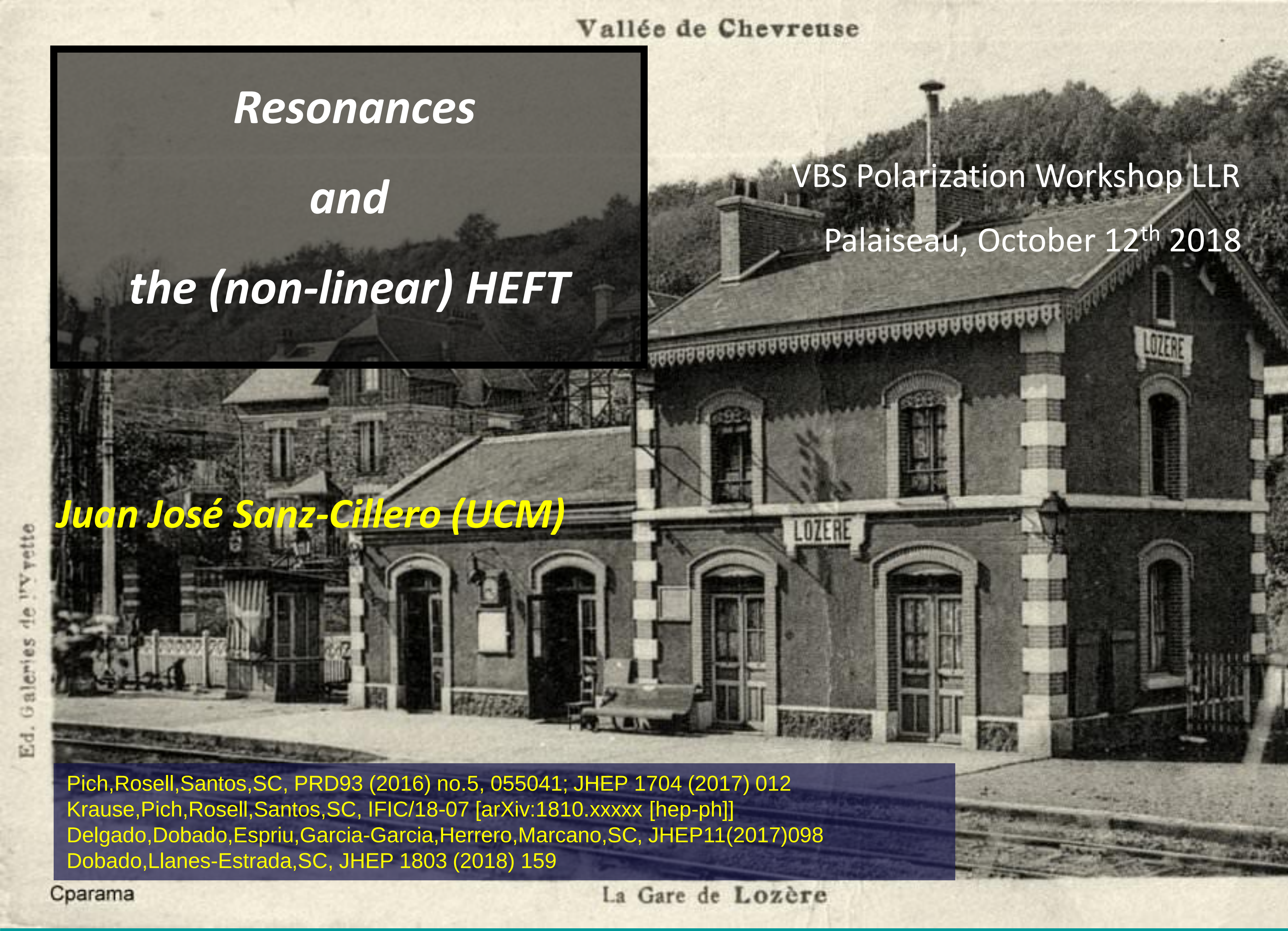


Resonances
and
the (non-linear) HEFT

VBS Polarization Workshop LLR

Palaiseau, October 12th 2018

Juan José Sanz-Cillero (UCM)

Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012
Krause,Pich,Rosell,Santos,SC, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]
Delgado,Dobado,Espriu,Garcia-Garcia,Herrero,Marcano,SC, JHEP11(2017)098
Dobado,Llanes-Estrada,SC, JHEP 1803 (2018) 159

Outline

1.) BSM searches: *bounds*

2.) (Non-linear) *HEFT* aka *EWχL* aka *EWET*

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

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

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

BSM searches:

bounds

- **Experimental bounds on NP seem to be getting tighter and tighter:**

1.) Diboson resonance searches have set $\mathbf{M_R \gtrsim 4}$ TeV (x)

2.) Contact interaction (4f ops.) searches have set $\Lambda \gtrsim \mathbf{10–20}$ TeV (+)

3.) *However,* EW precision test still allow R in the few TeV range

---

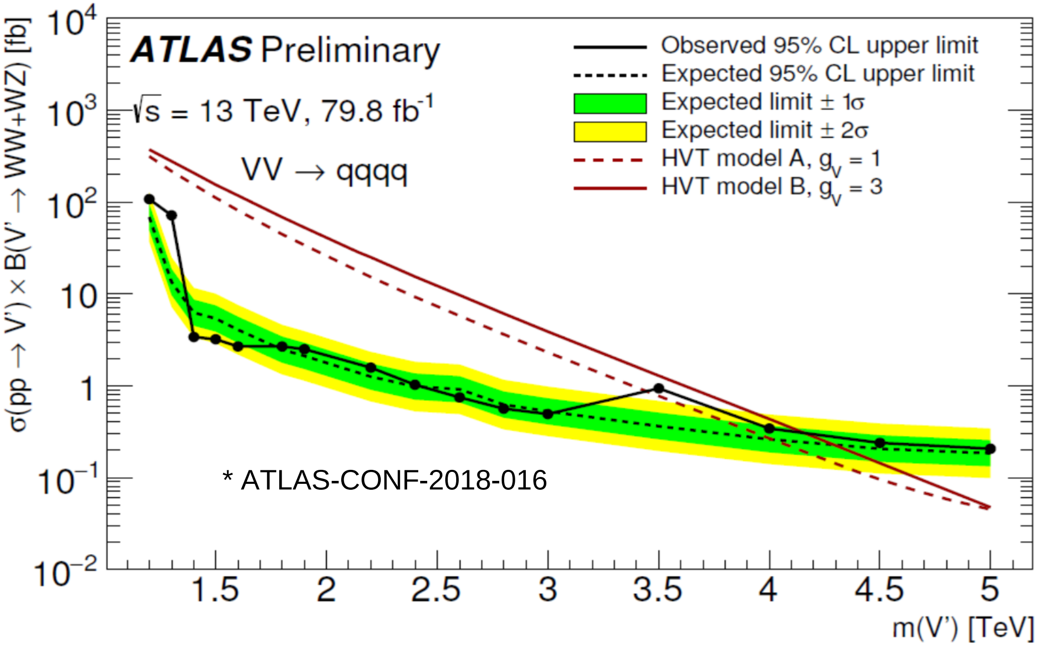
(x) See, e.g., rev: Dorigo, Prog. Part. Nucl. Phys. 100 (2018) 211

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

1.) R mass bounds:

- Analyses heavily rely on specific models, HVT model$^{(x)}$ in particular

Current most stringent bound on EW triplet-V



* ATLAS-CONF-2018-016

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

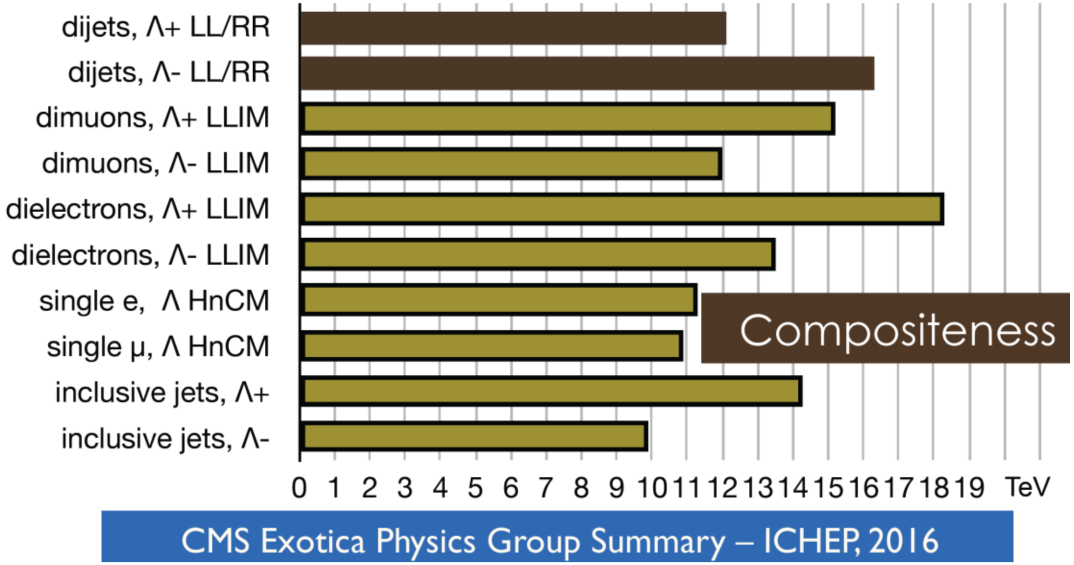
- We note that these analyses are **dominated by DY production**

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

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

2.) Contact 4-fermion interactions:

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



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

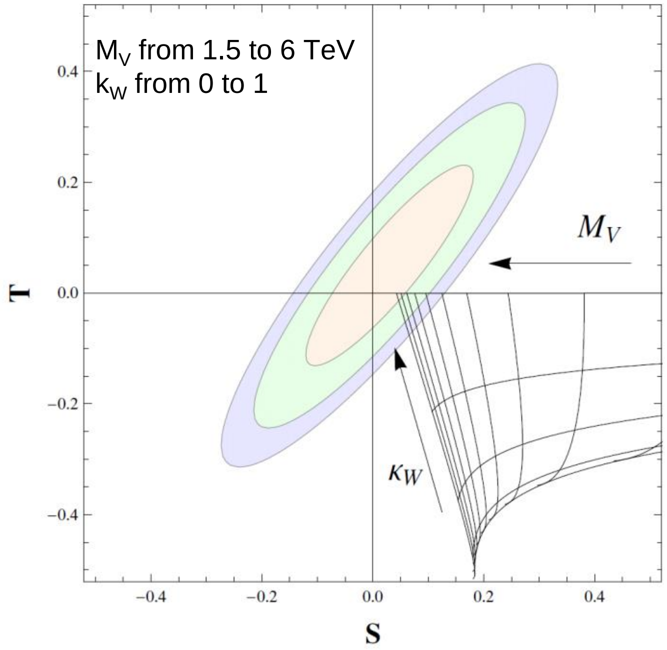
- Also bounds from low-E experiments *

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

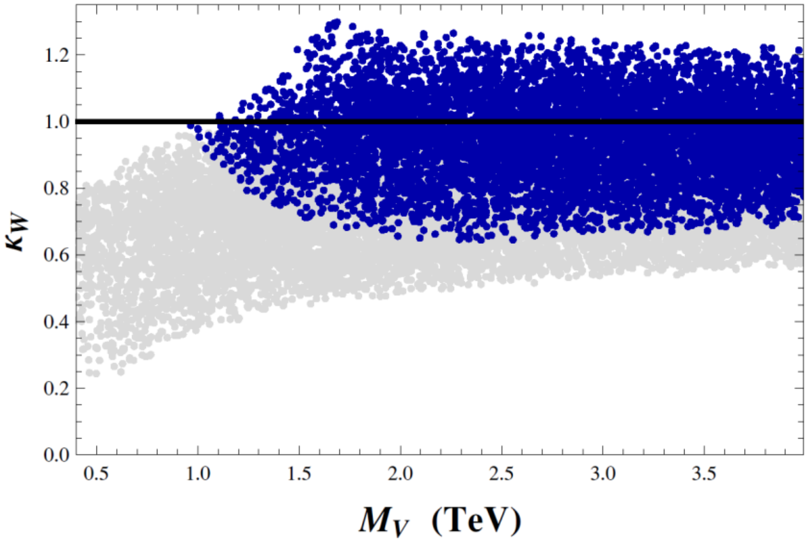
(+) Zhang, Chin. Phys. C 42 (2018) no.2, 023104
(+) Buckley et al, JHEP 1604 (2016) 015
(+) Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]
* Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]
* Isidori, arXiv:1302.0661 [hep-ph]
* Jung,Straub, arXiv:1801.01112 [hep-ph].

