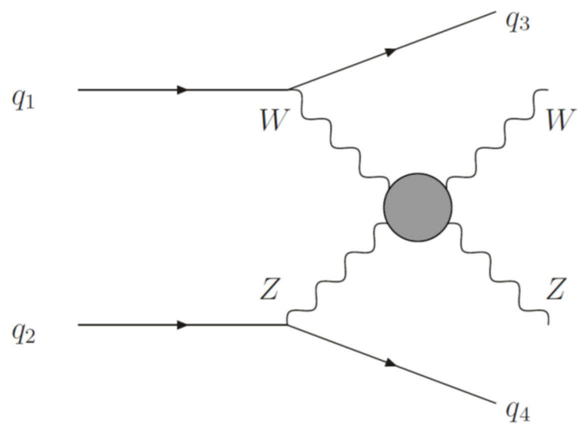
4.a) Resonant VBS diboson production:

WZ, evading current M_R bounds

Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP11(2017)098

$pp \to WZ j_1 j_2$

by $WZ \to WZ$ scattering



- Relevant HEFT Lagrangian up to NLO:

$$\mathcal{L}_2 = -\frac{1}{2g^2}\mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right) - \frac{1}{2g'^2}\mathrm{Tr}\left(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right) + \frac{v^2}{4}\left[1 + 2a\frac{H}{v} + b\frac{H^2}{v^2}\right]\mathrm{Tr}\left(D^\mu U^\dagger D_\mu U\right) + \frac{1}{2}\partial^\mu H\,\partial_\mu H + \dots ,$$

$$\mathcal{L}_4 = a_1 \mathrm{Tr}\left(U\hat{B}_{\mu\nu}U^\dagger \hat{W}^{\mu\nu}\right) + ia_2\mathrm{Tr}\left(U\hat{B}_{\mu\nu}U^\dagger[\mathcal{V}^\mu,\mathcal{V}^\nu]\right) - ia_3\mathrm{Tr}\left(\hat{W}_{\mu\nu}[\mathcal{V}^\mu,\mathcal{V}^\nu]\right) + a_4\left[\mathrm{Tr}(\mathcal{V}_\mu\mathcal{V}_\nu)\right]\left[\mathrm{Tr}(\mathcal{V}^\mu\mathcal{V}^\nu)\right] + a_5\left[\mathrm{Tr}(\mathcal{V}_\mu\mathcal{V}^\mu)\right]\left[\mathrm{Tr}(\mathcal{V}_\nu\mathcal{V}^\nu)\right] - c_W\frac{H}{v}\mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right) - c_B\frac{H}{v}\mathrm{Tr}\left(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right) + \dots$$

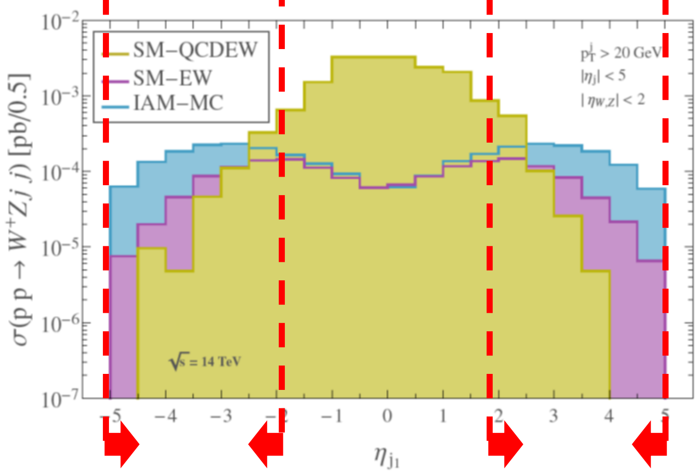
- Related to resonance parameters at higher energies

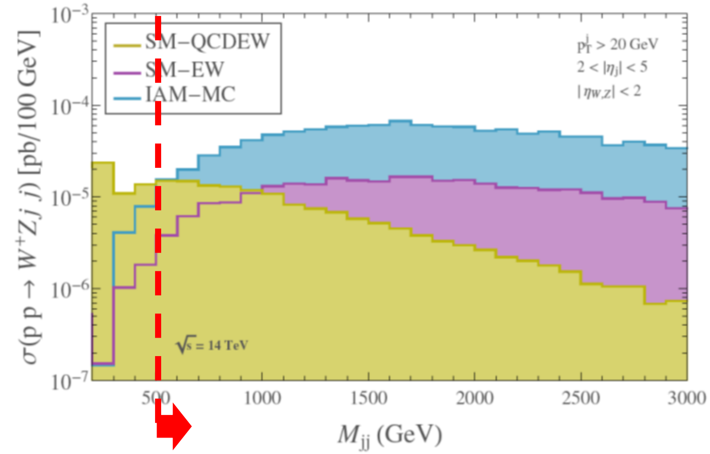
* Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP 11 (2017) 098

• 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:

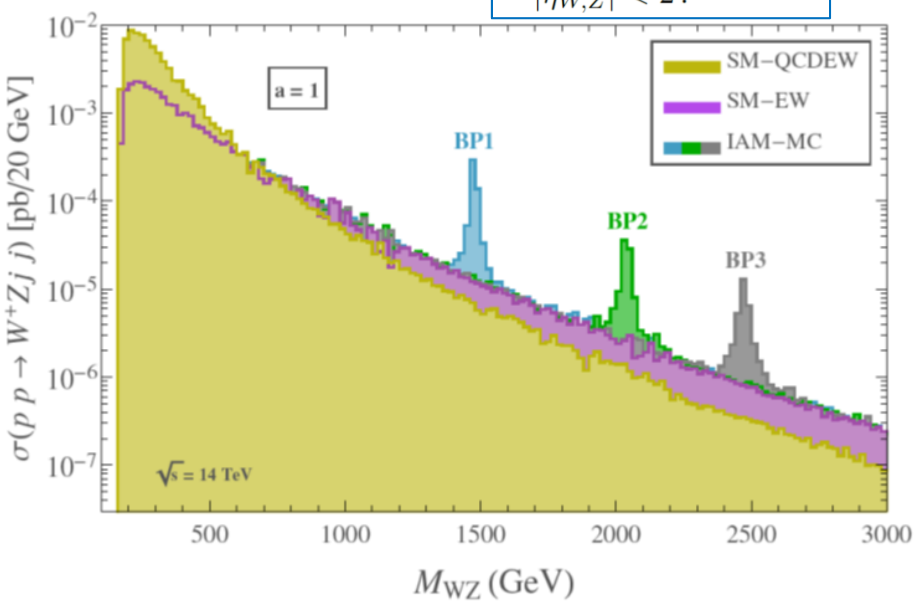


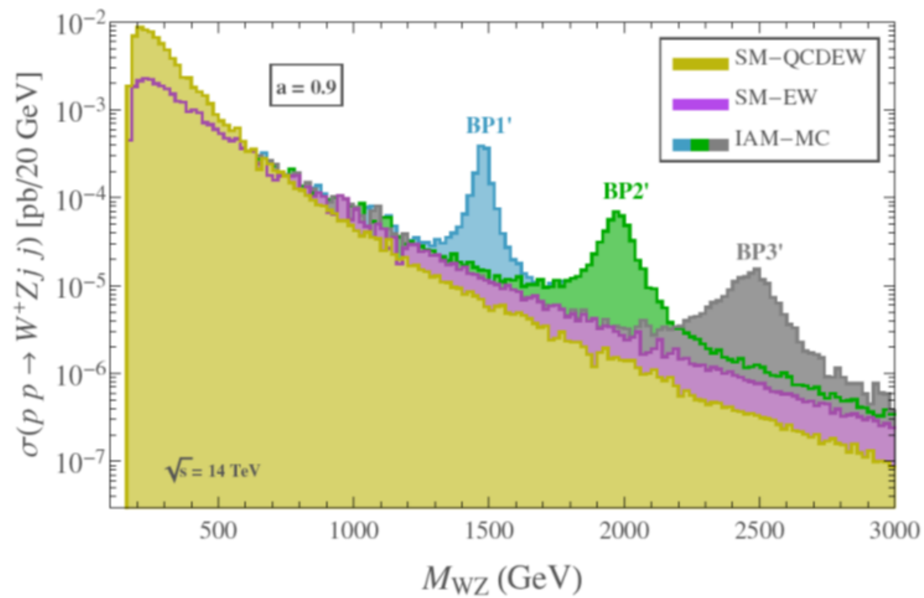


- Optimal VBS cuts: (*)

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

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

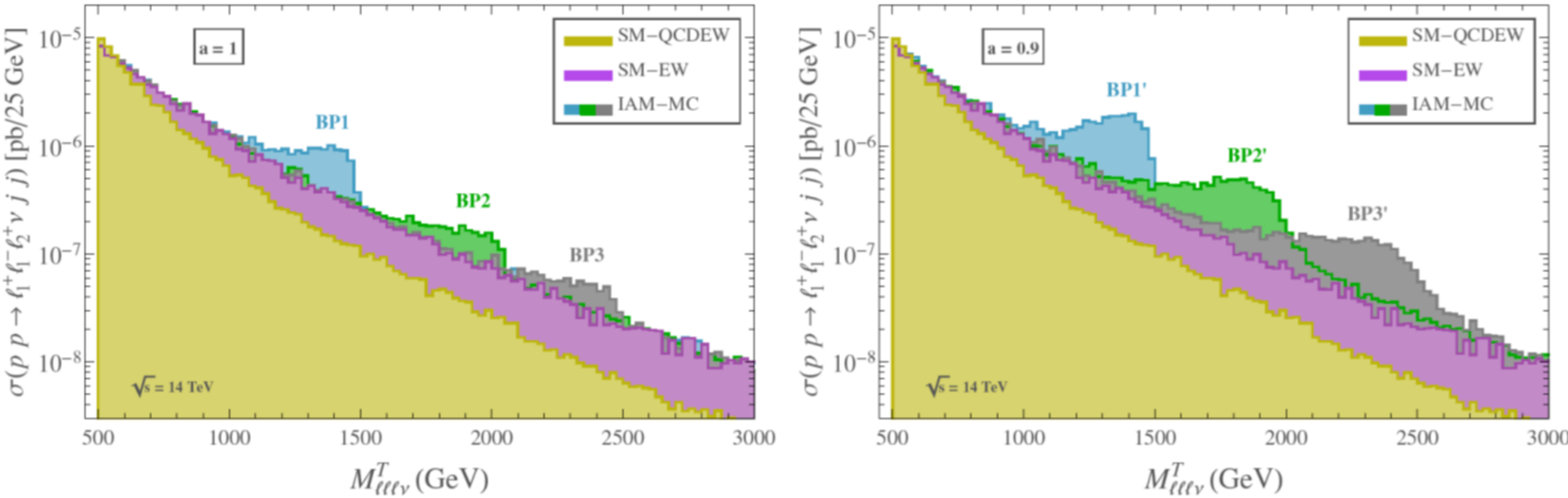




* Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP 11 (2017) 098 (x) Fabbrichesi,Pinamonti,Tonero,Urbano, PRD 93 (2016) 015004

- Fully leptonic decays:

14 TeV



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

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

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

ranges of $M^T_{\ell\ell\ell\nu}$:

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

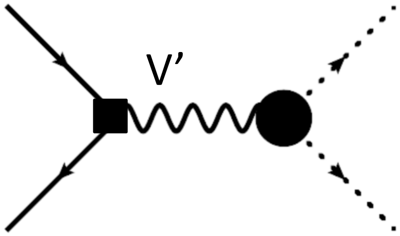
4.b) Resonant DY diboson production:

Wh, evading current M_R bounds

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

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

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

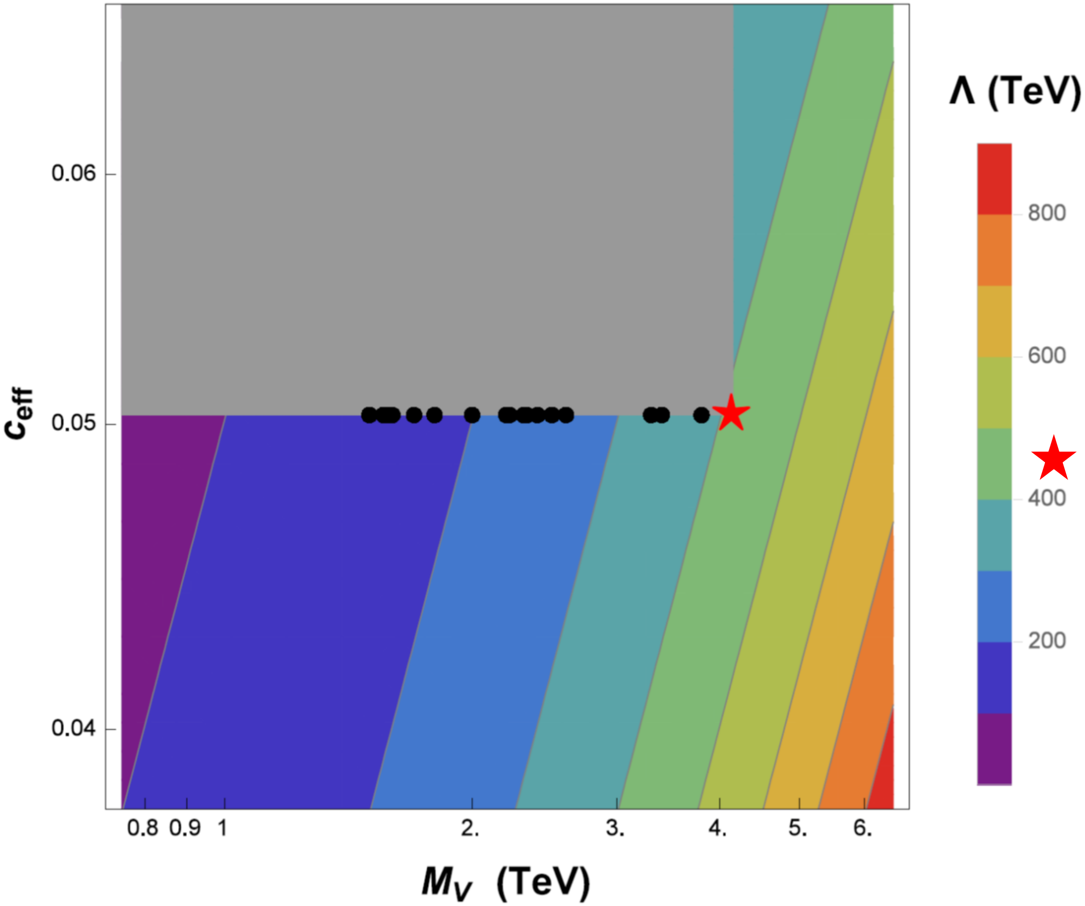


- Strongest bounds from HVT-B (g_V=3) [x]

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

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

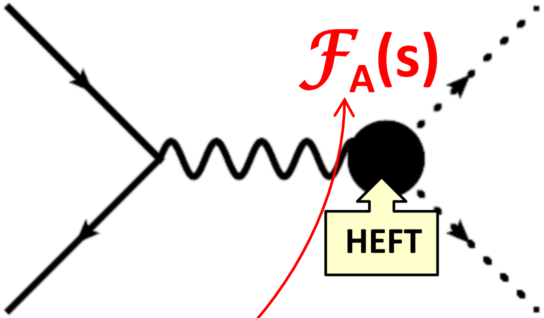
$$\frac{2\pi}{\Lambda^2} \equiv \mathcal{F}_7^{\psi^2} + \mathcal{F}_8^{\psi^2} + \frac{\mathcal{F}_{10}^{\psi^2}}{4} \overset{\text{integ. V}}{=} \frac{c_{\text{eff}}^2}{4M_V^2}$$