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**

  while still leaving a lot of space for VBS surprises at ~ 1 - 3 TeV

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

(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, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

Low-energy EFT (SM + …): representations

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

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

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

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

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

?

?

?

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

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

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

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

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

(i) SM content:

- Bosons χ: Higgs h + gauge bosons W^a_μ,B_μ *(and QCD)*
  + EW Golsdtones $\omega^\pm$,z [non-linearly realized via $U(\omega^a)$ [x]]
- Fermions ψ: (t,b)-type doublets

(ii) Symmetries:

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

(iii) Chiral power counting:

[boson] ⇔ order 0 ($\sim p^0$)

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

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

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

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

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

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

  - **O(p²), LO** ($\supset$ SM) :
$$\begin{aligned}\mathcal{L}_{\rm EWET}^{(2)} = {} & \sum_{\xi} \left[i\,\bar{\xi}\gamma^\mu d_\mu \xi - v\left(\,\bar{\xi}_L\,\mathcal{Y}\,\xi_R\,+\,\text{h.c.}\right)\right] \\ & - \frac{1}{2g^2}\langle \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\rangle_2 - \frac{1}{2g'^2}\langle \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\rangle_2 - \frac{1}{2g_s^2}\langle \hat{G}_{\mu\nu}\hat{G}^{\mu\nu}\rangle_3 \\ & + \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2\,h^2 - V(h/v) + \frac{v^2}{4}\mathcal{F}_u(h/v)\,\langle u_\mu u^\mu\rangle_2\end{aligned}$$

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

  - **O(p⁴), NLO** (pure BSM):
$$\begin{aligned}\mathcal{L}_{\rm EWET}^{(4)} = {} & \sum_{i=1}^{12}\mathcal{F}_i(h/v)\,\mathcal{O}_i + \sum_{i=1}^{3}\widetilde{\mathcal{F}}_i(h/v)\,\widetilde{\mathcal{O}}_i + \sum_{i=1}^{8}\mathcal{F}_i^{\psi^2}(h/v)\,\mathcal{O}_i^{\psi^2} + \sum_{i=1}^{3}\widetilde{\mathcal{F}}_i^{\psi^2}(h/v)\,\widetilde{\mathcal{O}}_i^{\psi^2} \\ & + \sum_{i=1}^{10}\mathcal{F}_i^{\psi^4}(h/v)\,\mathcal{O}_i^{\psi^4} + \sum_{i=1}^{2}\widetilde{\mathcal{F}}_i^{\psi^4}(h/v)\,\widetilde{\mathcal{O}}_i^{\psi^4}\,.\end{aligned}$$

(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
(x) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

Low-energy chiral expansion

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

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

Finite pieces from loops
(amplitude dependent) (+)

$$\mathcal{M}(2\to 2) \approx \frac{p^2}{v^2}\left[\underline{\;1\;} + \left(\underline{\frac{c_k^r\, p^2}{v^2}} - \underline{\frac{\Gamma_k\, p^2}{16\pi^2 v^2}\ln\frac{p}{\mu} + \ldots}\right) + \mathcal{O}(p^4)\right]$$

LO (tree)

NLO (tree)

suppression
~1/M^2 + …

(heavier states)

NLO (1-loop)

Typical loop suppression
~ Γ_k/ (16π^2v^2)

(non-linearity)

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

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

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

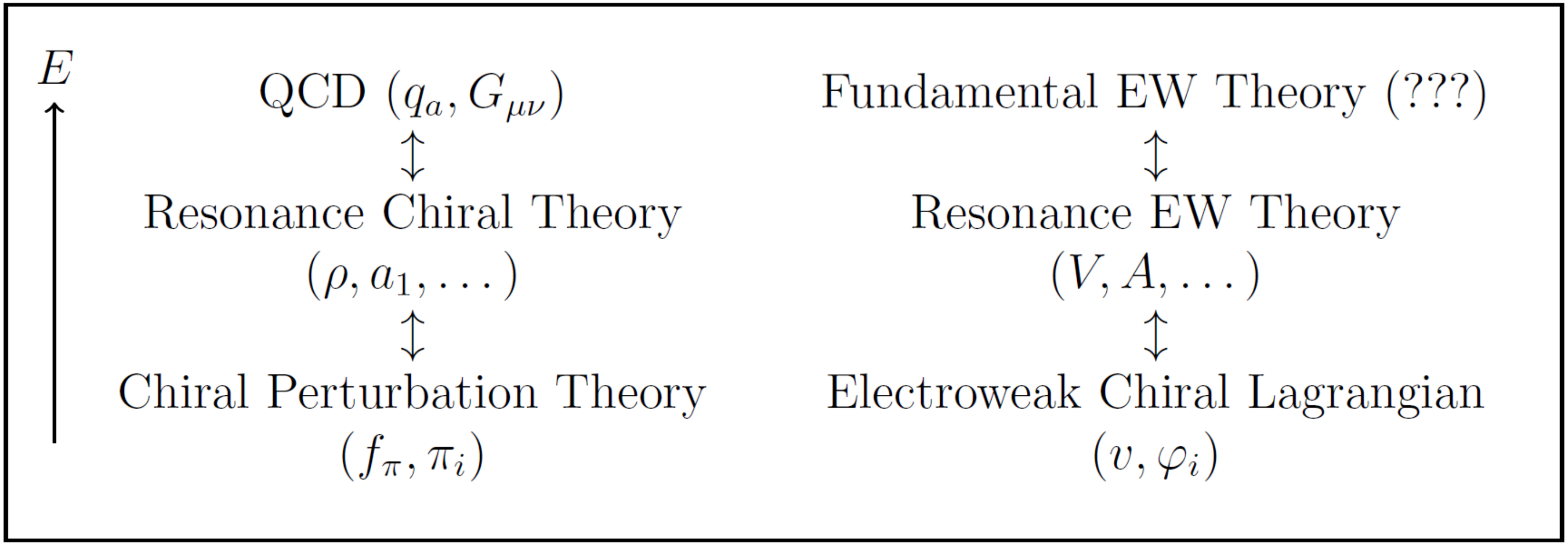
- Indeed, the SM has this arrangement but with $\frac{p^2}{16\pi^2 v^2} \sim \frac{g^{(\prime)\,2}}{(4\pi)^2}, \frac{\lambda}{(4\pi)^2}, \frac{\lambda_f^2}{(4\pi)^2} \ll 1$; **hence**

HEFT + Resonances:

what might we expect?

Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

- Analogy between QCD and possible (strongly interacting) EW extensions:



E

QCD $(q_a, G_{\mu\nu})$

$\updownarrow$

Resonance Chiral Theory

$(\rho, a_1, \dots)$

$\updownarrow$

Chiral Perturbation Theory

(f_π, π_i)

Fundamental EW Theory (???)

$\updownarrow$

Resonance EW Theory

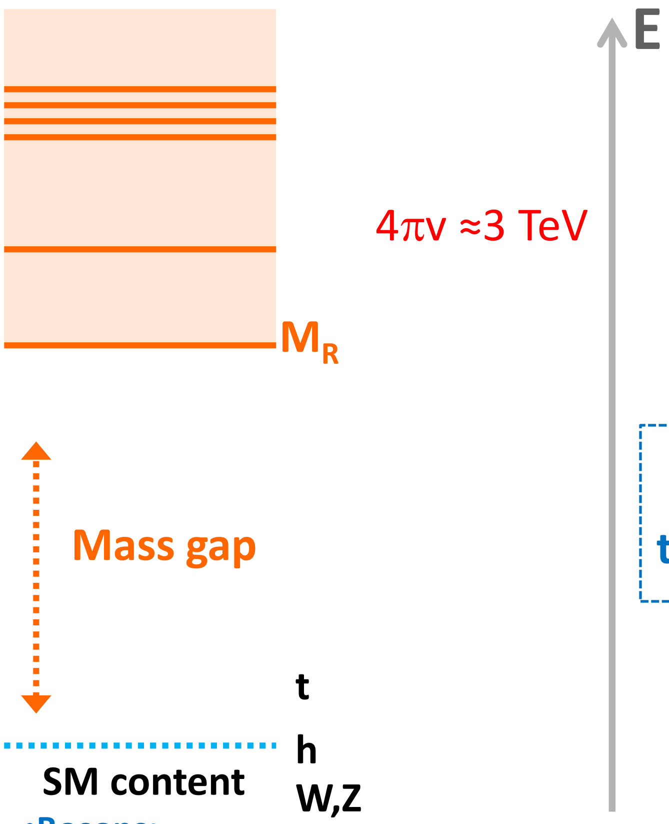
$(V, A, \dots)$

$\updownarrow$

Electroweak Chiral Lagrangian

(v, φ_i)

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



SM content

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

Custodial symmetry

+

Resonance Lagrangian

+

UV completion hypothesis

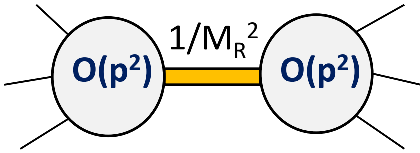
Resonance contributions *,**

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



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

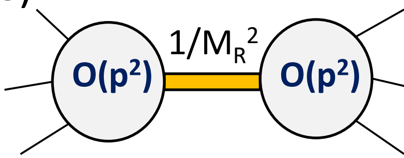
* Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012;
Krause,Pich,Rosell,Santos,SC, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

** 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

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

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



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

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

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

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

* Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

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

i	$\Delta\mathcal{F}_i$	$\Delta\widetilde{\mathcal{F}}_i$	i	$\Delta\mathcal{F}_i$
1	$-\frac{F_V^2-\widetilde{F}_V^2}{4M^2_{V_3^1}}+\frac{F_A^2-\widetilde{F}_A^2}{4M^2_{A_3^1}}$	$-\frac{\widetilde{F}_V G_V}{2M^2_{V_3^1}}-\frac{F_A\widetilde{G}_A}{2M^2_{A_3^1}}$	7	$\frac{d_P^2}{2M^2_{P_3^1}}+\frac{\lambda_1^{hA\,2}v^2}{M^2_{A_3^1}}+\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M^2_{V_3^1}}$
2	$-\frac{F_V^2+\widetilde{F}_V^2}{8M^2_{V_3^1}}-\frac{F_A^2+\widetilde{F}_A^2}{8M^2_{A_3^1}}$	$-\frac{F_V\widetilde{F}_V}{4M^2_{V_3^1}}-\frac{F_A\widetilde{F}_A}{4M^2_{A_3^1}}$	8	0
3	$-\frac{F_V G_V}{2M^2_{V_3^1}}-\frac{\widetilde{F}_A\widetilde{G}_A}{2M^2_{A_3^1}}$	$-\frac{F_V\widetilde{\lambda}_1^{hV}v}{M^2_{V_3^1}}-\frac{\widetilde{F}_A\lambda_1^{hA}v}{M^2_{A_3^1}}$	9	$-\frac{F_A\lambda_1^{hA}v}{M^2_{A_3^1}}-\frac{\widetilde{F}_V\widetilde{\lambda}_1^{hV}v}{M^2_{V_3^1}}$
4	$\frac{G_V^2}{4M^2_{V_3^1}}+\frac{\widetilde{G}_A^2}{4M^2_{A_3^1}}$	—	10	$-\frac{\widetilde{c}_T^2}{2M^2_{V_1^1}}-\frac{c_T^2}{2M^2_{A_1^1}}$
5	$\frac{c_d^2}{4M^2_{S_1^1}}-\frac{G_V^2}{4M^2_{V_3^1}}-\frac{\widetilde{G}_A^2}{4M^2_{A_3^1}}$	—	11	$-\frac{F_X^2}{M^2_{V_1^1}}-\frac{\widetilde{F}_X^2}{M^2_{A_1^1}}$
6	$-\frac{\widetilde{\lambda}_1^{hV\,2}v^2}{M^2_{V_3^1}}-\frac{\lambda_1^{hA\,2}v^2}{M^2_{A_3^1}}$	—	12	$-\frac{(C_G)^2}{2M^2_{V_1^8}}-\frac{(\widetilde{C}_G)^2}{2M^2_{A_1^8}}$

, etc.

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

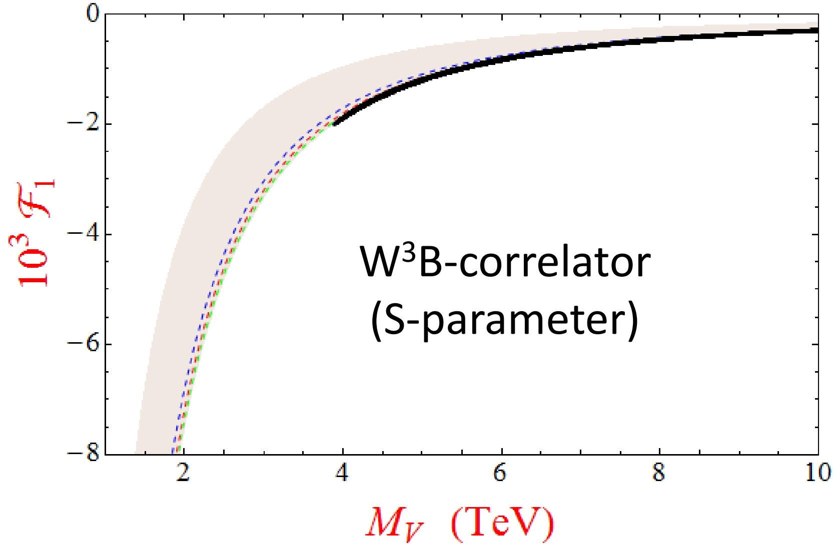
, etc.

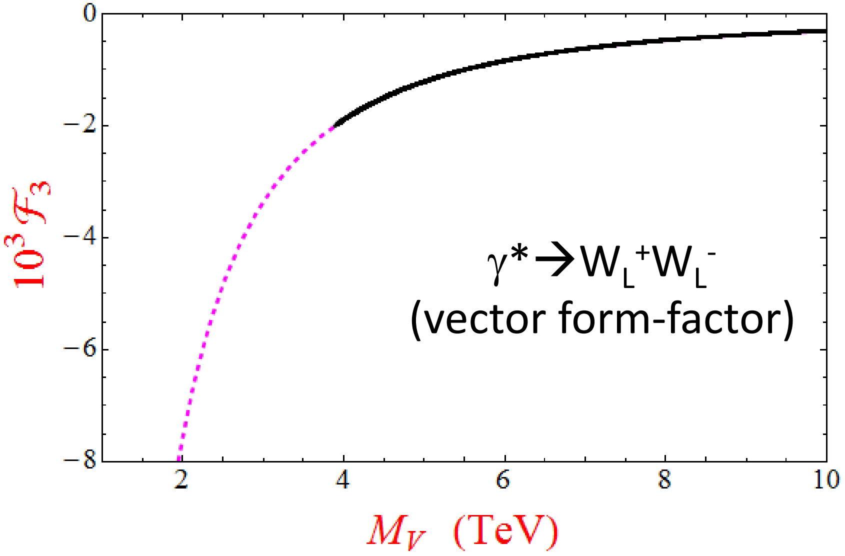
[Relation with Longhitanos's couplings $\mathcal{F}_j = a_j + O(h)$; notice: $a_{j\geq5}$ relabelled]

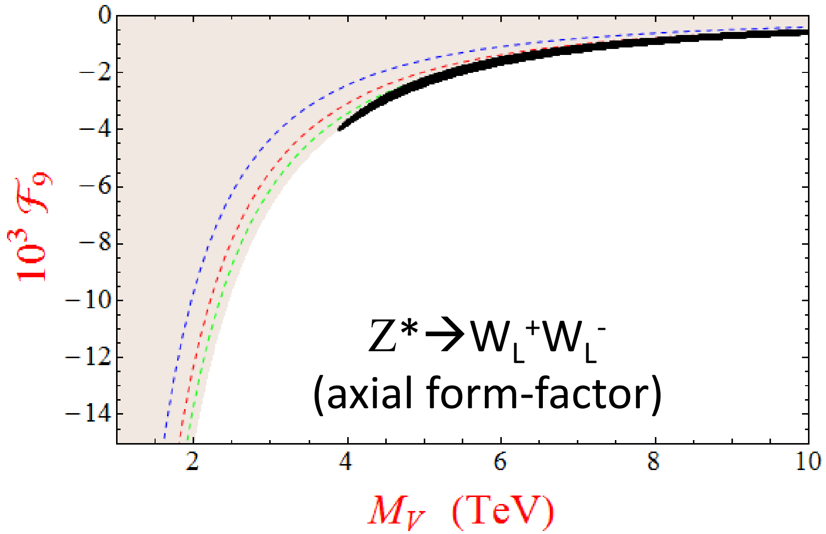
(*) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

Theory:

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


W^{3}B-correlator (S-parameter)


$\gamma^*\rightarrow W_L^+W_L^-$ (vector form-factor)

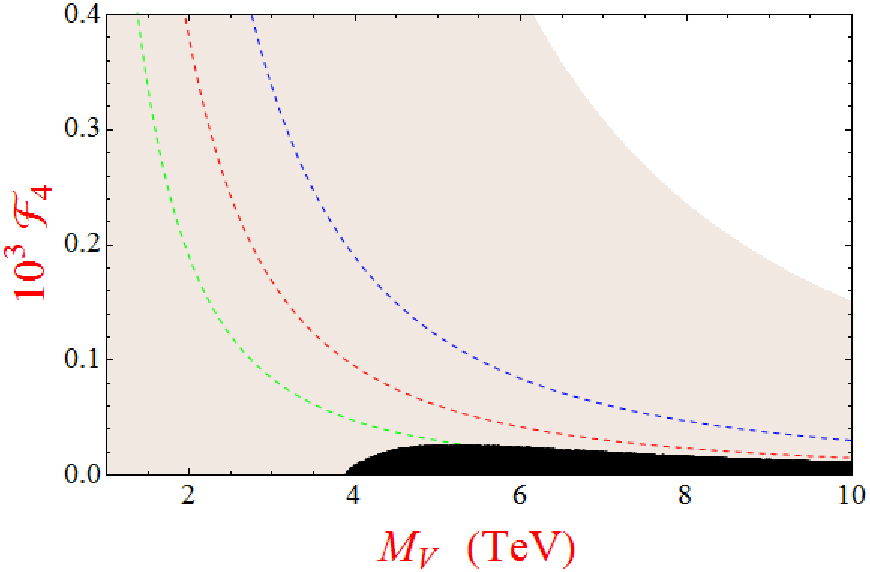

$Z^*\rightarrow W_L^+W_L^-$ (axial form-factor)

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

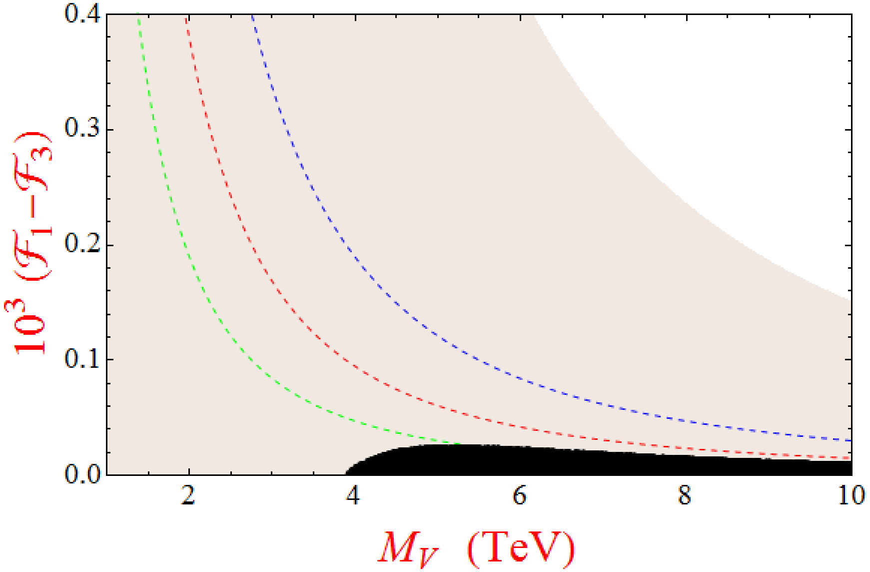
Theory:

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

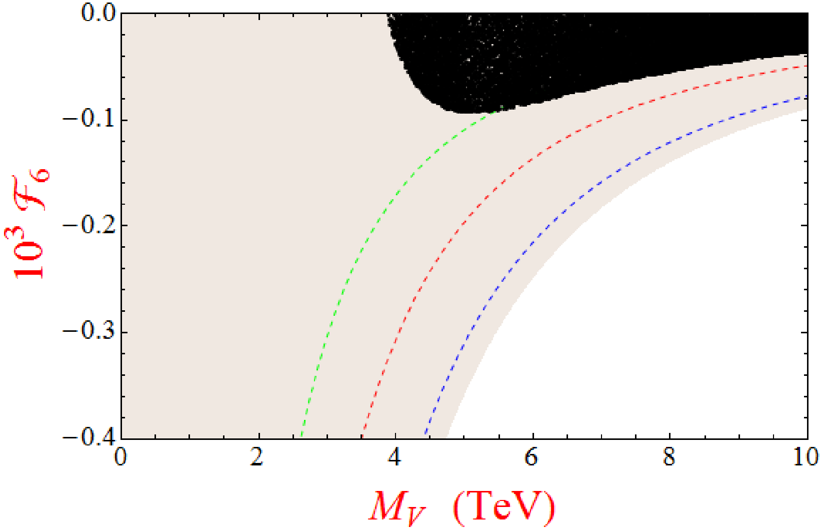
- $w^a w^b \rightarrow w^c\, w^d$ scattering



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



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



- $hh \rightarrow hh$ scattering $\rightarrow 0$

→ HEFT couplings in the range

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

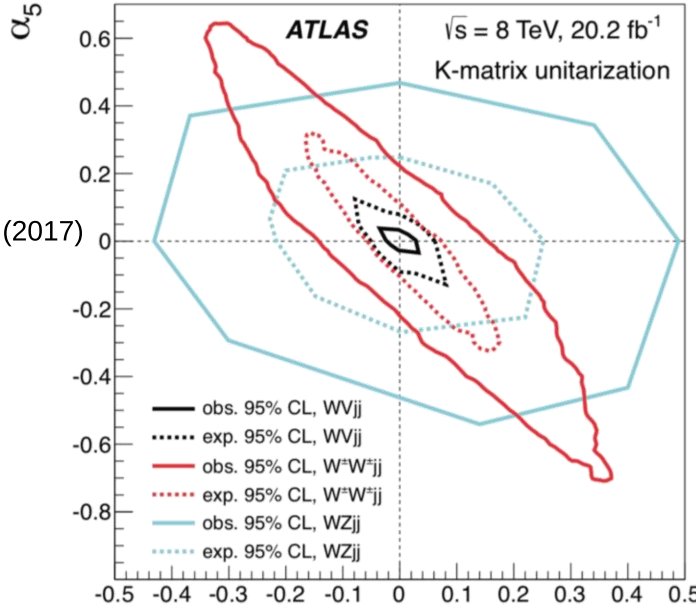
* Pich,Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801
* Pich,Rosell,Santos,SC, PRD 93 (2016) no.5, 055041