★ → Λ = 410 TeV

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

• Wh from DY via a gauge boson:



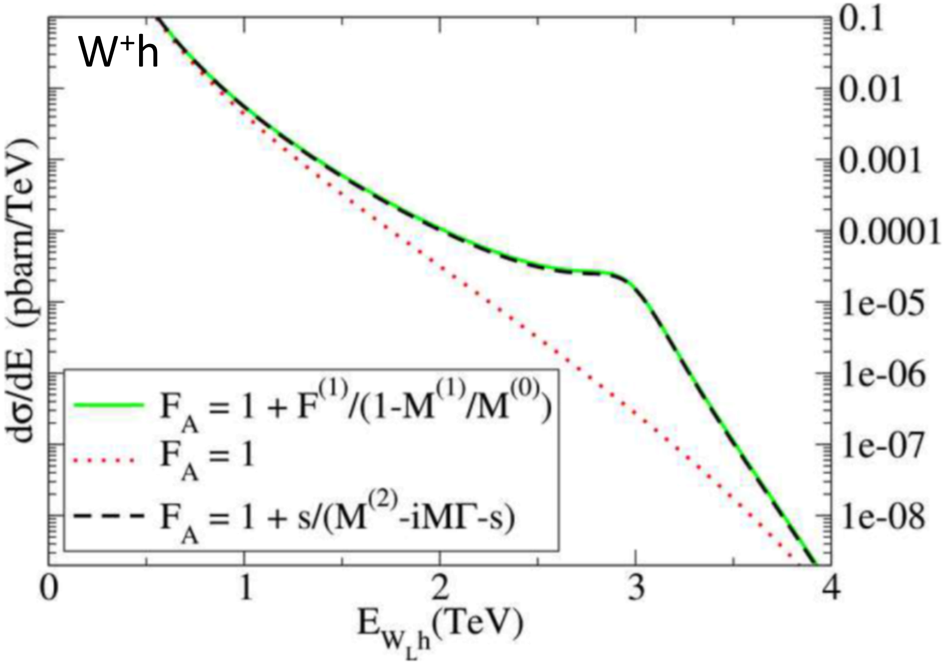
$$\tilde{T}(u_-\bar{d}_+ \to W_L^+ h) = \tilde{T}(d_-\bar{u}_+ \to W_L^- h) = \frac{g^2}{2\sqrt{2}} a \sin\theta e^{-i\varphi} \mathcal{F}_A(s)\,,$$

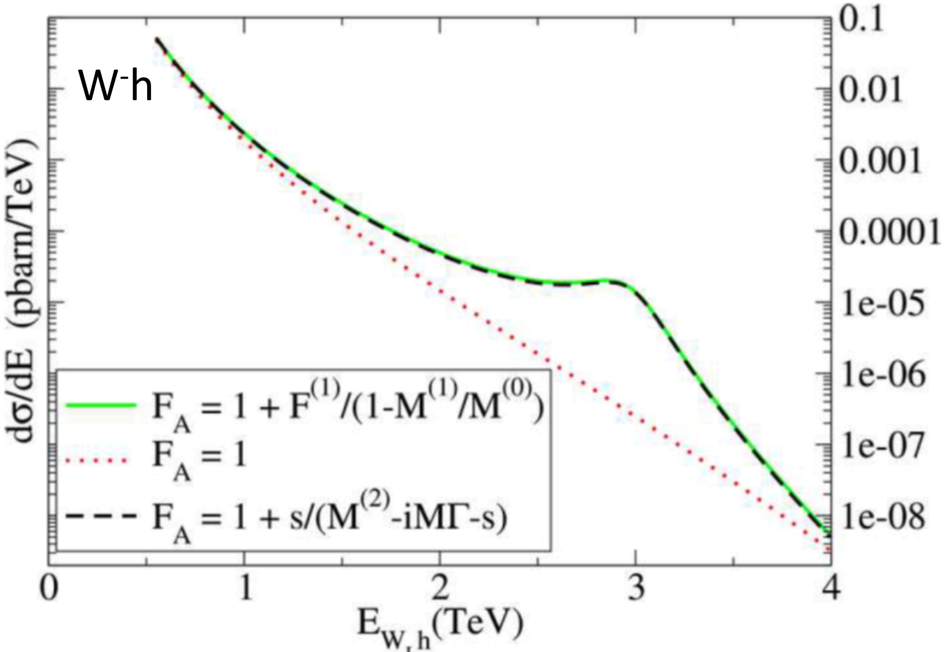
$$\tilde{T}(u_-\bar{u}_+ \to Z_L h) = -\tilde{T}(d_-\bar{d}_+ \to Z_L h) = \frac{g^2}{4} a \sin\theta e^{-i\varphi} \mathcal{F}_A(s)\,.$$

• HEFT:

$$\mathcal{L}_{\rm NLO} = d\,\frac{(\partial_\mu h \partial^\mu h)}{v^2}\,{\rm Tr}\{D_\nu U^\dagger D^\mu U\} + e\,\frac{(\partial_\mu h \partial^\nu h)}{v^2}\,{\rm Tr}\{D^\mu U^\dagger D_\nu U\}$$
$$-if_9\,\frac{(\partial_\mu h)}{v}\,{\rm Tr}\{\hat{W}^{\mu\nu}\, D_\nu U\, U^\dagger - \hat{B}^{\mu\nu}\, U^\dagger\, D_\nu U\}\,,$$

* 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→ $f_9(\mu) = -6 \cdot 10^{-3}$

IAM unitarization

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

5.) Suppressing

EWET fermion operators:

a simple model

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

• **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 $M_R \sim 1 - 3$ TeV

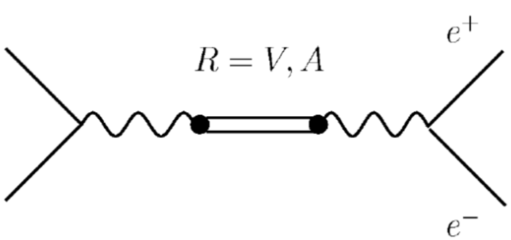
DY → tiny σ even for $M_R \sim 3$ TeV

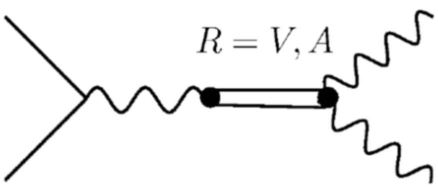
Here, R associated to EWET $a_j \sim 10^{-3}$

S+T allow $M_R \sim 1 - 5$ 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





• 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**

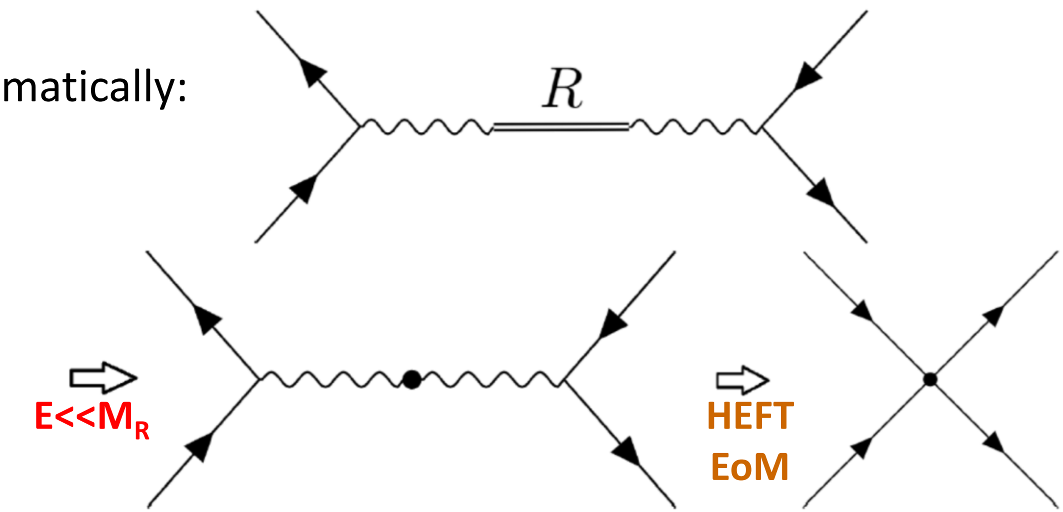
(*) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

- Terms with 6 D_μ from $\mathcal{L}_R$ (x): **O(p⁶) →** $\mathcal{L}_6^{\rm EWET} = -\sum_{R=V,A} 2\langle \nabla^\rho\left(\frac{\chi_{R,\rho\nu}}{M_R^2}\right)\nabla_\mu\left(\frac{\chi_R^{\mu\nu}}{M_R^2}\right)\rangle$

- **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

- **$\mathcal{L}_4$ EFT fermionic operators:** **present** *[O(p^6) suppressed]*

→Usual experimental paramatrization:

$$\mathcal{L}_{EWET} \supset \mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2}\left(\eta_{\ell\ell} J^{\ell}_{\mu} J^{\ell,\mu} + \eta_{rr} J^{r}_{\mu} J^{r,\mu} + 2\eta_{r\ell} J^{r}_{\mu} J^{\ell,\mu}\right)$$

[combinations of $\mathfrak{F}_j^{\psi 4}$ couplings in $\mathcal{L}_4$]

→ Most string bounds (+): $\eta_{\ell\ell} = \eta_{rr} = \eta_{r\ell} = -1 \Longrightarrow \Lambda \gtrsim 20$ TeV.

→ Our prediction:

$$\frac{2\pi}{\Lambda^2} = \frac{1}{M_V^2} \times \frac{4m_Z^4 - 8m_Z^2 m_W^2 + 7m_W^4}{24 v^2 M_V^2} \frac{r^3+1}{r^2(r-1)} \quad \text{where } r = M_A^2/M_V^2$$

$$9.6\cdot 10^{-5}\left(\frac{1\ \text{TeV}^2}{M_V^2}\right)$$

$\Lambda \geq 20$ TeV

$r = M_A^2/M_V^2$	lower bound for M_V
$1+10^{-3}$	1.9 TeV
1.1	0.6 TeV
2	0.3 TeV
∞	0.3 TeV

(+) See, e.g., rev: Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]

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

* Weinberg SR employed: $F_V^2 - F_A^2 - v^2 = 0$ and $F_V^2 M_V^2 - F_A^2 M_A^2 = 0$.

•$\mathcal{L}_4$ **EFT custodial breaking ops:** **present** *[O(p^6) suppressed]*

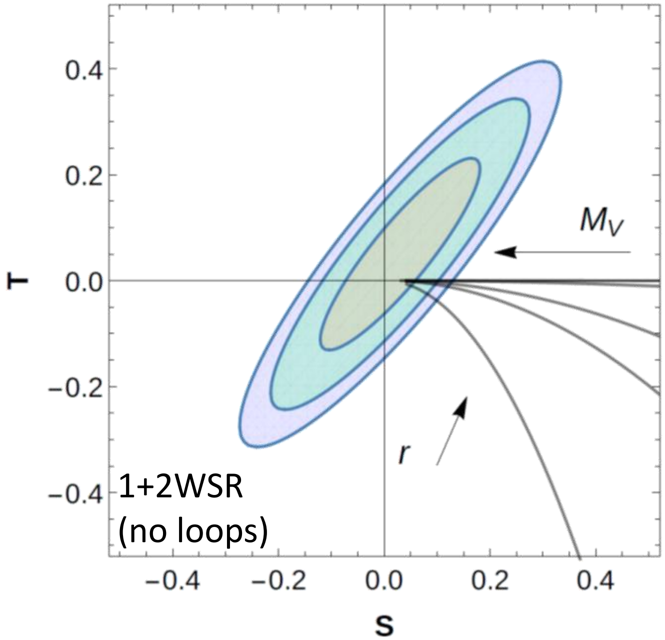
→ Our prediction *[caveat, loops* neglected]*:

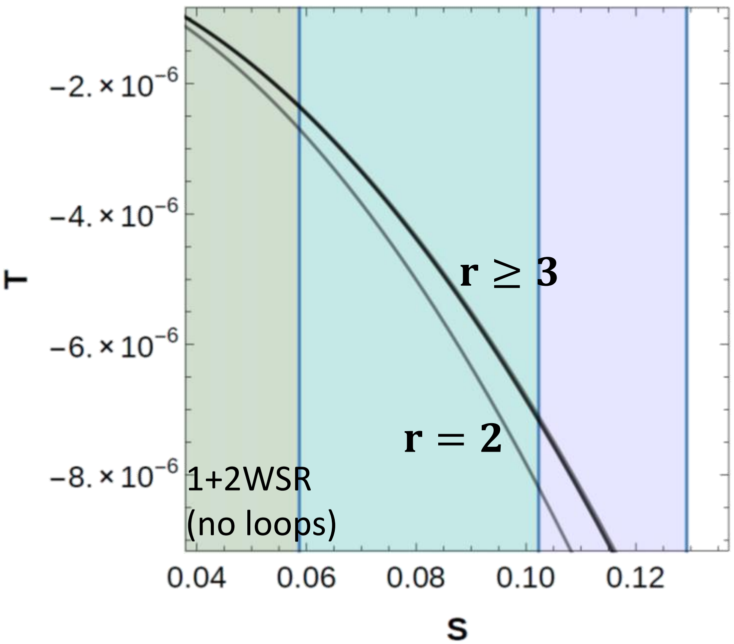
$$S = \frac{4\pi v^2}{M_V^2}\,\frac{r+1}{r},$$

$$T = -\pi\frac{v^2\left(m_Z^2-m_W^2\right)}{M_V^4}\,\frac{m_Z^2}{m_W^2}\,\frac{r^3+1}{r^2(r-1)}.$$

$$-4.5\cdot 10^{-4}\left(\frac{1\,\mathrm{TeV}^4}{M_V^4}\right)$$

$r = M_A^2/M_V^2$	lower bound 68%CL	for M_V 95%CL
$1+10^{-3}$	5.2 TeV	4.0 TeV
1.1	5.1 TeV	3.9 TeV
2	4.5 TeV	3.4 TeV
∞	3.7 TeV	2.8 TeV





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

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

Conclusions

✓ **Optimistic message:**

- *NP can be just around the corner (a few TeV), crouching*
- *Ok with "bosonic" measurements*
- *It just needs a proper $R \to f\bar{f}$ suppression.*
- *A pattern that fits this structure would be:*

✓ **This scenario (helped out by the HEFT & the chiral expansion) solves this issue**

✓ **Resonances with M_R ~ 2 TeV allowed**

- **LHC searches:** R production, WW scat: naturally small *(difficult; long term)*

  4-fermion ops. ("compositeness") *(maybe impossible)*

- **Low-E searches:** deviations in low-E bosonic EW precision observables

  (low E ≤ EW scale) *(maybe better; there's place to exp.improve; long-term)*

BACKUP

Low-energy EFT (SM + …): representations

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

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

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

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

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

? ? ?

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

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

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

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

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 :[*]

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

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

(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).