- In the ballpark of current experimental measurements,

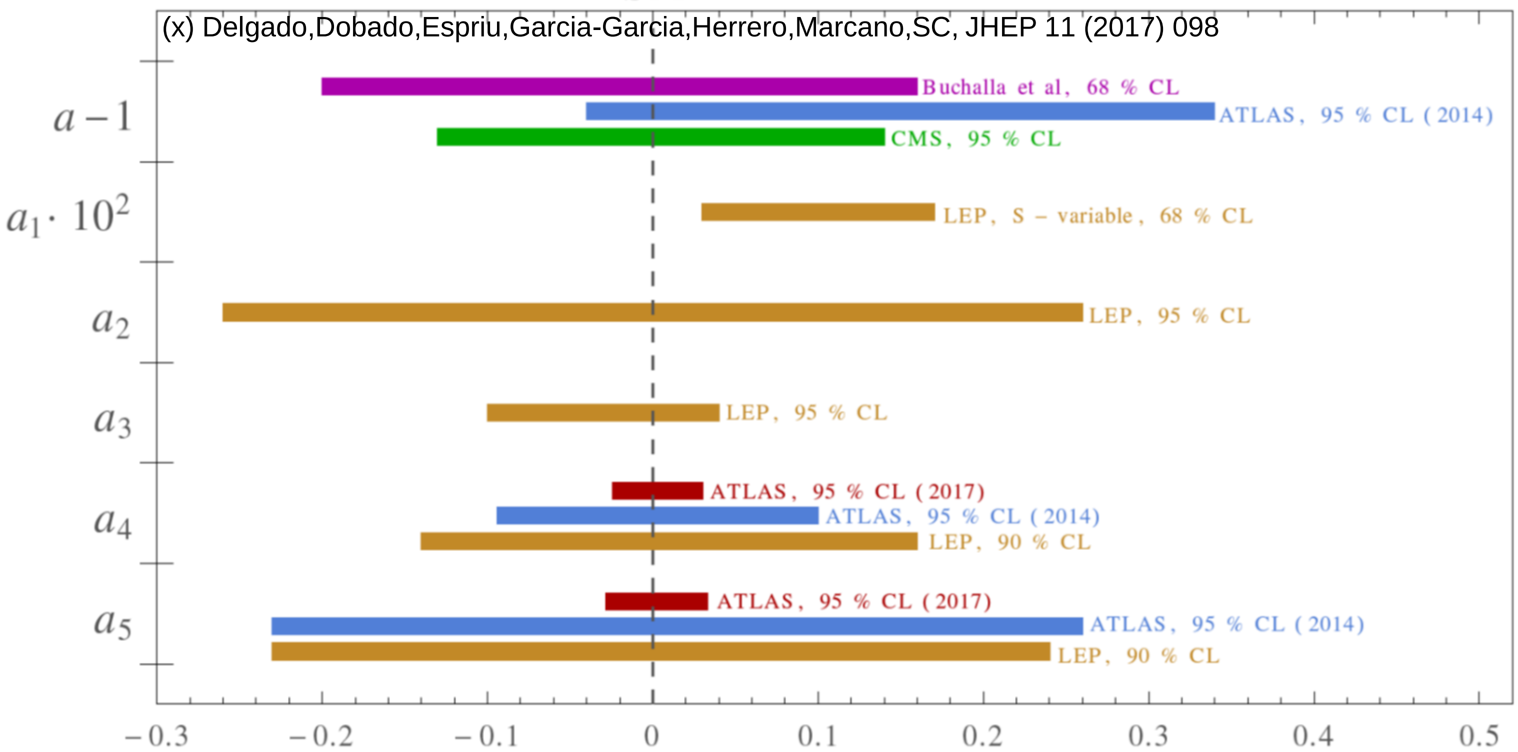
  with recent important improvements from VBS:

[ATLAS], PRD 95 032001 (2017)

See A. Apyan's talk



- Useful to observe the summary: (x)



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

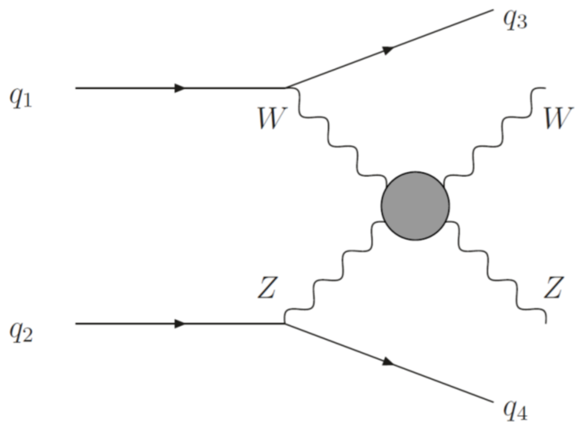
Resonant VBS diboson production:

WZ, evading current M_R bounds

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

$pp \to WZj_1j_2$

by $WZ \to WZ$ scattering



- Relevant HEFT Lagrangian up to NLO:

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

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

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

- $W_L Z_L \rightarrow W_L Z_L$ PWA unitarization: Inverse Amplitude Method (**IAM**)

1) PWA elastic unitarity:

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

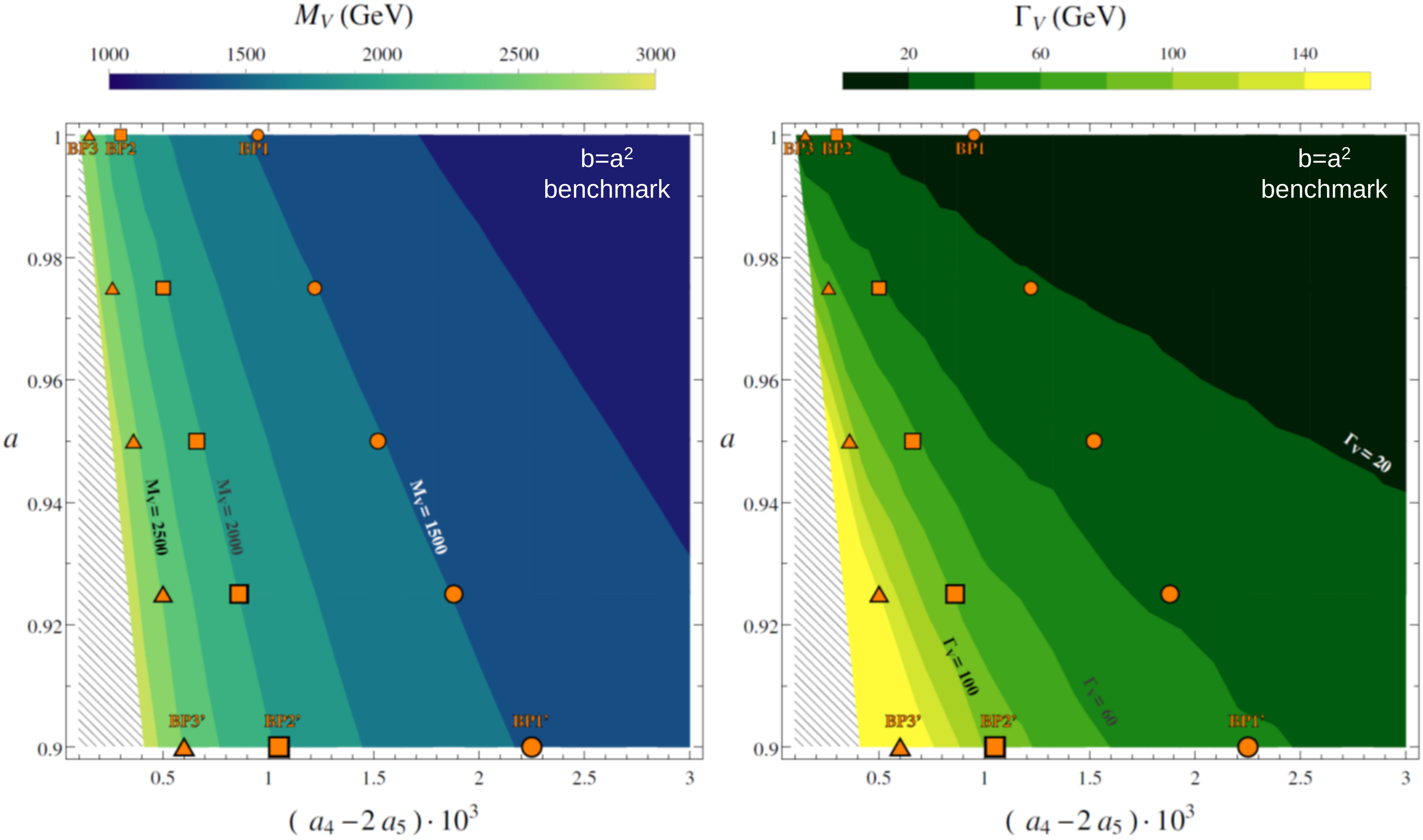
2) Low-E matching to HEFT up to NLO, $\mathcal{M}_{IJ}(s) = \mathcal{M}_{IJ}^{(0)}(s) + \mathcal{M}_{IJ}^{(1)}(s) + \ldots$

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

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

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]

- $W_LZ_L \to W_LZ_L$ IAM unitarization ➔ Resonance pole generated at $s_{pole} = (M_V - i\Gamma_V/2)^2$



- Analytical expressions in the Equiv.Theor. Limit:

  [although $W_LZ_L \to W_LZ_L$ in our analysis **!!!** *]*

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

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

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

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

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

Suppressed at high-E

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

(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, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

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

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

$$(a, a_4, a_5) \xrightarrow{\left|a_{11}^{\mathrm{EChL}^{(2)}_{\mathrm{tree}}+\mathcal{L}_V}(s=M_V^2)\right| = \left|a_{11}^{\mathrm{IAM}}(s=M_V^2)\right|}$$

(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

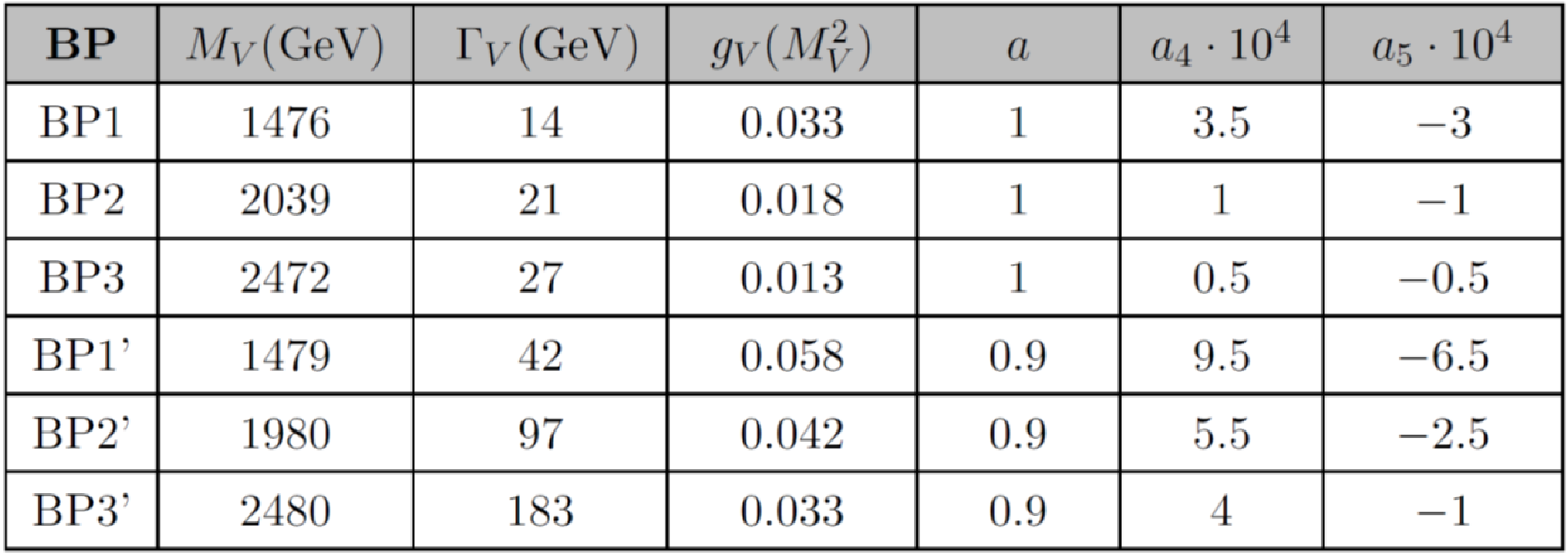
$$g_V^2(z) = g_V^2(M_V^2)\frac{M_V^2}{z} \quad \text{for } s < M_V^2$$

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

$\text{with } z = t, u$

[although crossing partially lost]

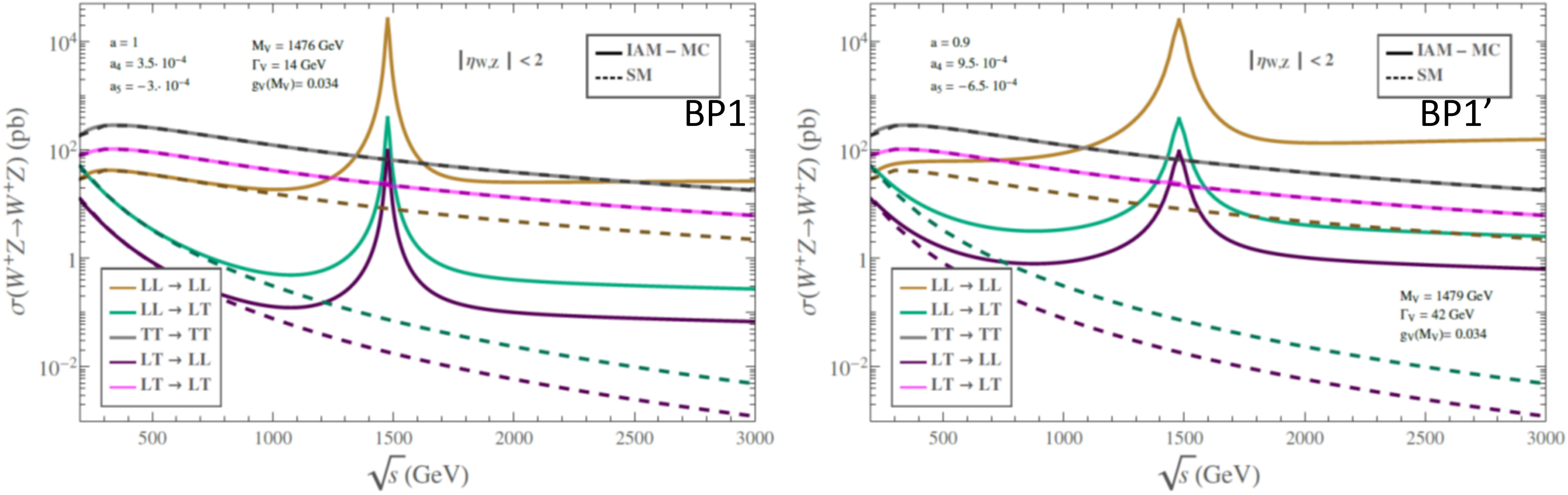
- Benchmark points of this study:



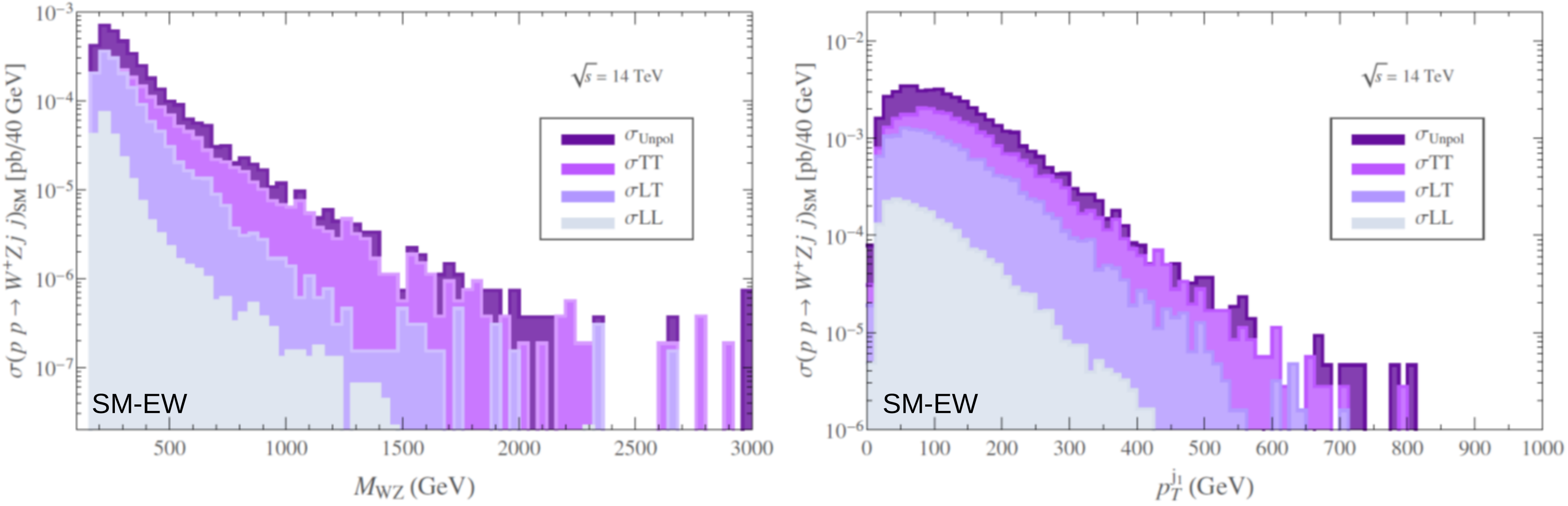
BP	$M_V(\mathrm{GeV})$	$\Gamma_V(\mathrm{GeV})$	$g_V(M_V^2)$	a	$a_4 \cdot 10^4$	$a_5 \cdot 10^4$
BP1	1476	14	0.033	1	3.5	-3
BP2	2039	21	0.018	1	1	-1
BP3	2472	27	0.013	1	0.5	-0.5
BP1'	1479	42	0.058	0.9	9.5	-6.5
BP2'	1980	97	0.042	0.9	5.5	-2.5
BP3'	2480	183	0.033	0.9	4	-1

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

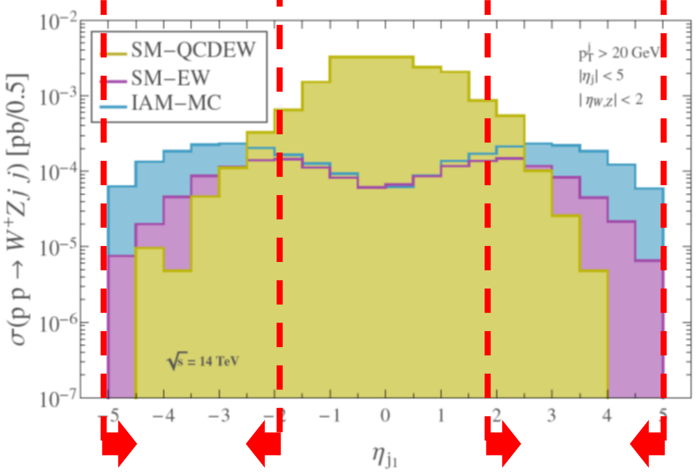
$\sigma(LL \to LL) \gg \sigma(LL \to LT) > \sigma(LT \to LL) > \sigma(TT \to TT) > \sigma(LT \to LT)$

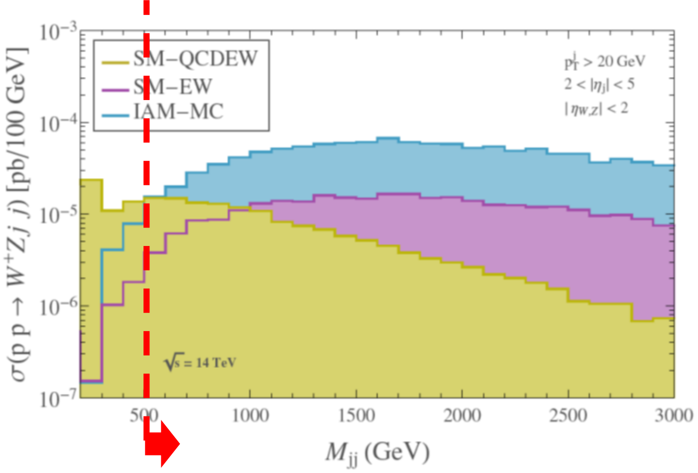


- pp→jjWZ at LHC: SM backgrounds and polarizations (in the WZ rest frame)



- Backgrounds:

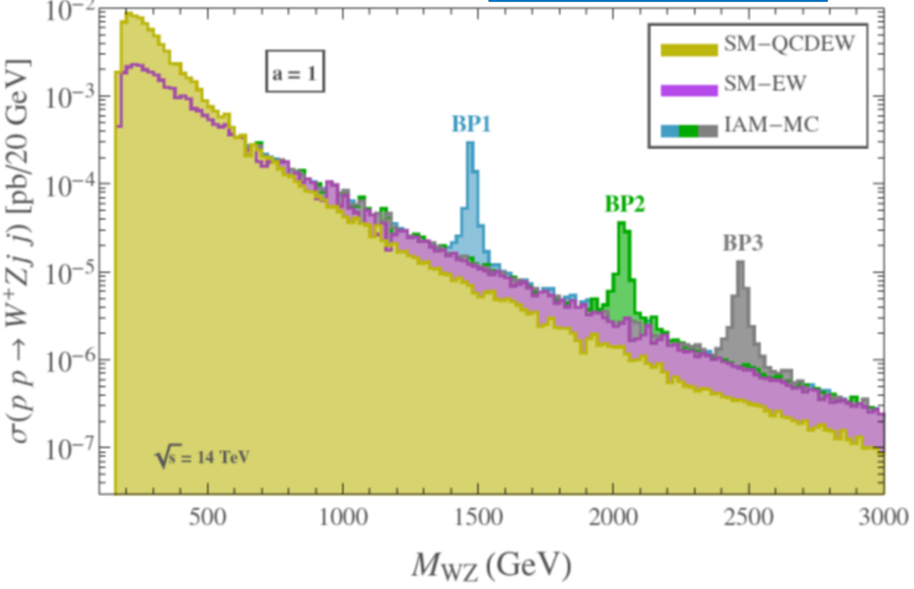


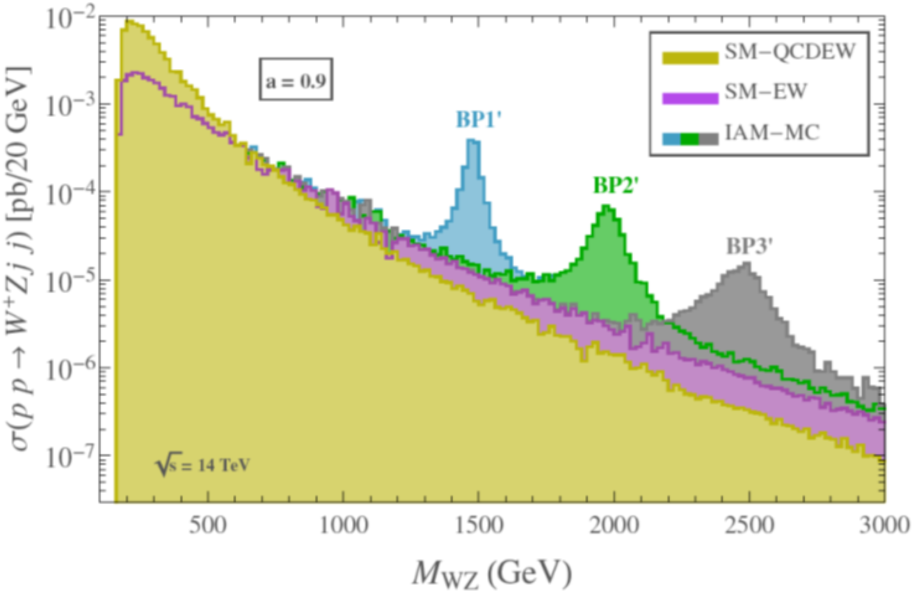


- Optimal VBS cuts: (*)