Scale suppression in the loops

- Observables at 1 loop: previous computations (-)
- 1 loop of h & ωᵃ 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(p⁴) 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

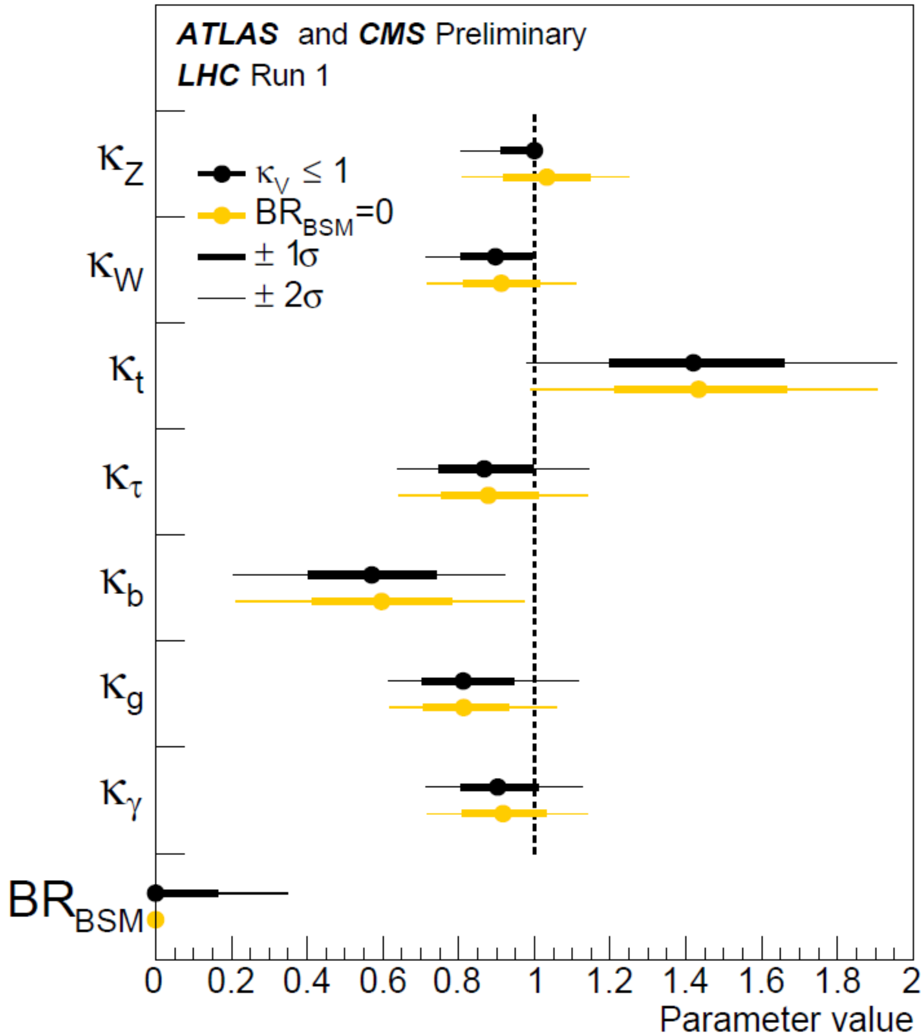
(x) $\mathcal{L}_2$ + $\mathcal{L}_4^{\rm Fer}$ corrected by fermions & gauge boson loops: Du,Guo,Ruiz-Femenía,SC, in preparation.

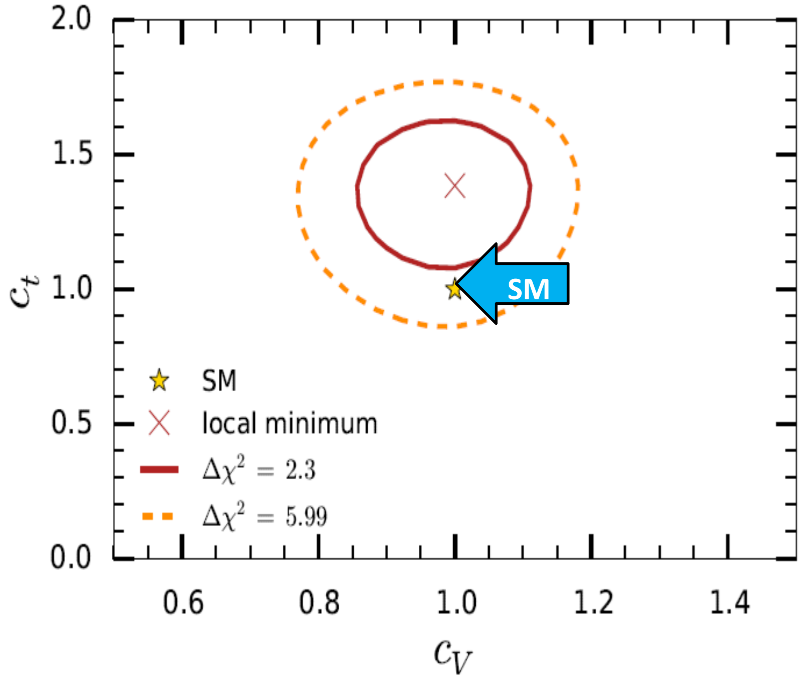
- For instance, P-even bosonic low-energy EFT at $O(p^4)$: *

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

Same operators as in the 1-loop eff. action

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





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

Figure 14: Fit results for the two parameterisations allowing BSM loop couplings, with $\kappa_V \leq 1$, where 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 $\mathrm{BR}_{\mathrm{BSM}} = 0$.

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

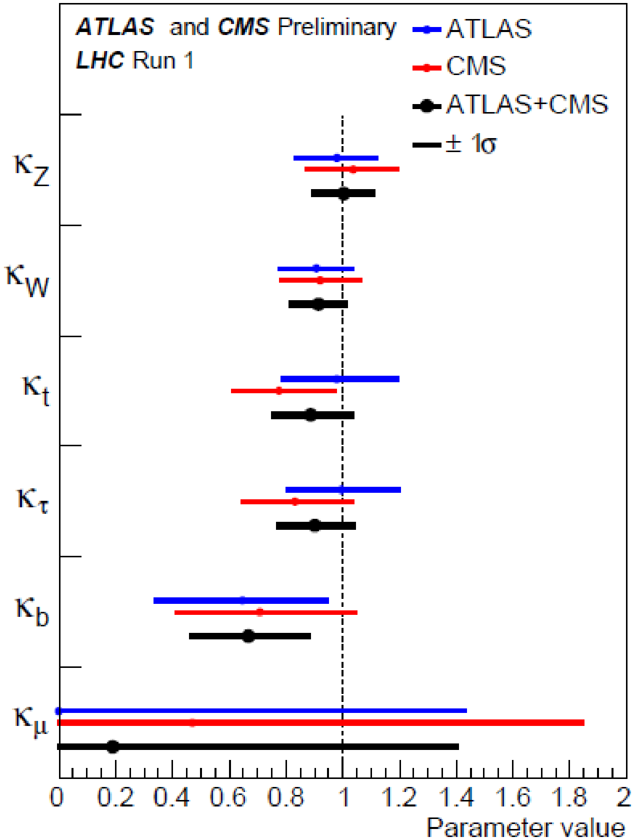
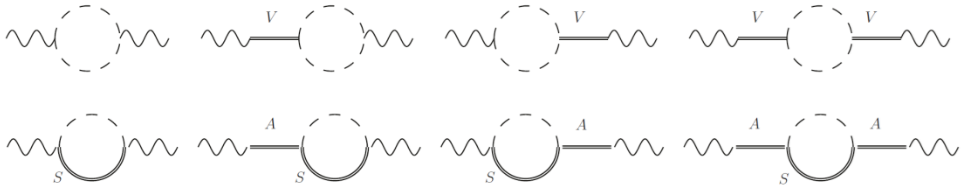


Table 15: Fit results for the parameterisation assuming the absence of BSM particles in the loops, $BR_{BSM} = 0$, and $\kappa_j \geq 0$. The measured results with their measured and expected uncertainties are reported for the combination of ATLAS and CMS, together with the measured results with their 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 $\kappa_j = 0$.

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



V,A resonances + 1-loop + 2 WSRs

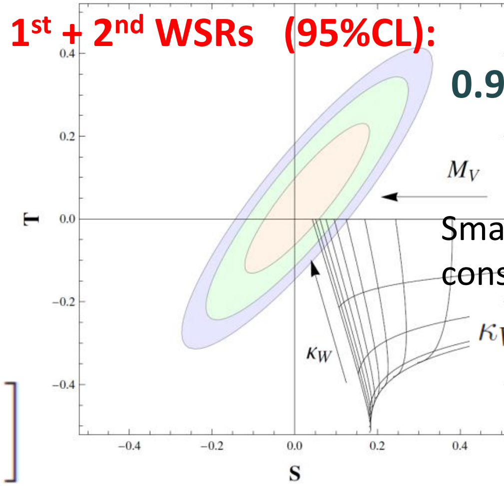
$$\mathrm{S} = -16\pi\Bigg[\underbrace{a_1^r(M_V)}_{\substack{\sim -2\times 10^{-3} \\ \Lambda^{-2}\sim (5\,\mathrm{TeV})^{-2}}} + \underbrace{\frac{a^2-1}{192\pi^2}\left(\ln\frac{M_V^2}{m_h^2}+\frac{5}{6}\right)}_{\substack{\sim -6\times 10^{-5} \\ \Lambda^{-2}\sim (30\,\mathrm{TeV})^{-2}}}\Bigg]$$

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

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

1^{st} + 2^{nd} WSRs (95%CL): $M_V > 4$ TeV

$0.94 < a=\kappa_W < 1$

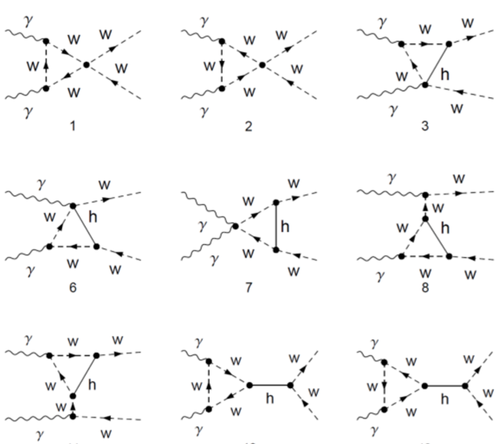


Small splitting due to constraints from WSRs

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

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

(only charged shown here)



+30 more

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

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

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

* 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

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

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

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

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

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

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

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

SUMMARY: NAÏVE `CHIRAL' COUNTING

- "Chiral" counting *

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

and for the building blocks,

$$u(\varphi/v),\, U(\varphi/v),\, \frac{h}{v},\, \frac{W^a_\mu}{v},\, \frac{B_\mu}{v} \sim \mathcal{O}\left(p^0\right),$$

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

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

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

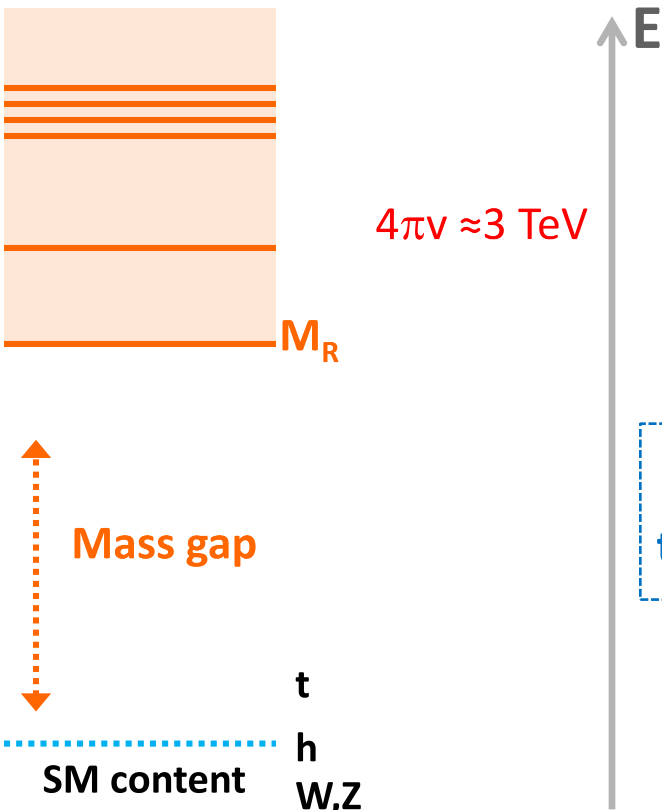
$$\frac{\xi}{v} \sim \mathcal{O}\left(p^{\frac{1}{2}}\right)$$

- 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

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



SM content

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

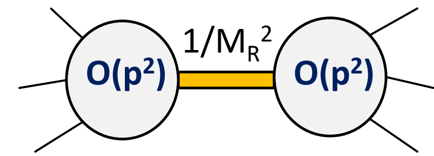
Custodial symmetry
+
Resonance Lagrangian
+
UV completion hypothesis

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



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

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

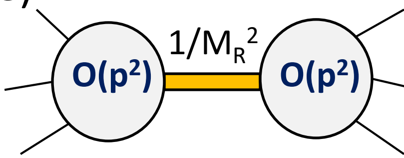
** See also: Alboteanu, Kilian, Reuter, JHEP 0811 (2008) 010; Pappadopulo, Thamm, Torre, Wulzer, JHEP 1409 (2014) 060; Corbett, Joglekar, Li, Yu, [arXiv:1705.02551 [hep-ph]]; Corbett,Éboli,Gonzalez-Garcia,PRD93 (2016) no.1, 015005; Buchalla, Cata, Celis, Krause, NPB917 (2017) 209; de Blas,Criado,Perez-Victoria,Santiago,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

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



(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: $\;{\rm R_{cl}}[\ell{\rm ight}] \;\sim\; \frac{1}{{\rm M_R^2}}\chi_{\rm R}[\ell{\rm ight}] + \mathcal{O}\left(\frac{{\rm p}^4}{{\rm M_R^4}}\right)$

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

- Evaluate $\;\mathcal{L}^{\rm EFT}[\ell{\rm ight}] \;=\; \mathcal{L}^{\rm HE}[{\rm R_{cl}}[\ell{\rm ight}]\,,\,\ell{\rm ight}] \;\sim\; \mathcal{L}_2[\ell{\rm ight}] \;+\; \frac{1}{{\rm M_R^2}}(\chi_{\rm R}[\ell{\rm ight}])^2 \;+\; ...$

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

• The High-E Resonances leave a **specific imprint in the Low-E couplings**: (*)