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

[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

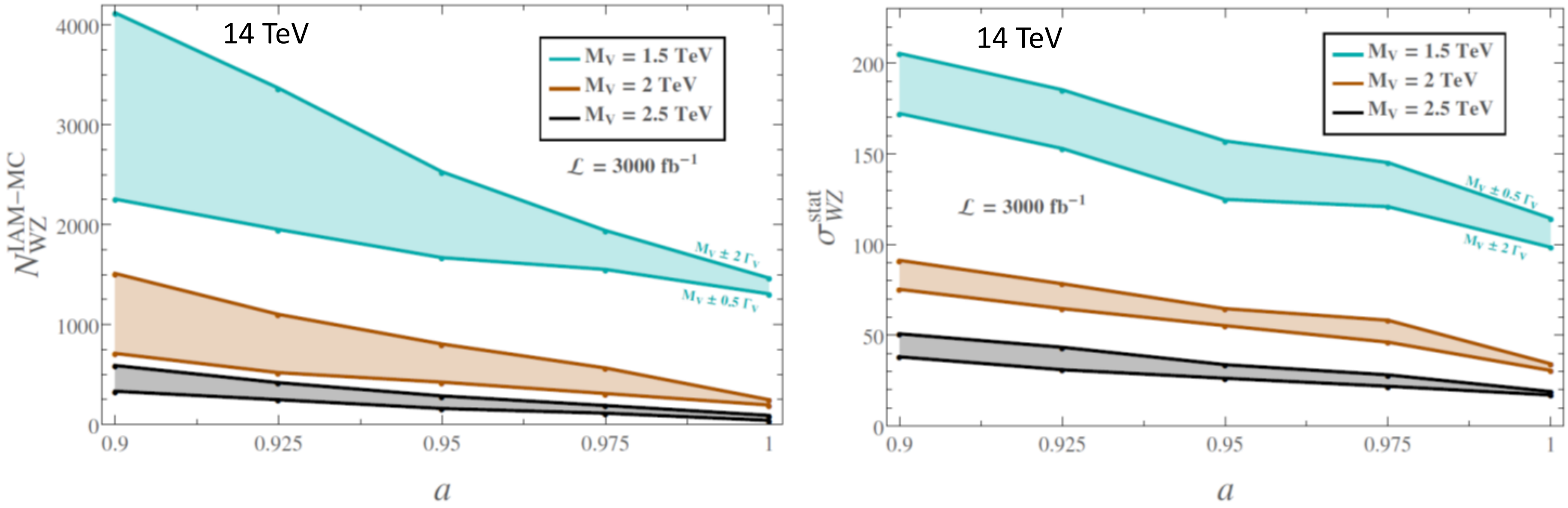
- Sensitivity with perfect WZ reconstruction efficiency:

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

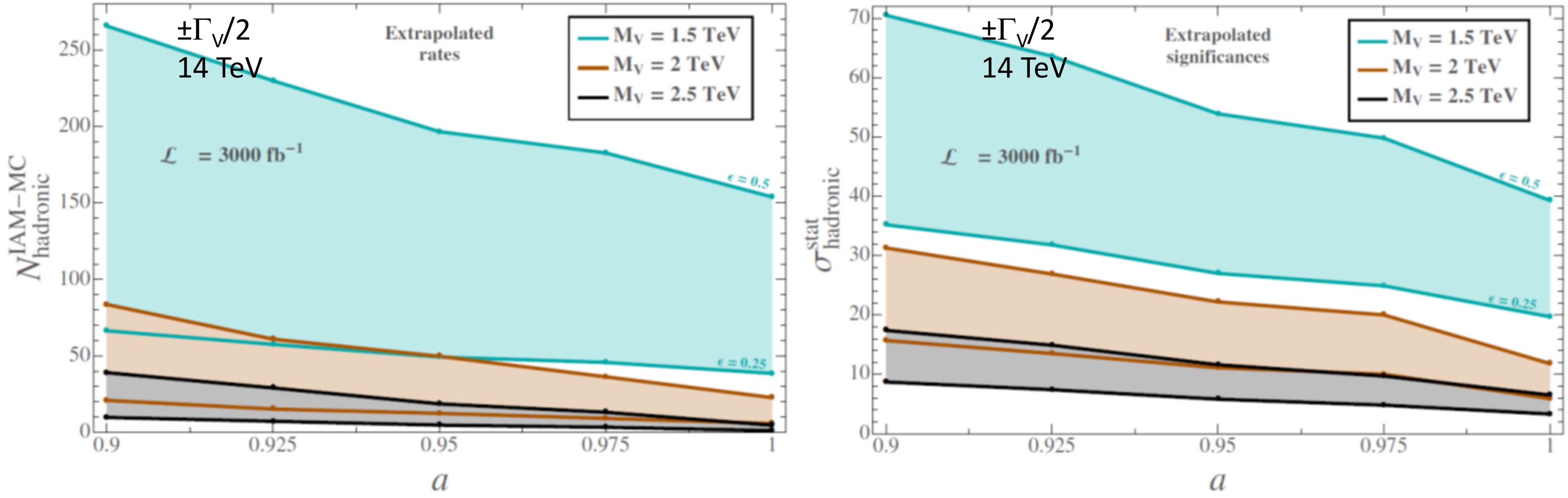
$$\sigma_{WZ}^{\text{stat}} = \frac{S_{WZ}}{\sqrt{B_{WZ}}}$$

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

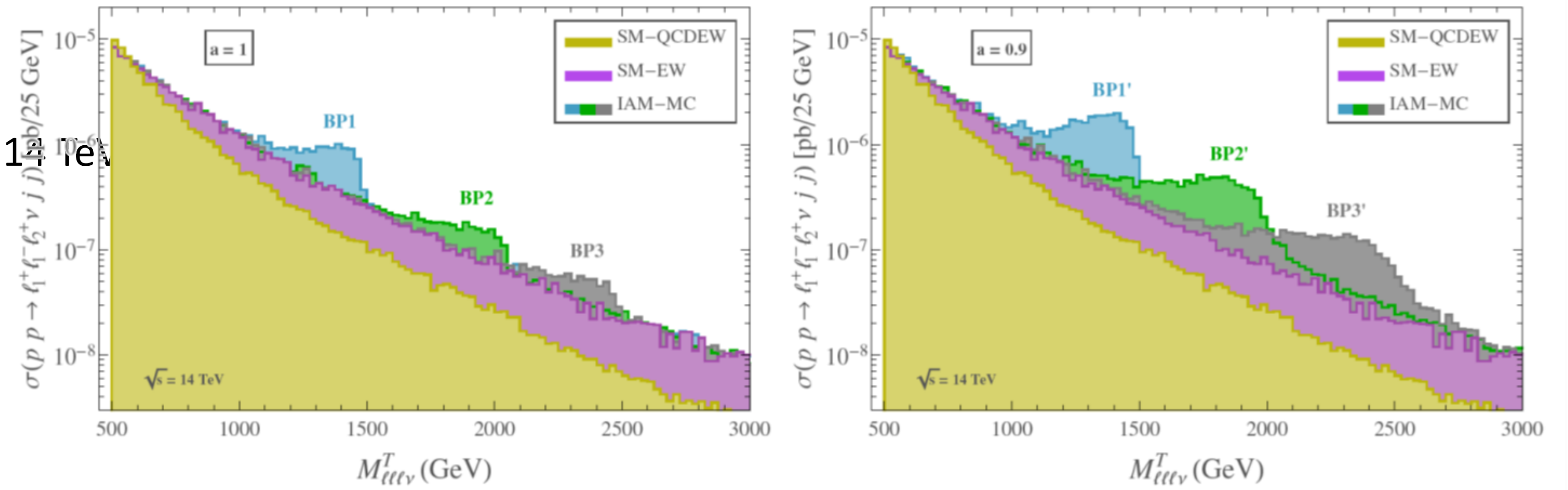
- Sensitivity with 100% WZ efficiency reconstruction:



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



- Fully leptonic decays (no polarization cuts):



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

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

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

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

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

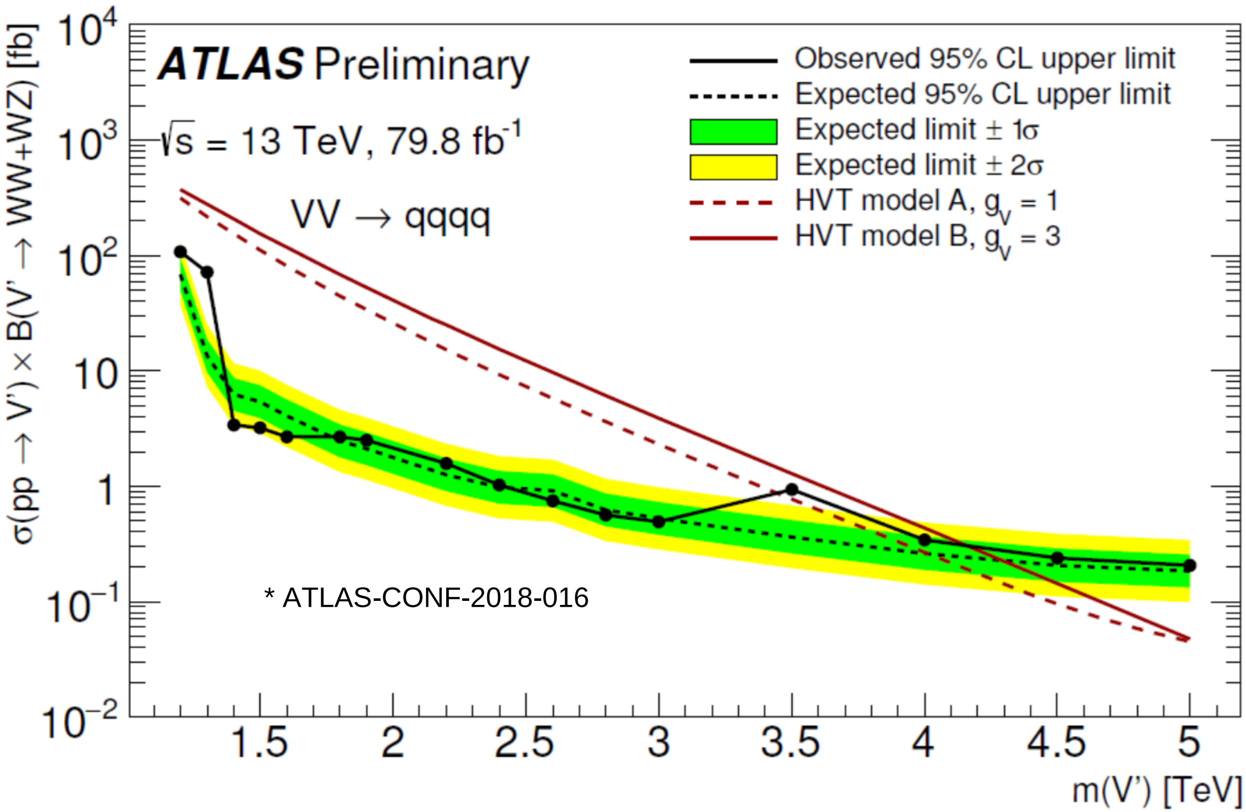
	14 TeV	BP1	BP2	BP3	BP1’	BP2’	BP3’
$\mathcal{L} = 300\ \mathrm{fb}^{-1}$	$\mathrm{N}_\ell^{\mathrm{IAM-MC}}$	2	0.5	0.1	5	2	0.7
	$\mathrm{N}_\ell^{\mathrm{SM}}$	1	0.4	0.1	2	0.6	0.3
	$\sigma_\ell^{\mathrm{stat}}$	0.9	–	–	2.8	1.4	–
$\mathcal{L} = 1000\ \mathrm{fb}^{-1}$	$\mathrm{N}_\ell^{\mathrm{IAM-MC}}$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

Resonant DY diboson production:

Wh, evading current M_R bounds

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

- SM fermion interactions → extremely suppressed in BSM
- HVT diboson searches: $\sigma(pp\to V\to \text{diboson}) \simeq \sum_{q,\bar{q}'} \frac{48\pi^2\gamma_{q\bar{q}'}}{4N_C^2}\frac{dL_{q,\bar{q}'}}{d\hat{s}}\Big|_{\hat{s}=M_V^2}$, $\gamma_{ij} = \frac{\Gamma_{V\to ij}}{M_V}\times\mathcal{B}_{V\to\text{dibos}}$
- Strongest bounds from HVT-B (g_V=3) (x)