- Contributions to purely bosonic operators

i	$\Delta\mathcal{F}_i$	$\Delta\widetilde{\mathcal{F}}_i$	i	$\Delta\mathcal{F}_i$
1	$-\frac{F_V^2-\widetilde{F}_V^2}{4M^2_{V^1_3}} + \frac{F_A^2-\widetilde{F}_A^2}{4M^2_{A^1_3}}$	$-\frac{\widetilde{F}_V G_V}{2M^2_{V^1_3}} - \frac{F_A \widetilde{G}_A}{2M^2_{A^1_3}}$	7	$\frac{d_P^2}{2M^2_{P^1_3}} + \frac{\lambda_1^{hA\,2}v^2}{M^2_{A^1_3}} + \frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M^2_{V^1_3}}$
2	$-\frac{F_V^2+\widetilde{F}_V^2}{8M^2_{V^1_3}} - \frac{F_A^2+\widetilde{F}_A^2}{8M^2_{A^1_3}}$	$-\frac{F_V\widetilde{F}_V}{4M^2_{V^1_3}} - \frac{F_A\widetilde{F}_A}{4M^2_{A^1_3}}$	8	0
3	$-\frac{F_V G_V}{2M^2_{V^1_3}} - \frac{\widetilde{F}_A\widetilde{G}_A}{2M^2_{A^1_3}}$	$-\frac{F_V\widetilde{\lambda}_1^{hV}v}{M^2_{V^1_3}} - \frac{\widetilde{F}_A\lambda_1^{hA}v}{M^2_{A^1_3}}$	9	$-\frac{F_A\lambda_1^{hA}v}{M^2_{A^1_3}} - \frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M^2_{V^1_3}}$
4	$\frac{G_V^2}{4M^2_{V^1_3}} + \frac{\widetilde{G}_A^2}{4M^2_{A^1_3}}$	—	10	$-\frac{\widetilde{c}_T^2}{2M^2_{V^1_1}} - \frac{c_T^2}{2M^2_{A^1_1}}$
5	$\frac{c_d^2}{4M^2_{S^1_1}} - \frac{G_V^2}{4M^2_{V^1_3}} - \frac{\widetilde{G}_A^2}{4M^2_{A^1_3}}$	—	11	$-\frac{F_X^2}{M^2_{V^1_1}} - \frac{\widetilde{F}_X^2}{M^2_{A^1_1}}$
6	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M^2_{V^1_3}} - \frac{\lambda_1^{hA\,2}v^2}{M^2_{A^1_3}}$	—	12	$-\frac{(C_G)^2}{2M^2_{V^8_1}} - \frac{(\widetilde{C}_G)^2}{2M^2_{A^8_1}}$

[Relation with Longhitanos's couplings $\mathcal{F}_j = a_j + O(h)$; <u>notice</u>: $a_{j\geq5}$ relabelled]

[Coloured contributions checked, e.g., with Manohar-Wise model (x)]

(*) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092
(x) Manohar,Wise, PRD74 (2006) 035009

• The High-E Resonances leave a **specific imprint in the Low-E couplings**: (*)

- Contributions to ψ^2 and ψ^4 operators

i	$\Delta\mathcal{F}_i^{\psi^2}$	i	$\Delta\mathcal{F}_i^{\psi^2}$
1	$\frac{c_d c^{S_1^1}}{2M^2_{S_1^1}} + \frac{\widetilde{\lambda}_1^2 - \lambda_1^2}{2M_\Psi}$	5	$\frac{d_P c^{P_3^1}}{M^2_{P_3^1}} + \frac{2(\lambda_1\lambda_2 - \widetilde{\lambda}_1\widetilde{\lambda}_2)}{M_\Psi}$
2	$-\frac{G_V C_0^{V_3^1}}{\sqrt{2}M^2_{V_3^1}} - \frac{\widetilde{G}_A \widetilde{C}_0^{A_3^1}}{\sqrt{2}M^2_{A_3^1}} - \frac{\widetilde{\lambda}_1^2 - \lambda_1^2}{2M_\Psi}$	6	$-\frac{\widetilde{c}_T \widetilde{c}^{\hat{V}_1^1}}{\sqrt{2}M^2_{V_1^1}} - \frac{c_T c^{\hat{A}_1^1}}{\sqrt{2}M^2_{A_1^1}} + \frac{(\lambda_0\lambda_1 + \widetilde{\lambda}_0\widetilde{\lambda}_1)}{M_\Psi}$
3	$-\frac{F_V C_0^{V_3^1}}{\sqrt{2}M^2_{V_3^1}} - \frac{\widetilde{F}_A \widetilde{C}_0^{A_3^1}}{\sqrt{2}M^2_{A_3^1}}$	7	$\frac{\lambda_2^2 - \widetilde{\lambda}_2^2}{M_\Psi}$
4	$-\frac{\sqrt{2}F_X C_0^{V_1^1}}{M^2_{V_1^1}} - \frac{\sqrt{2}\widetilde{F}_X \widetilde{C}_0^{A_1^1}}{M^2_{A_1^1}}$	8	$-\frac{C_G C_0^{V_1^8}}{\sqrt{2}M^2_{V_1^8}} - \frac{\widetilde{C}_G \widetilde{C}_0^{A_1^8}}{\sqrt{2}M^2_{A_1^8}}$

+ ψ^4 ops. (more tedious)

E.g., in particular, the lowest order Fermion R contribution has the form:

$$\Delta\mathcal{L}_\Psi^{\mathcal{O}(p^4)} = \frac{1}{M_\Psi}\overline{\chi}_\Psi\,\chi_\Psi = \frac{g'^2(\lambda_0^2 - \widetilde{\lambda}_0^2)}{4M_\Psi}\bar{\xi}\xi + \sum_{j=1,2,5,6,7}\Delta\mathcal{F}_j^{\psi^2}\mathcal{O}_j^{\psi^2} + \sum_{j=2,3}\Delta\widetilde{\mathcal{F}}_j^{\psi^2}\widetilde{\mathcal{O}}_j^{\psi^2}$$

with $\chi_\Psi = u_\mu\gamma^\mu(\lambda_1\gamma_5 + \widetilde{\lambda}_1)\xi - i\frac{(\partial_\mu h)}{v}\gamma^\mu(\lambda_2 + \widetilde{\lambda}_2\gamma_5)\xi + (\lambda_0 + \widetilde{\lambda}_0\gamma_5)\mathcal{T}\xi$

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

- Light fermion operators $O_j^{\psi 4}$:

$$|\mathcal{F}_j^{\psi^4}| = 2\pi/\Lambda^2$$

1. From dijet production.-
   - $\Lambda \geq 21.8$ TeV from ATLAS [63],
   - $\Lambda \geq 18.6$ TeV from CMS [64],
   - $\Lambda \geq 16.2$ TeV from LEP [67].

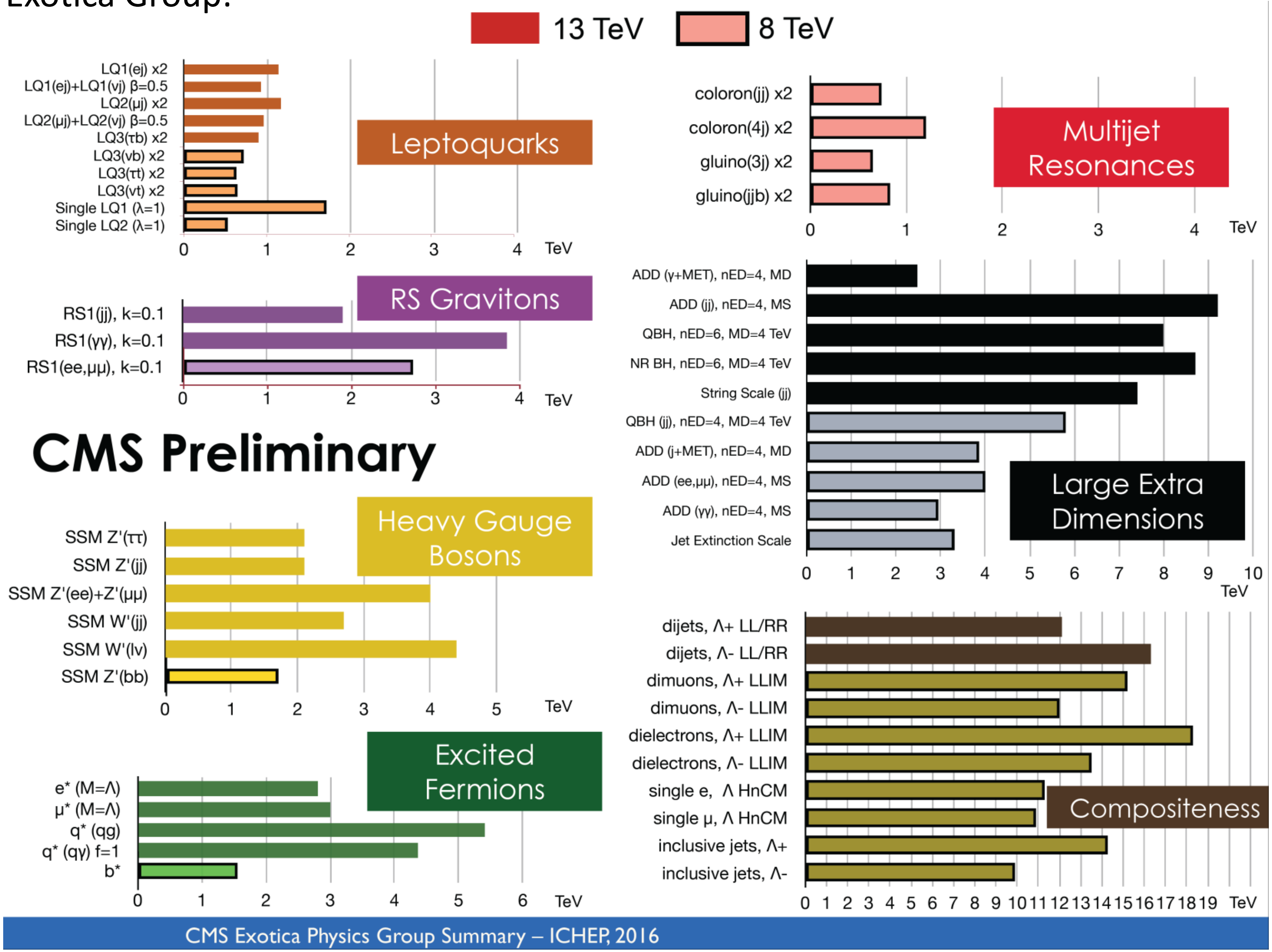
2. From dilepton production.-
   - $\Lambda \geq 26.3$ TeV from ATLAS [65],
   - $\Lambda \geq 19.0$ TeV from CMS [66],
   - $\Lambda \geq 24.6$ TeV from LEP [67].

- 3rd generation operators $O_j^{\psi 4}$:

1. From high-energy collider studies.-
   - $\Lambda \geq 1.5$ **TeV from multi-top production at LHC and Tevatron [69],**
   - $\Lambda \geq 2.3$ **TeV from t and $t\bar{t}$ production at LHC and Tevatron [70],**
   - $\Lambda \geq 4.7$ **TeV from dilepton production at LHC [71].**

2. From low-energy studies.-
   - $\Lambda \geq 14.5$ **TeV from $B_s - \overline{B}_s$ mixing [72],**
   - $\Lambda \geq 3.3$ **TeV from semileptonic B decays [73].**

• CMS Exotica Group:



• https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

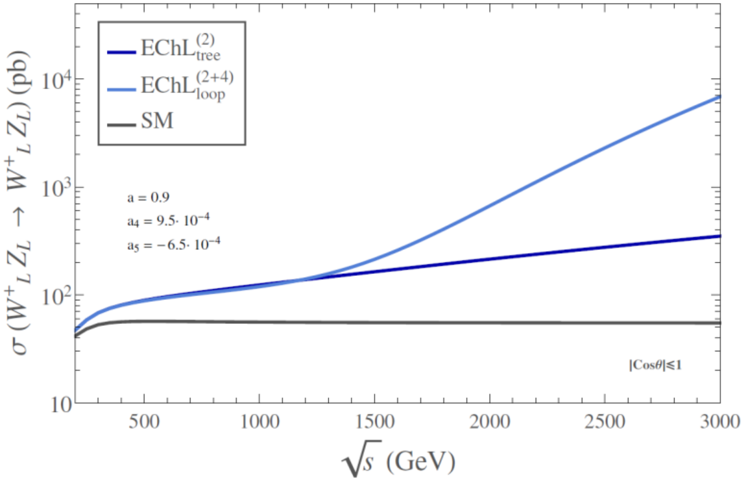
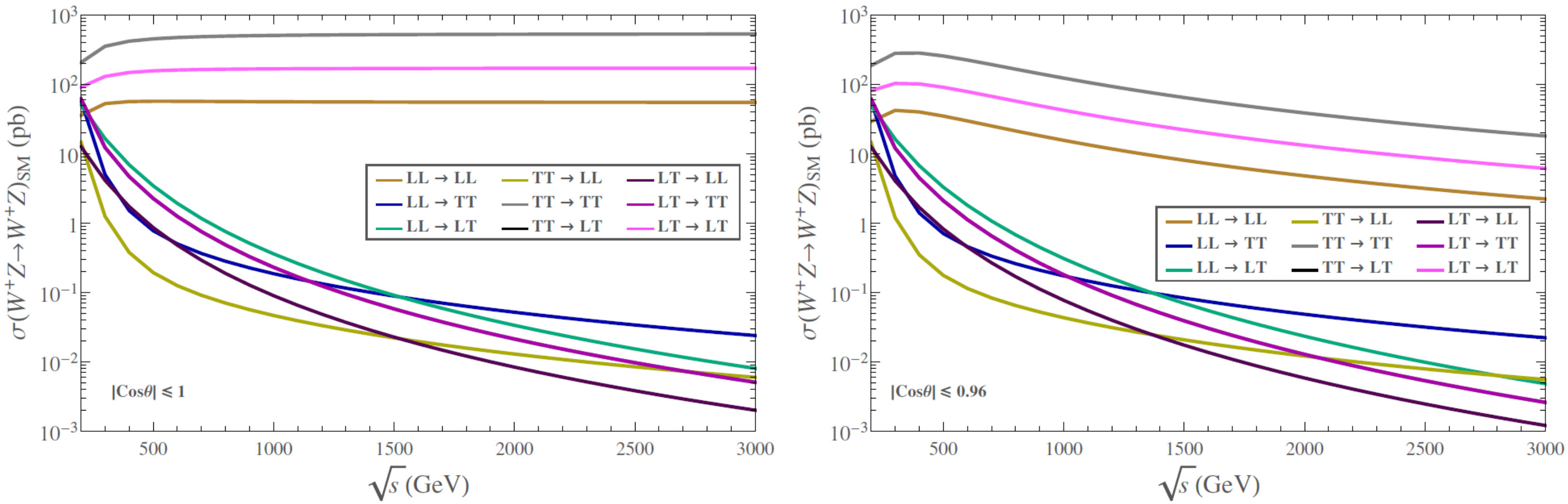


Figure 2. Predictions of the cross section $\sigma(W_L Z_L \to W_L Z_L)$ as a function of the center of mass energy $\sqrt{s}$ from the EChL. The predictions at leading order, $\mathrm{EChL}^{(2)}_{\mathrm{tree}}$, and next to leading order, $\mathrm{EChL}^{(2+4)}_{\mathrm{loop}}$, are displayed separately. The EChL coefficients are set here to $a = 0.9$, $b = a^2$, $a_4 = 9.5 \times 10^{-4}$ and $a_5 = -6.5 \times 10^{-4}$. Here the integration is done in the whole $|\cos\theta| \leq 1$ interval of the centre of mass scattering angle θ. The prediction of the SM cross section is also included, for comparison. All predictions have been obtained using FormCalc and our private Mathematica code and checked with MadGraph5.

- Hyearchies in the SM for the subprocess WZ→ WZ:

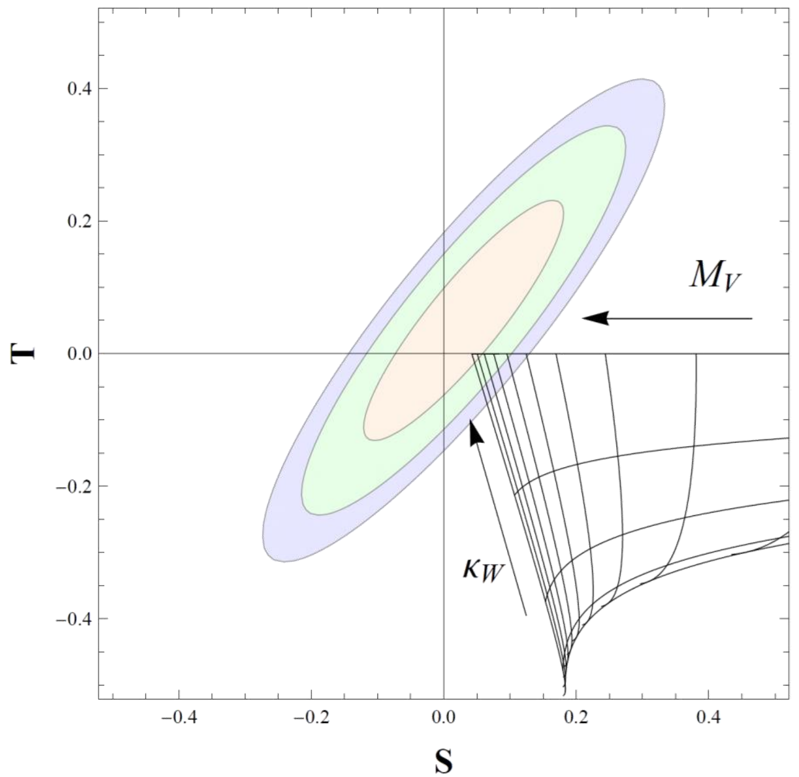


$$c_{\rm eff}^2 \;\equiv\; (c^{\hat{V}_3^1})^2 + (\widetilde{c}^{\hat{V}_3^1})^2 + \frac{1}{2}(C_0^{V_3^1})^2 \;=\; \frac{24\pi}{N_C}\,\frac{\gamma_{q\bar{q}}}{\mathcal{B}_{V^0\to\rm dibos.}} \;\geq\; \frac{24\pi}{N_C}\,\gamma_{q\bar{q}} \;\equiv\; (c_{\rm eff}^{\rm bound})^2$$

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

NLO results: 1st and 2nd WSRs

(*asymptotically-free theories*)



[Pich,Rosell,SC '12]

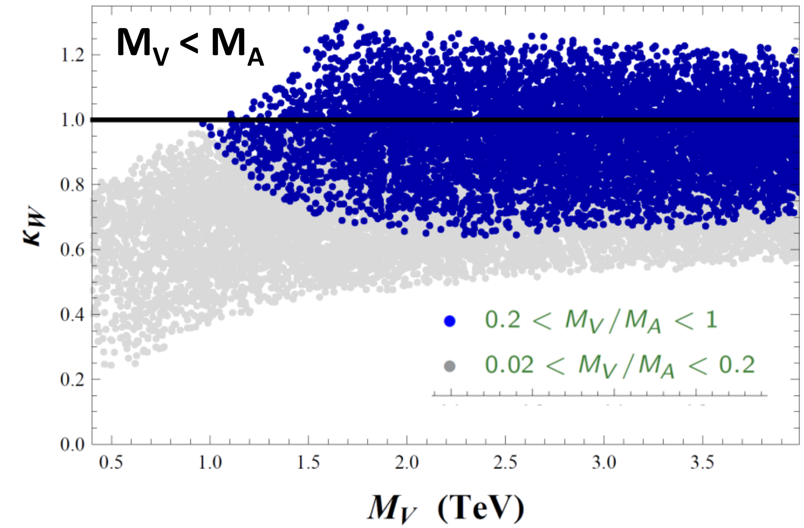
At NLO with the 1st and 2nd WSRs

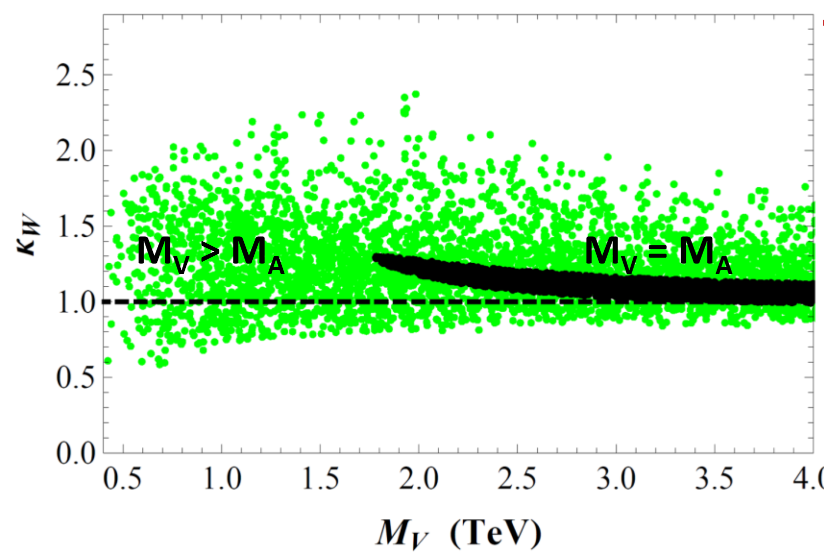
$M_V > 5.4$ TeV, $0.97 < \kappa_W < 1$ at 68% CL

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

NLO results: only 1st WSR

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





[Pich,Rosell,SC '12]

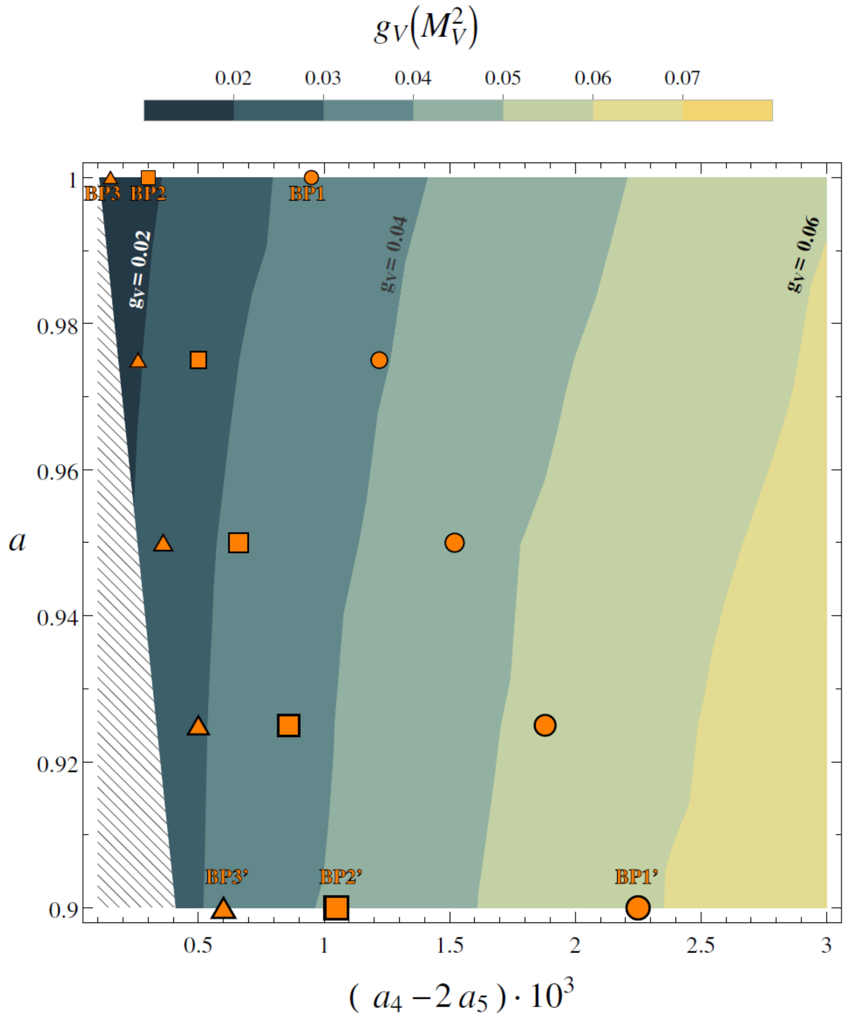


Figure 6. Predictions of $g_V(M_V^2)$ as a function of a and $(a_4 - 2a_5)$ computed from eq. (4.10), as discussed in the text. The benchmark points specified with geometric symbols correspond respectively to those in figure 4.

• $W_L Z_L \to W_L Z_L$ PWA unitarization: Inverse Amplitude Method (**IAM**)

1) PWA elastic unitarity:

$$\mathrm{Im}\{\mathcal{M}_{\mathbf{IJ}}(\mathrm{s})\} = \sigma(\mathrm{s})|\mathcal{M}_{\mathbf{IJ}}(\mathrm{s})|^2 \qquad \longrightarrow \qquad \mathrm{Im}\{\mathcal{M}_{\mathbf{IJ}}(\mathrm{s})^{-1}\} = -\sigma(\mathrm{s})$$

2) Low-E matching to HEFT up to NLO, $\mathcal{M}_{IJ}(s) = \mathcal{M}_{IJ}^{(0)}(s) + \mathcal{M}_{IJ}^{(1)}(s) + \ldots$

$$\mathcal{M}_{\mathbf{IJ}}(\mathrm{s})^{-1} = \mathrm{Re}\{\mathcal{M}_{\mathbf{IJ}}(\mathrm{s})^{-1}\} - \mathrm{i}\sigma(\mathrm{s}) \quad \xrightarrow{\text{NLO matching to HEFT}} \quad \mathcal{M}_{\mathbf{IJ}}(\mathrm{s})^{-1} = \frac{\mathcal{M}_{\mathbf{IJ}}^{(0)}(\mathrm{s}) - \mathcal{M}_{\mathbf{IJ}}^{(1)}(\mathrm{s})}{\mathcal{M}_{\mathbf{IJ}}^{(0)}(\mathrm{s})^2}$$

$$\mathcal{M}_{\mathbf{IJ}}^{\mathbf{IAM}} = \frac{\mathcal{M}_{\mathbf{IJ}}^{(0)}(\mathrm{s})^2}{\mathcal{M}_{\mathbf{IJ}}^{(0)}(\mathrm{s}) - \mathcal{M}_{\mathbf{IJ}}^{(1)}(\mathrm{s})}$$

See, e.g., (and refs therein): classical Works,
(x) Truong, PRL 61 (1988) 2526
(x) Dobado,Herrero,Truong, PLB 235 (1990) 134
(x) Dobado,Pelaez, PRD 47 (1993) 4883
(x) T. Hannah, PRD 51 (1995) 103
(x) Dobado,Herrero,Truong, PLB 235 (1990) 129
and more recent,
(x) Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP 11 (2017) 098
(x) Espriu,Mescia, PRD 90 (2014) no.1, 015035; Espriu,Mescia,Yencho,PRD 88 (2013) 055002
(x) Delgado,Dobado,Llanes-Estrada, JPG 41 (2014) 025002; JHEP 1402 (2014) 121; PRL 114 (2015) no.22, 221803; PRD 91 (2015) no.7, 075017
(x) Buarque Franzosi,Ferrarese, PRD 96 (2017) no.5, 055037
(+) For alternative unitarizations, e.g., K-matrix, see D. Zeppenfeld and Reuter's talk; Perez,Sekulla,Zeppenfeld, EPJC 78 (2018) no.9, 759; Kilian,Ohl,Reuter,Sekulla, PRD 93 (2016) no.3, 036004; Brass,Fleper,Kilian,Reuter,Sekulla, arXiv:1807.02512 [hep-ph]

- **HEFT+R Lagrangian used to implement IAM*** ➔ IAM-MC ufo ➔ MG5_aMC

$$\mathcal{L}_2 = -\frac{1}{2g^2}\mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right) - \frac{1}{2g'^2}\mathrm{Tr}\left(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right) + \frac{v^2}{4}\left[1 + 2a\frac{H}{v} + b\frac{H^2}{v^2}\right]\mathrm{Tr}\left(D^\mu U^\dagger D_\mu U\right) + \frac{1}{2}\partial^\mu H\,\partial_\mu H + \dots,$$

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

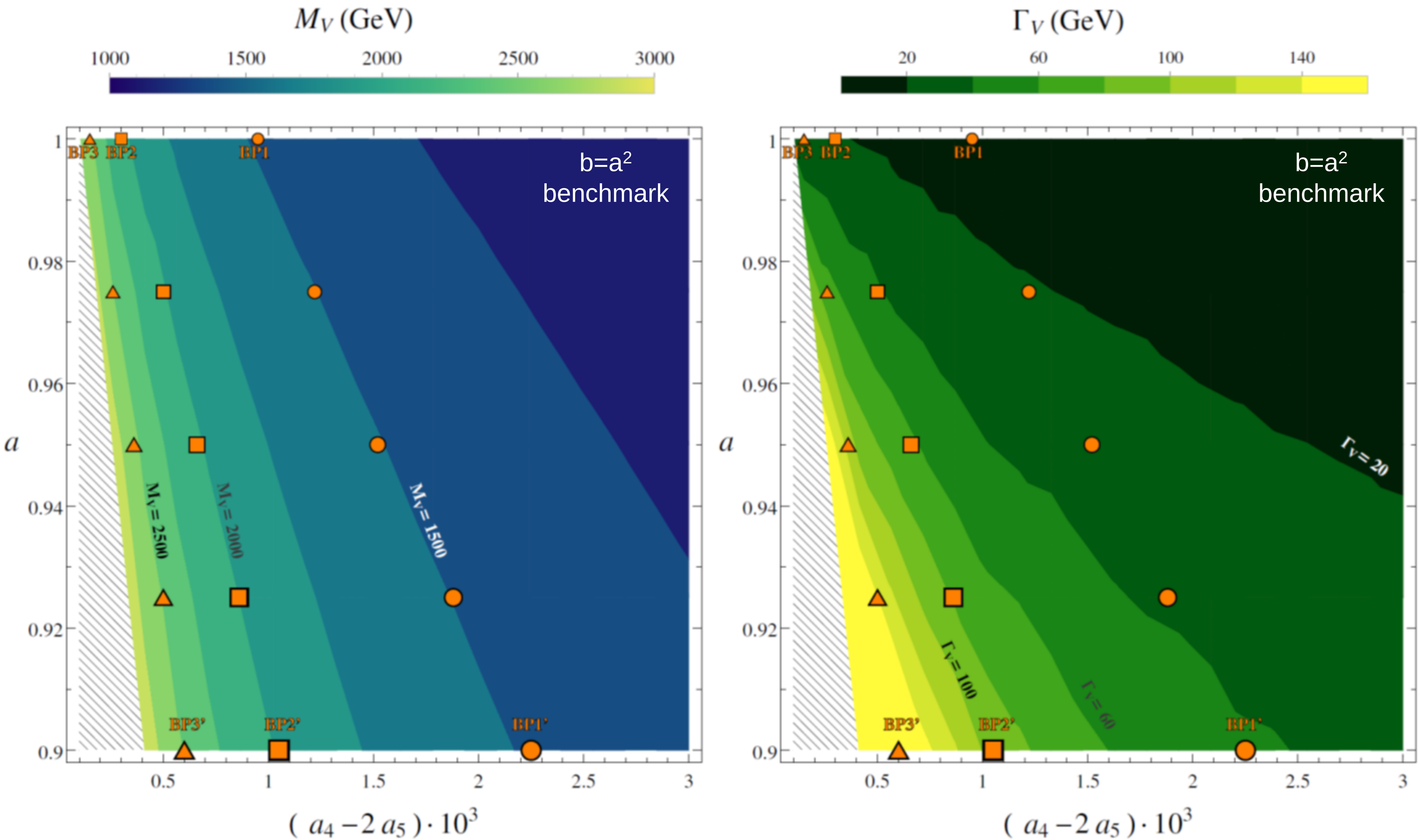
Suppressed at high-E

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

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

(x) Ecker,Gasser,Leutwyler,Pich,de Rafael, PLB 223 (1989) 425-432
(x) Barbieri,Isidori,Rychkov,Trincherini, PRD 78 (2008) 036012
(x) D'Ambrosio,Espriu, PLB 638 (2006) 487
(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