* ATLAS-CONF-2018-016

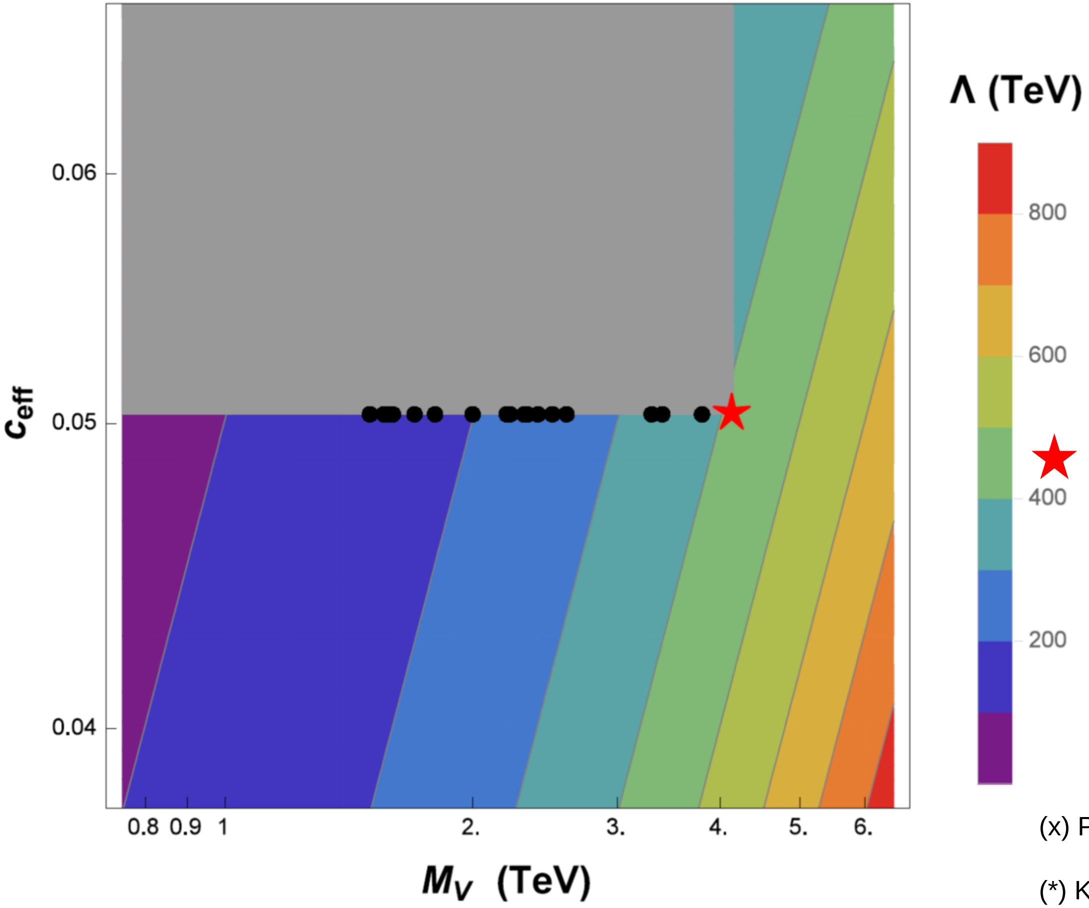
(a) HVT $V' \to WW + WZ$

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

- SM fermion interactions → extremely suppressed in BSM
- HVT diboson searches: $\sigma(pp \to V \to \text{diboson}) \simeq \sum_{q,\bar{q}'} \frac{48\pi^2 \gamma_{q\bar{q}'}}{4N_C^2} \frac{dL_{q,\bar{q}'}}{d\hat{s}}\Big|_{\hat{s}=M_V^2}, \quad \gamma_{ij} = \frac{\Gamma_{V\to ij}}{M_V} \times \mathcal{B}_{V\to\text{dibos}}$
- 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 (*)

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



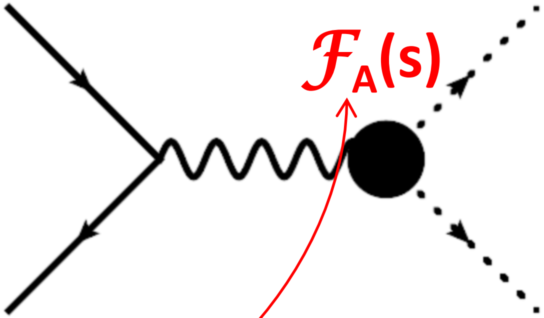
★ → Λ = 410 TeV

(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, IFIC/18-07 [arXiv:1810.xxxxx [hep-ph]]

- DY production via a gauge boson:



$\mathcal{F}_A(s)$

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

[elastic $W^a h$ PWA scat]

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

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

- HEFT:

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

$$-i f_9\,\frac{(\partial_\mu h)}{v}\,{\rm Tr}\{\hat{W}^{\mu\nu}\, D_\nu U\, U^\dagger - \hat{B}^{\mu\nu}\, U^\dagger\, D_\nu U\}\,,$$

$$T\left(W_L^\pm (Z_L) h \to W_L^\pm (Z_L) h\right) = -T\left(\omega^\pm(\omega^0) h \to \omega^\pm(\omega^0) h\right) + \mathcal{O}\left(\frac{M_W}{\sqrt{s}}\right)$$

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

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 $M_{11}(s)$.

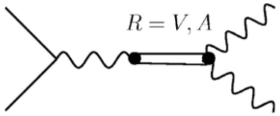
c Elastic unitarity.

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



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

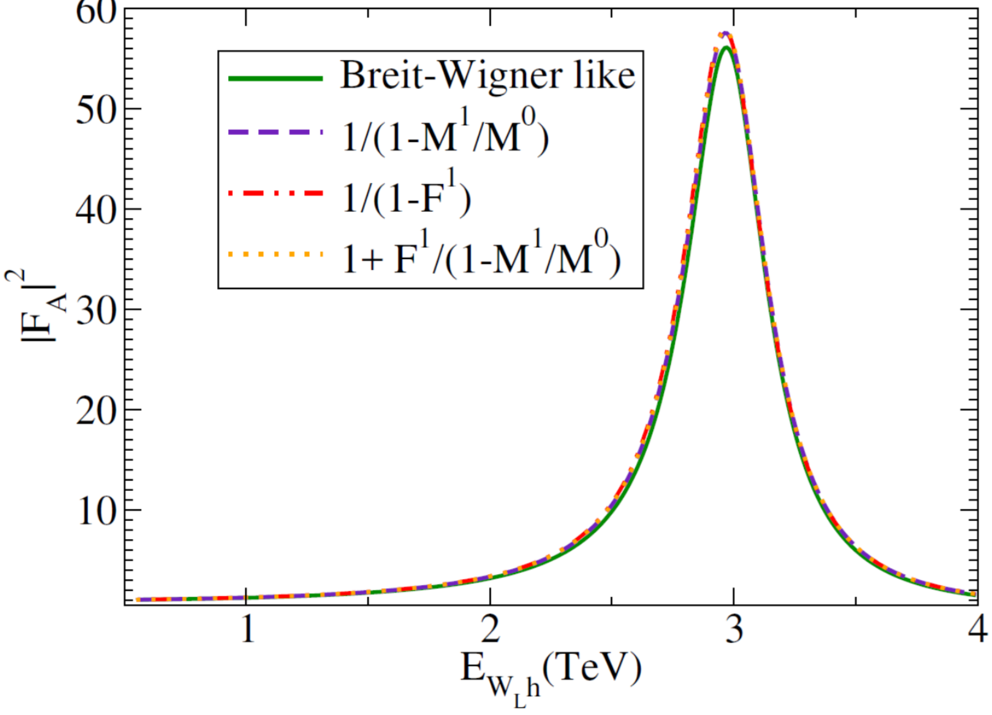
a) & d)

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

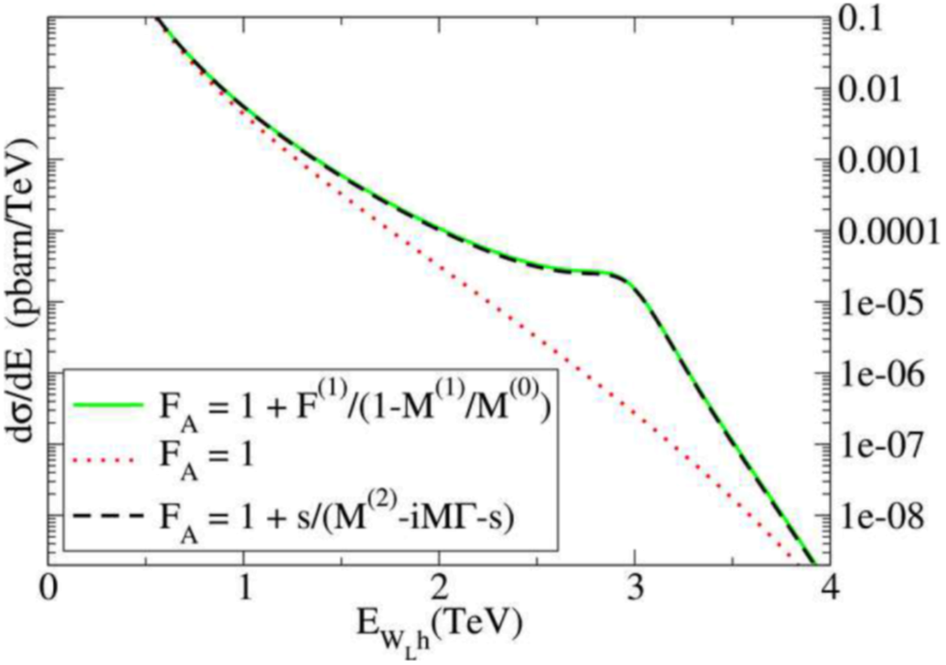
b) & c)

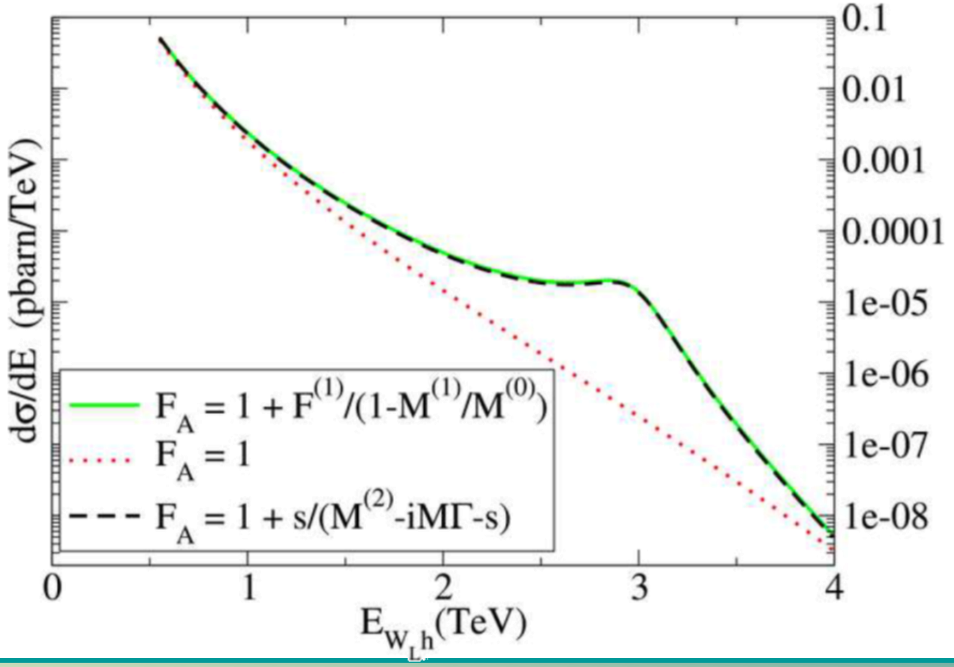
$$\mathcal{F}_A(s) = 1 + \frac{\mathcal{F}_A^{(1)}(s) M_{11}^{(0)}(s)}{M_{11}^{(0)}(s) - M_{11}^{(1)}(s)} . \qquad \text{(Model IV)}$$

b), c) & d)