• $W_L Z_L \rightarrow W_L Z_L$ IAM unitarization ➔ Resonance pole generated at $s_{pole} = (M_V - i\Gamma_V/2)^2$



• Analytical expressions in the Equiv.Theor. Limit:

[although $W_L Z_L \rightarrow W_L Z_L$ in our analysis!!!]

$$(M_V^2)_{\rm ET} = \frac{1152\pi^2 v^2(1-a^2)}{8(1-a^2)^2 - 75(a^2-b)^2 + 4608\pi^2(a_4(\mu) - 2a_5(\mu))},$$

$$(\Gamma_V)_{\rm ET} = \frac{(1-a^2)}{96\pi v^2} M_V^3 \left[1 + \frac{(a^2-b)^2}{32\pi^2 v^2(1-a^2)} M_V^2\right]^{-1},$$

- IAM-MC model for $A(W_L Z_L \to W_L Z_L)$:

Benchmark $b=a^2$, $f_v=0$

$$\left|a_{11}^{\mathrm{EChL}^{(2)}_{\mathrm{tree}}+\mathcal{L}_V}(s=M_V^2)\right| = \left|a_{11}^{\mathrm{IAM}}(s=M_V^2)\right|$$

(a, a_4, a_5) ⟶

(M_V, Γ_V) in MG5_aMC from IAM pole

$g_V = g_V(M_V^2)$

• 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)

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

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

In summary, we follow the subsequent steps to get $A(W_L Z_L \to W_L Z_L)_{\rm IAM-MC}$ for each of the given (a, a_4, a_5) input values:

1) Compute the amplitude from the tree level diagrams with the Feynman rules from $\mathcal{L}_2 + \mathcal{L}_V$. This gives a result in terms of a, M_V, g_V and Γ_V.

2) For the given values of (a, a_4, a_5), then set M_V and Γ_V to the corresponding values found from the poles of $a_{11}^{\rm IAM}$.

3) Extract the value of $g_V(M_V^2)$ by solving numerically eq. (4.10).

4) Substitute g_V by $g_V(s)$ in the s-channel and by $g_V(u)$ in the u-channel (for the process of study, $WZ \to WZ$, the charged vector resonance only propagates in these two channels) and use eqs. (4.12) and (4.13).

5) Above the resonance we assume that the deviations with respect to the SM come dominantly from $\mathcal{L}_V$, which means in practice that the proper Lagrangian for the computation of the IAM simulated amplitude is $\mathcal{L}_{\rm SM} + \mathcal{L}_V$ rather than $\mathcal{L}_2 + \mathcal{L}_V$. This is obviously equivalent to use $\mathcal{L}_2 + \mathcal{L}_V$ with $a = 1$ at energies above the resonance.

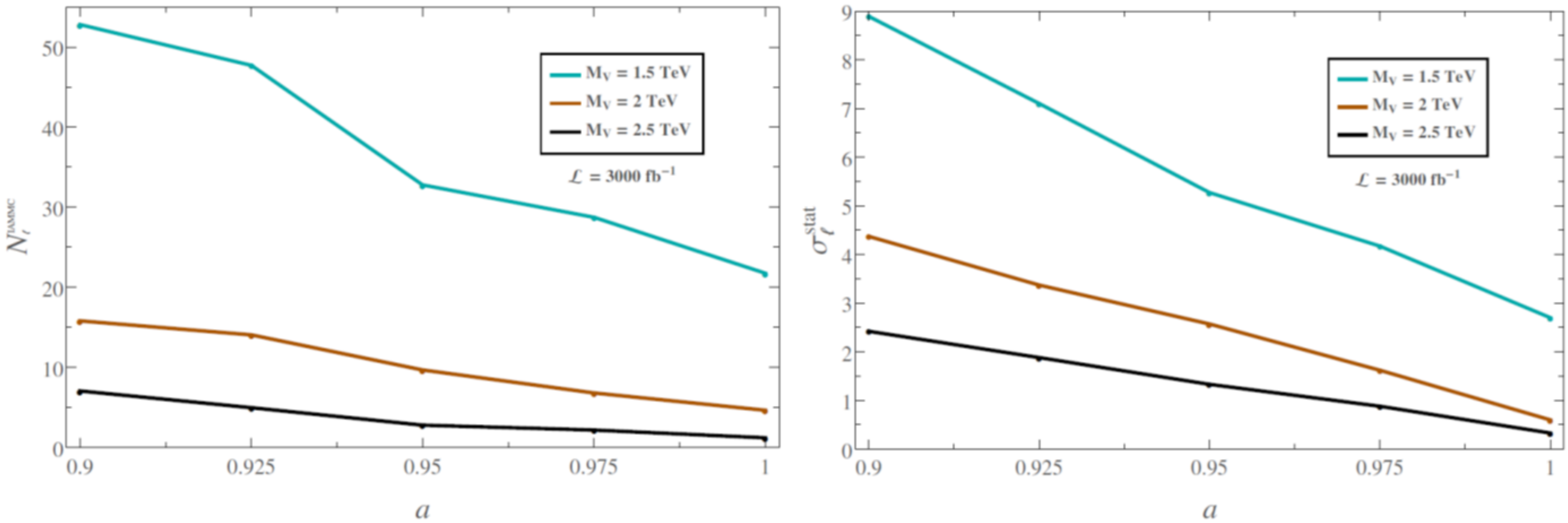
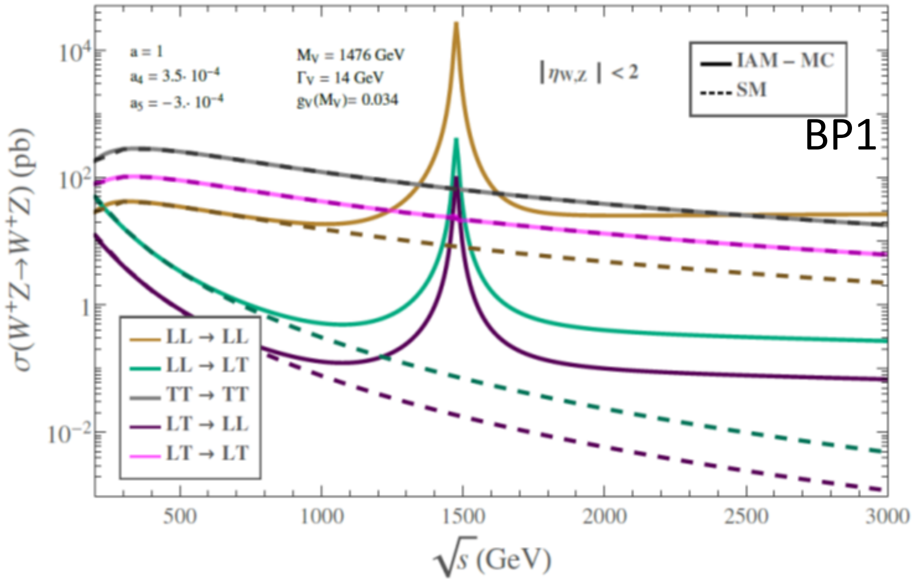
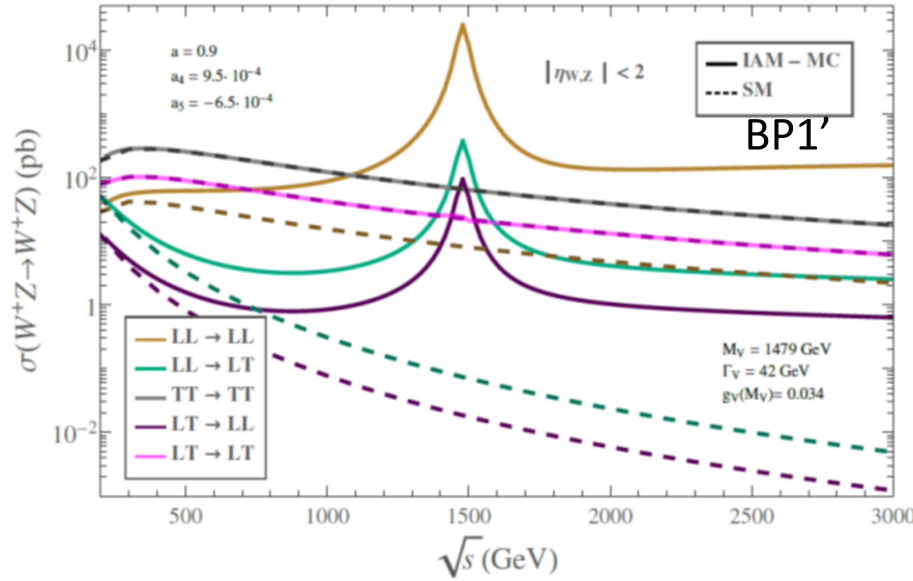


Figure 17. Predictions for the number of $pp \to \ell_1^+ \ell_1^- \ell_2^+ \nu jj$ events, $\mathrm{N}_\ell^{\mathrm{IAM-MC}}$, (left panel) and the statistical significance, $\sigma_\ell^{\mathrm{stat}}$, (right panel) as a function of the parameter a for $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$. Marked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

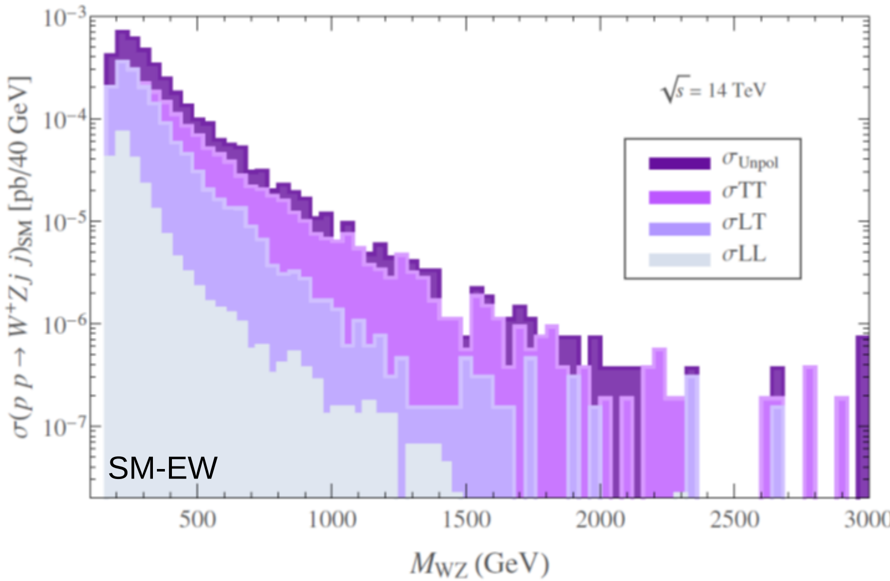
• WZ→WZ subprocess: polarizations (in the WZ rest frame)

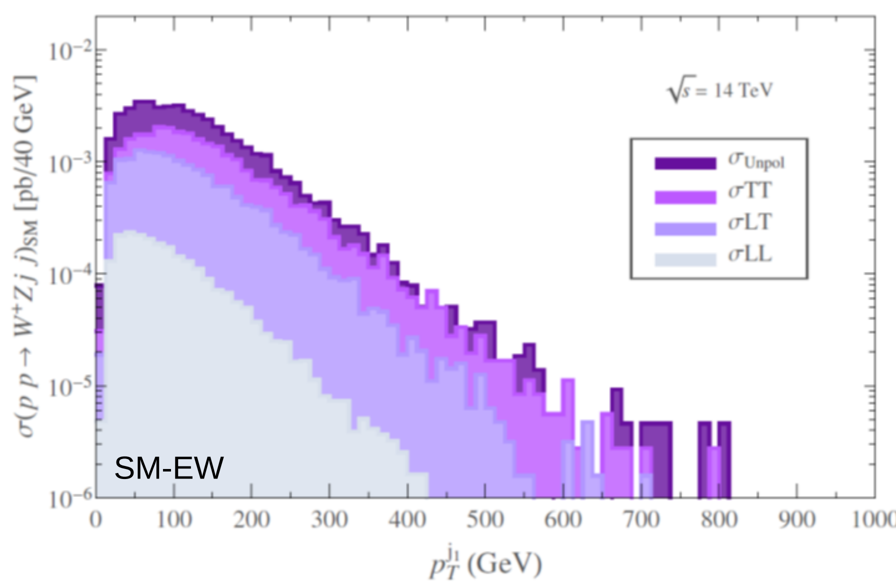
$\sigma(LL \to LL) \gg \sigma(LL \to LT) > \sigma(LT \to LL) > \sigma(TT \to TT) > \sigma(LT \to LT)$



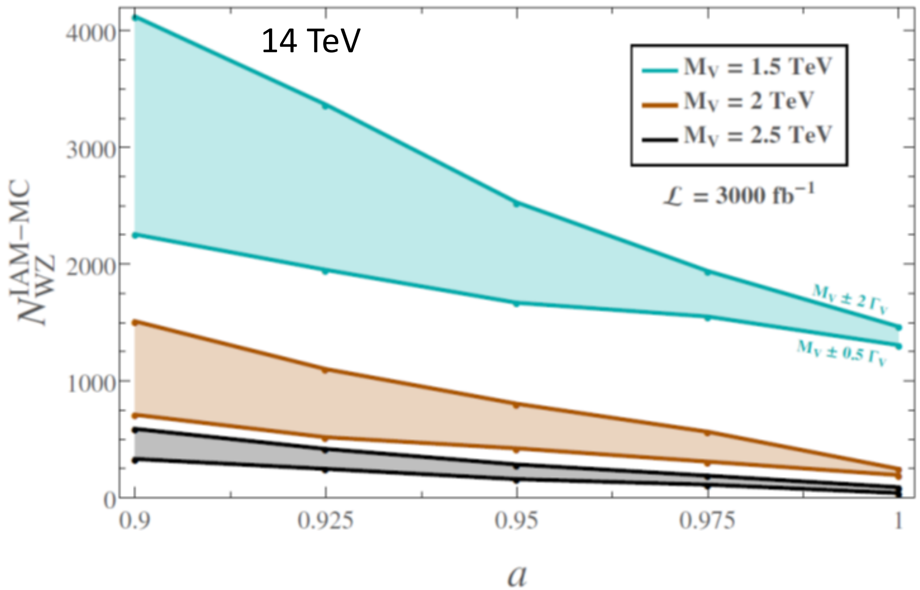


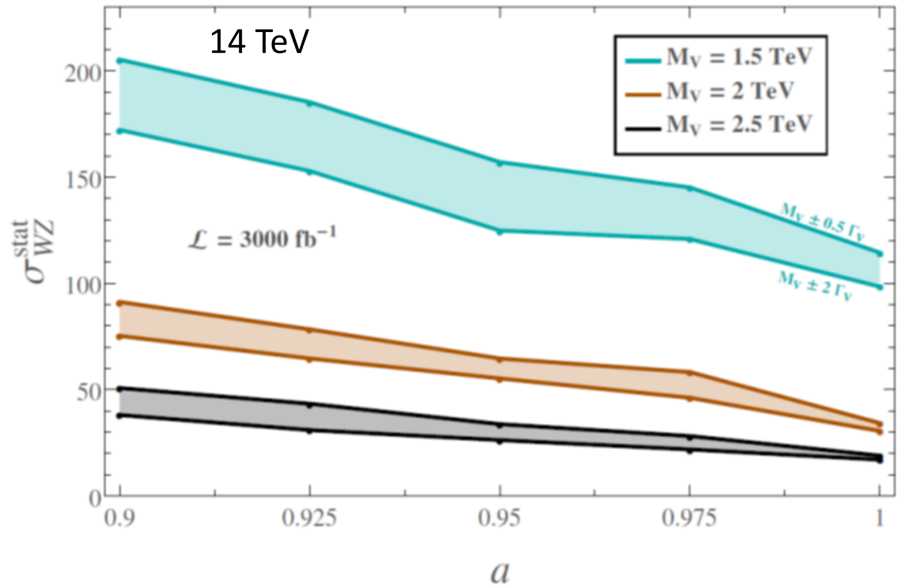
• pp→jjWZ at LHC: SM backgrounds and polarizations (in the WZ rest frame)



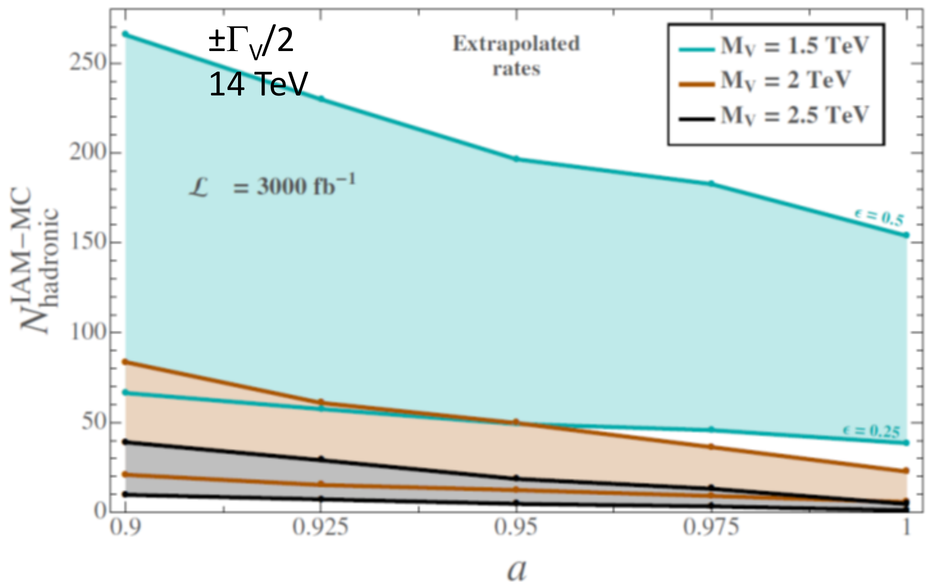


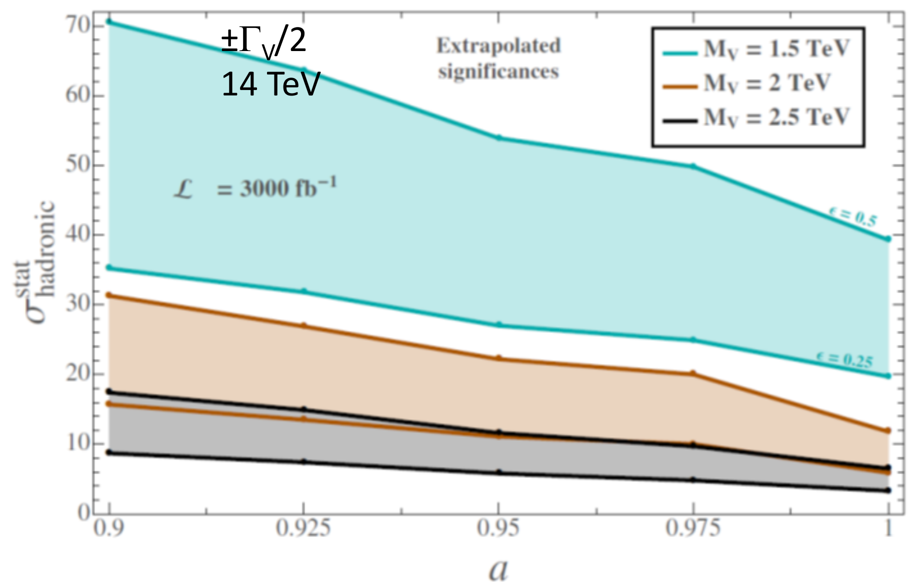
• Sensitivity with 100% WZ efficiency reconstruction:





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





- IAM-MC model for $A(W_L Z_L \to W_L Z_L)$:

Benchmark $b=a^2$, $f_v=0$

$$\left| a_{11}^{\mathrm{EChL}^{(2)}_{\mathrm{tree}}+\mathcal{L}_V}(s=M_V^2)\right| = \left| a_{11}^{\mathrm{IAM}}(s=M_V^2)\right|$$

(a, a_4, a_5) ⟶

(M_V, Γ_V) in MG5_aMC from IAM pole

$$g_V = g_V(M_V^2)$$

- Requirements: $g_V(s)$

*Recovery of $\mathrm{EChL}^{(2+4)}_{\mathrm{loop}}$ at low-E

* Froissart bound $\sigma(s) \le \sigma_0 \log^2\left(\frac{s}{s_0}\right)$

To avoid a moderate violation of unitarity ➔

$$g_V^2(s) = g_V^2(M_V^2)\frac{M_V^2}{s} \quad \text{for } s < M_V^2$$

$$g_V^2(s) = g_V^2(M_V^2)\frac{M_V^4}{s^2} \quad \text{for } s > M_V^2$$

with z=s

$$g_V^2(z) = g_V^2(M_V^2)\frac{M_V^2}{z} \quad \text{for } s < M_V^2$$

$$g_V^2(z) = g_V^2(M_V^2)\frac{M_V^4}{z^2} \quad \text{for } s > M_V^2$$

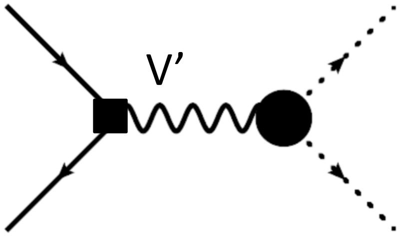
with $z = t, u$

[although crossing partially lost]

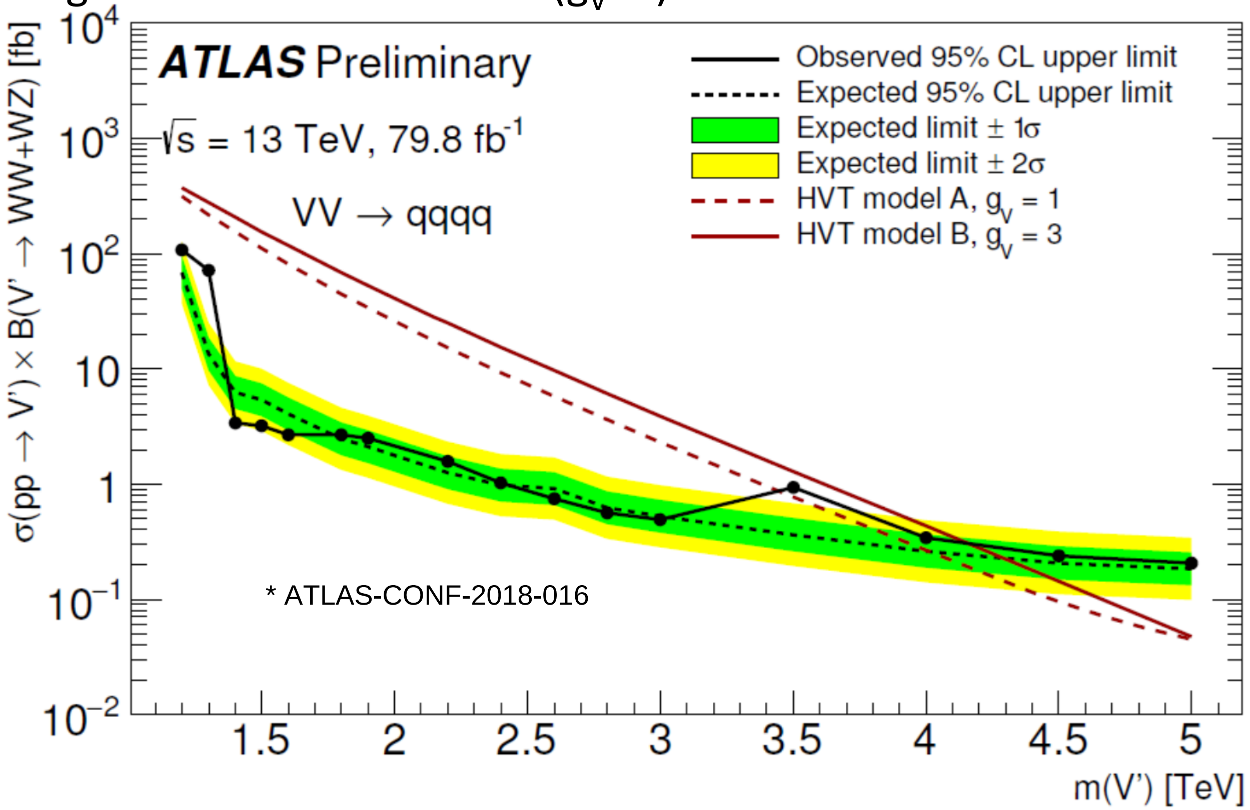
- HVT diboson searches: in practice, **DY dominated**

,

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



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

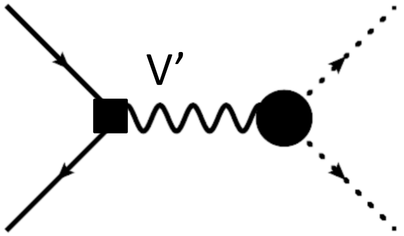


(a) HVT $V' \to WW + WZ$

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

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

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

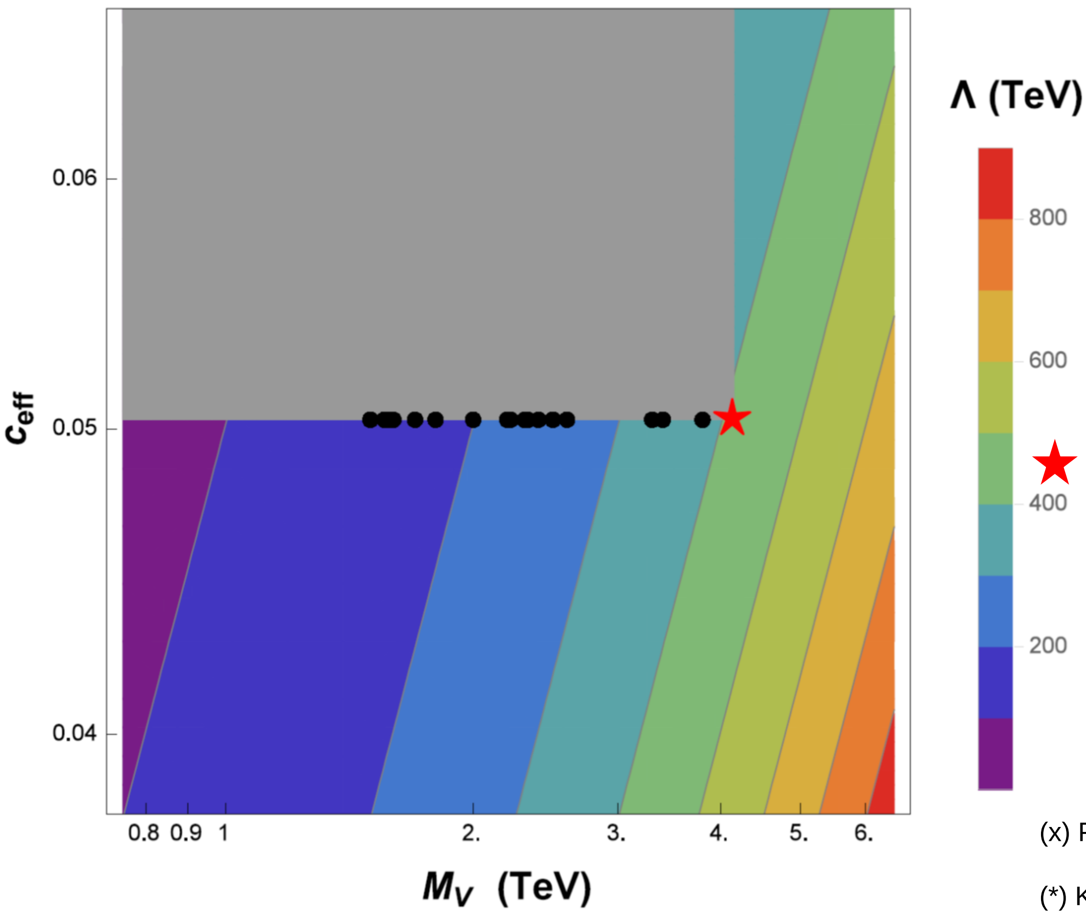


- Strongest bounds from HVT-B (g_V=3) [(x)]

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

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

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



★ → Λ = 410 TeV

(a reanalysis for several $\gamma_{q\bar q}$ is advised, to enlarge the exclusión región)

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

(*) Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

Unitarized HEFT parametrizations of the axial form factor

a Analiticity in the complex s plane, featuring just a right cut for physical s. (We already know empirically that there are no bound state poles below threshold in the 100-GeV spectrum).

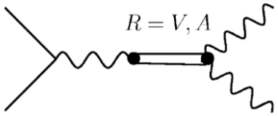
b Coincidence of any resonance poles (in the second Riemann sheet) with those of the elastic amplitude $M_{11}(s)$.

c Elastic unitarity.

d Low-energy behavior that reproduces the chiral expansion $\mathcal{F}_A(s) = \mathcal{F}_A^{(0)}(s) + \mathcal{F}_A^{(1)}(s) + O(s^2/v^4)$.

$$\mathcal{F}_A(s) = 1 + \frac{s}{M_A^2 - iM_A\Gamma_A - s}. \qquad \text{(Model I)}$$ **b) & d)**

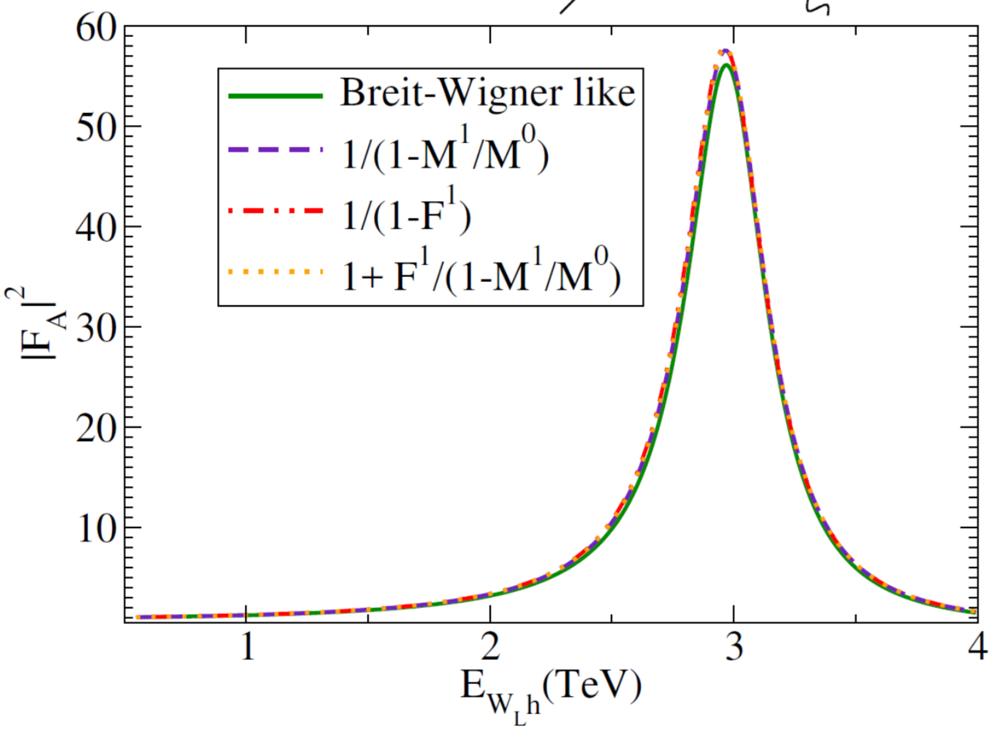
(x) Analogous to WW prod. in DY:
Cata,Isidori,Kamenik, NPB 822 (2009) 230-244



$$\mathcal{F}_A(s) = \frac{(\mathcal{F}_A^{(0)}(s))^2}{\mathcal{F}_A^{(0)}(s) - \mathcal{F}_A^{(1)}(s)} = 1 + \frac{\mathcal{F}_A^{(1)}(s)}{1 - \mathcal{F}_A^{(1)}(s)} = \frac{1}{1 - \mathcal{F}_A^{(1)}(s)}, \qquad \text{(Model II)}$$ **a) & d)**

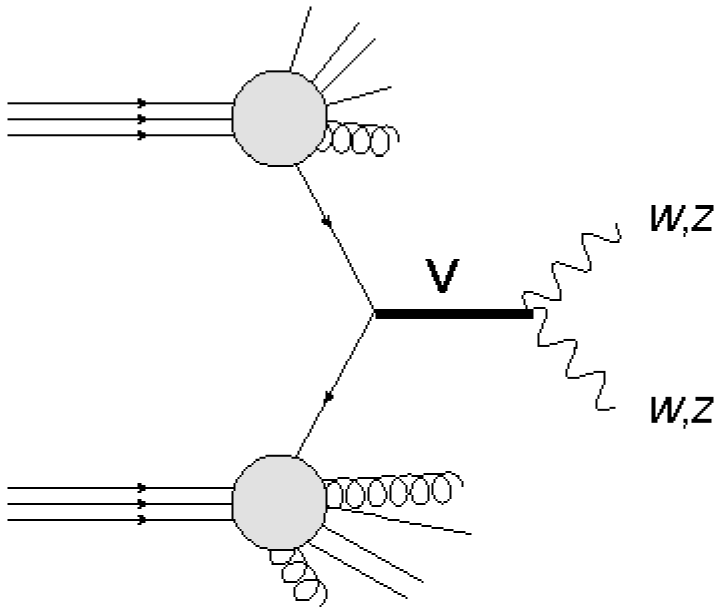
$$\mathcal{F}_A(s) = 1 + \frac{M_{11}^{(1)}(s)}{M_{11}^{(0)}(s) - M_{11}^{(1)}(s)} = \frac{1}{1 - \frac{M_{11}^{(1)}(s)}{M_{11}^{(0)}(s)}}, \qquad \text{(Model III)}$$ **b) & c)**

$$\mathcal{F}_A(s) = 1 + \frac{\mathcal{F}_A^{(1)}(s) M_{11}^{(0)}(s)}{M_{11}^{(0)}(s) - M_{11}^{(1)}(s)}. \qquad \text{(Model IV)}$$ **b), c) & d)**



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

• **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]

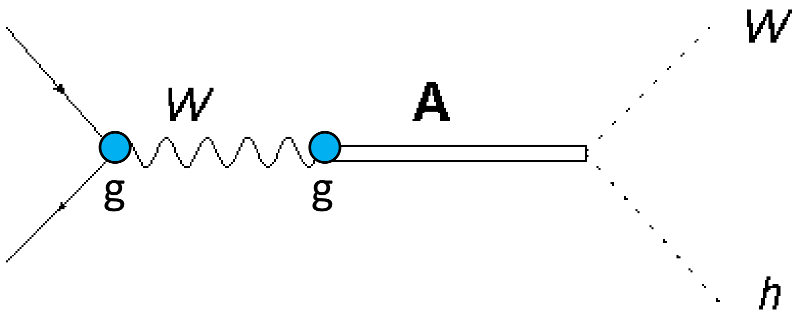
$$\hat{\sigma}(u\overline{d} \to W^+ h) = a^2 \frac{\pi}{48 s} \frac{\alpha^2}{s_W^4} \mid \mathcal{F}_A(s) \mid^2$$

$$\frac{d\sigma}{ds}(pp \to W_L^+ h + X) = \int_{\frac{s}{E_{\rm tot}^2}}^1 \frac{dx_u}{x_u E_{\rm tot}^2} \hat{\sigma}_{u\bar{d}\to W_L^+ h}(s) F_{p/u}(x_u) F_{p/\bar{d}}(x_{\bar{d}})$$

$$\frac{d\sigma}{ds}(pp \to W_L^- h + X) = \int_{\frac{s}{E_{\rm tot}^2}}^1 \frac{dx_d}{x_d E_{\rm tot}^2} \hat{\sigma}_{d\bar{u}\to W_L^- h}(s) F_{p/d}(x_d) F_{p/\bar{u}}(x_{\bar{u}})$$

plotted in figure 6, we have set $E_{\rm tot}$ at 13 TeV. There, a resonance of mass 3 TeV and width 0.4 TeV has been injected with two of the form factors from figure 5. The LO parameters are $a = 0.95$, $b = 0.7a^2$ (away from their SM values $a = b = 1$), and the NLO ones $e(\mu) - 2d(\mu) = 1.64 \times 10^{-3}$ and $f_9(\mu) = -0.6 \times 10^{-2}$ for $\mu = 3$ TeV.[4]

[4]This $f_9 = -6 \times 10^{-3}$, which leads to $M_A = 3$ TeV and $\Gamma_A = 0.4$ TeV, is very close to the value one would obtain from $e - 2d$ through (6.12), $f_9 = -5.6 \times 10^{-3}$. The proximity of this two values relies on the fact that both expressions lead to the same resonance pole and the conditions from (6.9)–(6.11) for BSM theories, $b = 4a^2 - 3 = 0.61$, is approximately fulfilled by our benchmark point $b = 0.7a^2 = 0.63$.



• **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

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

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

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

(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**

NOTE:
RGE down to low-E, not studied here

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

•$\mathcal{L}_4$ EFT custodial breaking ops: present [$O(p^6)$ suppressed]

$$a_0 = -\frac{g'^2}{v^2}\mathcal{F}_{10} = -\mathcal{F}_u \frac{(F_V - \widetilde{F}_V)^2}{2v^2}\frac{(m_Z^2 - m_W^2)^2}{M_V^4}$$

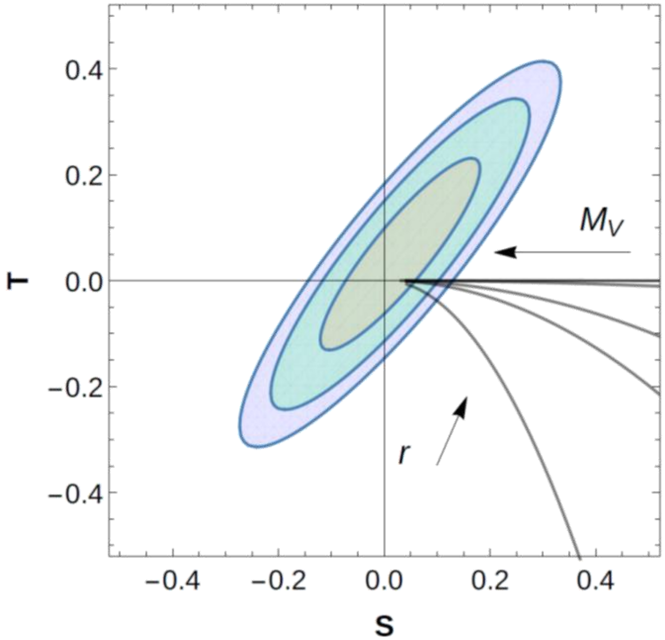
→ Our prediction:

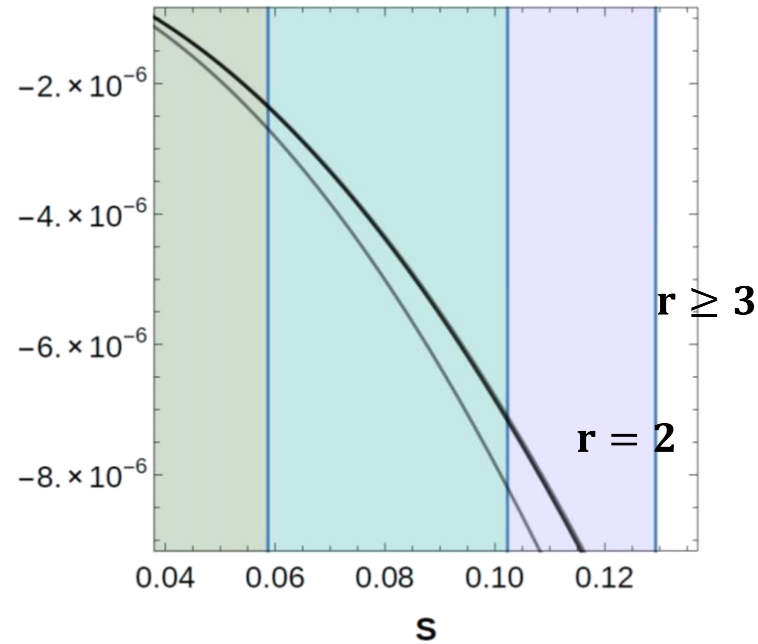
$$S = \frac{4\pi v^2}{M_V^2}\,\frac{r+1}{r},$$

$$T = -\pi\frac{v^2\left(m_Z^2 - m_W^2\right)}{M_V^4}\,\frac{m_Z^2}{m_W^2}\,\frac{r^3+1}{r^2(r-1)}.$$

$$-4.5\cdot 10^{-4}\left(\frac{1\ \mathrm{TeV}^4}{M_V^4}\right)$$

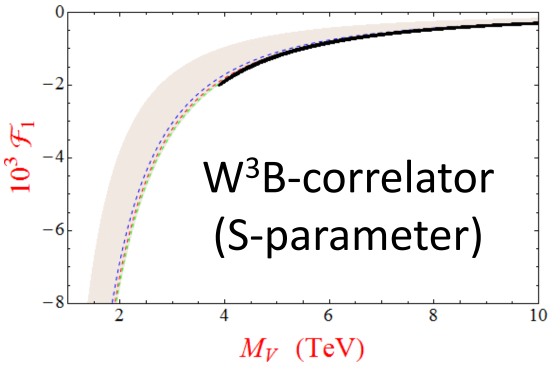
$r = M_A^2/M_V^2$	lower bound 68%CL	for M_V 95%CL
$1+10^{-3}$	5.2 TeV	4.0 TeV
1.1	5.1 TeV	3.9 TeV
2	4.5 TeV	3.4 TeV
∞	3.7 TeV	2.8 TeV

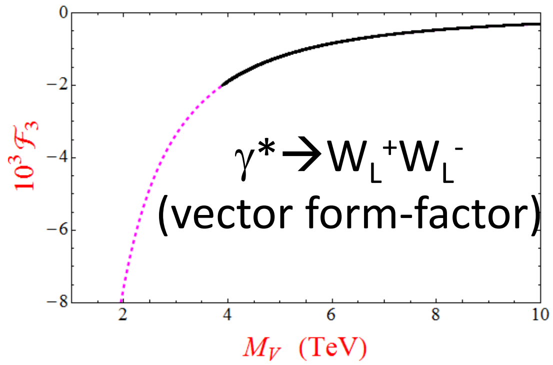


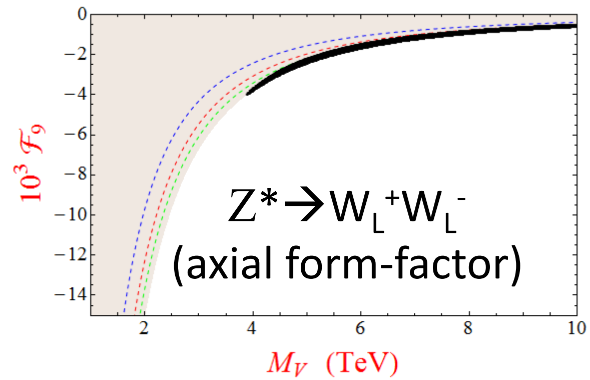


(x) Alvarado,Guevara,SC, arXiv:1909.00875 [hep-ph]; in preparation

• On the other hand, the bosonic & custodial preserving predictions remain unchanged *:







• An estimate of these bosonic observable gives,

$$
\begin{aligned}
T &= -1.1 \cdot 10^{-5} \left(\frac{3\ \text{TeV}}{M_V}\right)^4 , \\
U &= 0\,, \\
S &= 0.13 \left(\frac{3\ \text{TeV}}{M_V}\right)^2 , \\
\Delta g_1^Z = g_1^Z - 1 &= -0.92 \cdot 10^{-3} \left(\frac{3\ \text{TeV}}{M_V}\right)^2 , \\
\Delta \kappa_\gamma = \kappa_\gamma - 1 &= -0.36 \cdot 10^{-3} \left(\frac{3\ \text{TeV}}{M_V}\right)^2 , \\
\Delta \kappa_Z = \kappa_Z - 1 &= -0.82 \cdot 10^{-3} \left(\frac{3\ \text{TeV}}{M_V}\right)^2 .
\end{aligned}
$$

← **Large suppression** (for T)

Estimates for 2 WSRs (*) + $M_A^2=2M_V^2$

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

Suppressing BSM effects in SM-fermion operators

Matter To The Deepest 2019

[Chorzów, September 5th]

Juan José Sanz-Cillero (UCM-IPARCOS)

IPARCOS

UNIVERSIDAD COMPLUTENSE MADRID

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