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



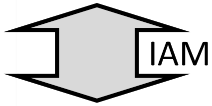


BENCHMARK point

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

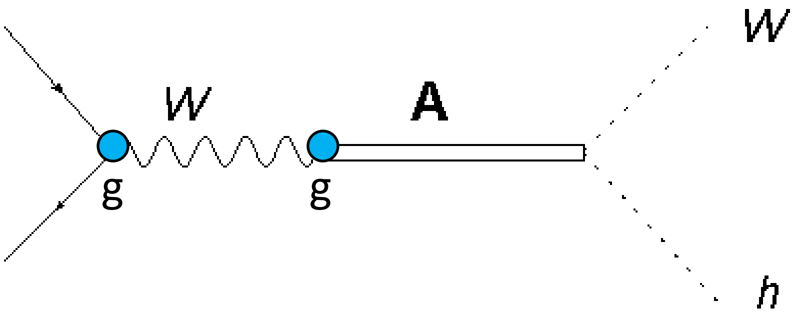
HEFT+R: $M_A = 3$ TeV, $\Gamma_A = 0.4$ TeV

- **HVT searches**: BSM excess ~ 1 fb

vs

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

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



- **In the HEFT case,**

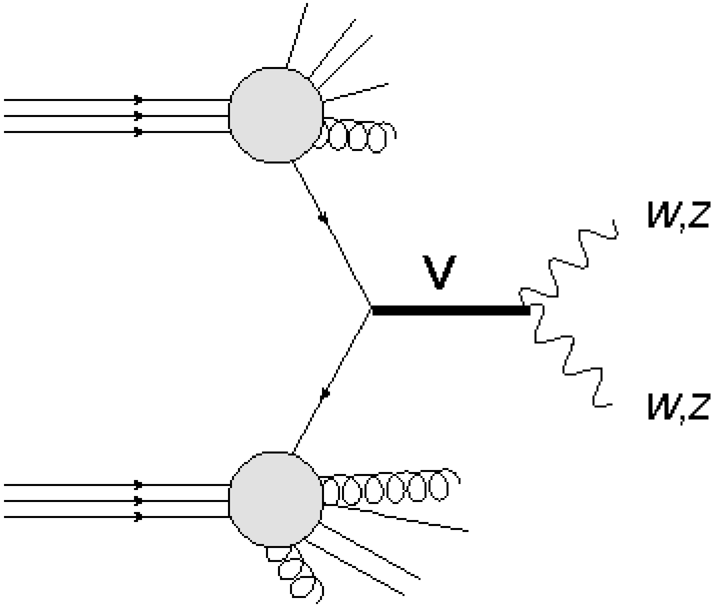
1) DY produces the gauge bosons
[with a weak coupling suppression]

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

- **Additional chiral suppression** ➔ Much more suppressed experimentally:

Resonances with M_R ~ 3 TeV perfectly allowed

- Drell-Yan production mechanism ➔ Completely dominant in all HVT search bounds



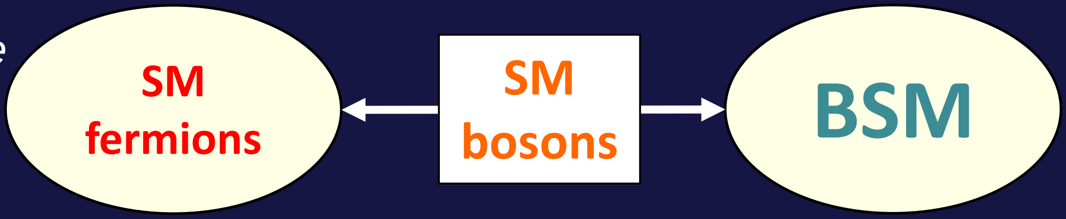
- If DY removed $[\mathcal{B}(R \to q\bar{q}) \ll 10^{-4} - 10^{-6}]$ ➔ No significant exp. lower bound for M_R

[Suppressed
$R \to q\bar{q}$ is not enough;
huge suppression needed]

Conclusions

✓ **Optimistic message:**

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



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

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

✓ **VBS seem to be very promising if these Resonances are where we expect them to be**

✓ **Better data analysis techniques will greatly improve (crucial) VBS and DY searches:**

- **T vs L polarization discrimination** *(e.g., in WZ; see Sauvan and Bittrich ‘s talk)*
- **W, Z, h tagging through “fat” jets** *(e.g., see Apyan’s talk)*

BACKUP

Scale suppression in the loops

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

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

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

➔ 1 loop UV-div:(+)

$$\begin{aligned} S^{1\ell} &= -\frac{\mu^{d-4}}{16\pi^2(d-4)}\int \mathrm{d^dx\,Tr}\left\{\frac{1}{12}[d_\mu,d_\nu]\,[d^\mu,d^\nu] + \frac{1}{2}\Lambda^2\right\} + \text{ finite} \\ &= -\frac{\mu^{d-4}}{16\pi^2(d-4)}\int \mathrm{d^dx}\sum_k \Gamma_k \mathcal{O}_k + \text{ finite} \end{aligned}$$

➔ O(p⁴) renormalization:*,(x) $\delta\mathcal{L}_2 + \delta\mathcal{L}_4^{\mathrm{Fer}} + \delta\mathcal{L}_4^{\mathrm{Bos}}$

- 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 $O(p^4)$: *

$$\mathcal{O}_1 = \frac{1}{4}\langle f_+^{\mu\nu} f_{+\mu\nu} - f_-^{\mu\nu} f_{-\mu\nu}\rangle$$

$$\mathcal{O}_2 = \frac{1}{2}\langle f_+^{\mu\nu} f_{+\mu\nu} + f_-^{\mu\nu} f_{-\mu\nu}\rangle$$

$$\mathcal{O}_3 = \frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle$$

$$\mathcal{O}_4 = \langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle$$

$$\mathcal{O}_5 = \langle u_\mu u^\mu\rangle^2$$

$$\mathcal{O}_6 = \frac{1}{v^2}(\partial_\mu h)(\partial^\mu h)\langle u_\nu u^\nu\rangle$$

$$\mathcal{O}_7 = \frac{1}{v^2}(\partial_\mu h)(\partial_\nu h)\langle u^\mu u^\nu\rangle$$

$$\mathcal{O}_8 = \frac{1}{v^4}(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)$$

$$\mathcal{O}_9 = \frac{1}{v}(\partial_\mu h)\langle f_-^{\mu\nu} u_\nu\rangle$$

$$\mathcal{F}_1 = \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2} = -\frac{v^2}{4}\left(\frac{1}{M_V^2} + \frac{1}{M_A^2}\right)$$

$$\mathcal{F}_2 = -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2} = -\frac{v^2(M_V^4+M_A^4)}{8M_V^2 M_A^2(M_A^2-M_V^2)}$$

$$\mathcal{F}_3 = -\frac{F_V G_V}{2M_V^2} = -\frac{v^2}{2M_V^2}$$

$$\mathcal{F}_4 = \frac{G_V^2}{4M_V^2} = \frac{(M_A^2-M_V^2)v^2}{4M_V^2 M_A^2}$$

$$\mathcal{F}_5 = \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} = \frac{c_d^2}{4M_{S_1}^2} - \frac{(M_A^2-M_V^2)v^2}{4M_V^2 M_A^2}$$

$$\mathcal{F}_6 = -\frac{(\lambda_1^{hA})^2 v^2}{M_A^2} = -\frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6}$$

$$\mathcal{F}_7 = \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2 v^2}{M_A^2} = \frac{d_P^2}{2M_P^2} + \frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6}$$

$$\mathcal{F}_8 = 0$$

$$\mathcal{F}_9 = -\frac{F_A \lambda_1^{hA} v}{M_A^2} = -\frac{M_V^2 v^2}{M_A^4}$$

Same operators as in the 1-loop eff. action

---

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

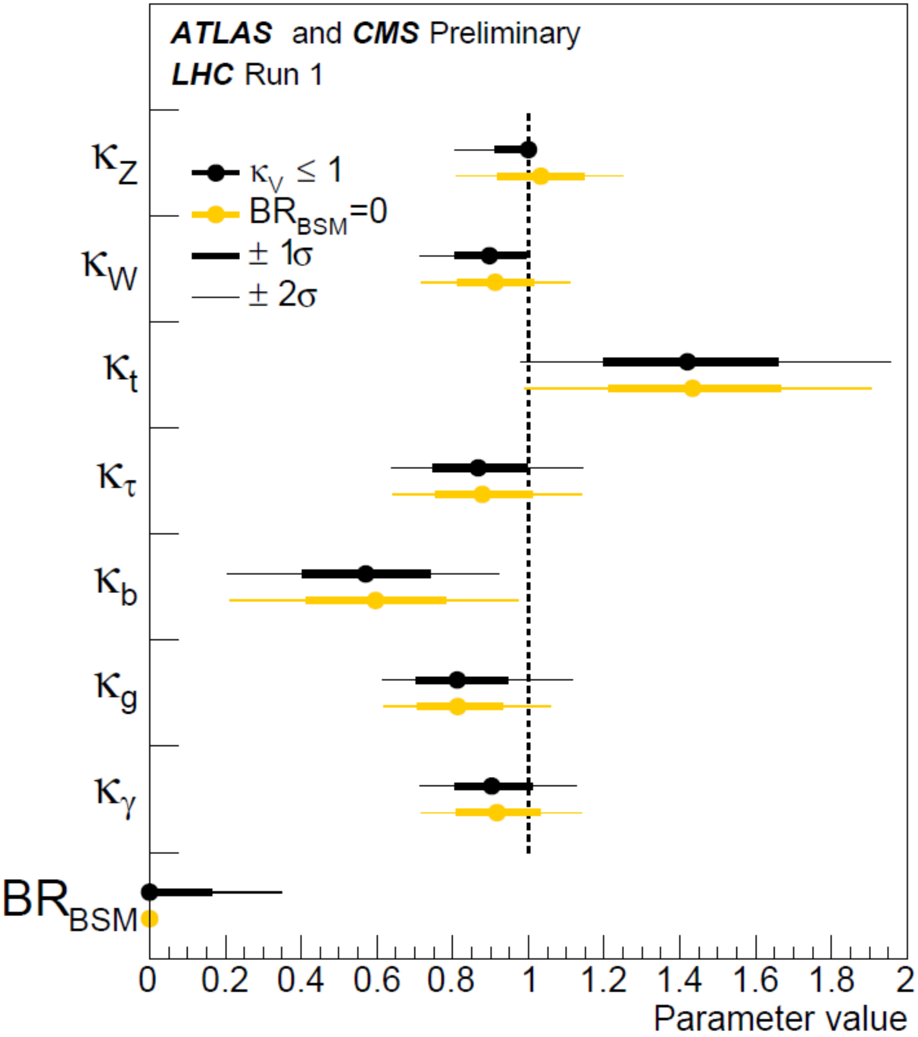
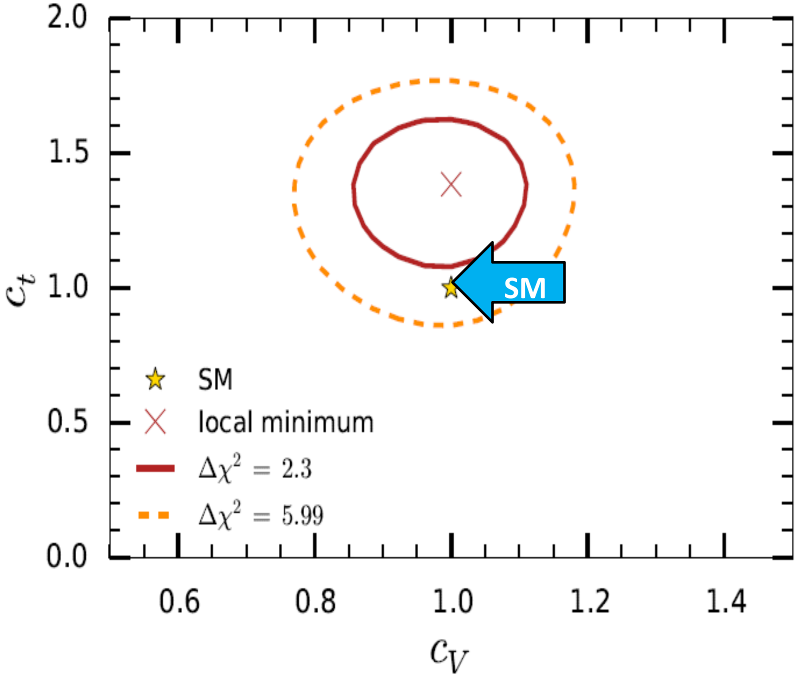


Figure 14: Fit results for the two parameterisations allowing BSM loop couplings, with $\kappa_V \leq 1$, where κ_V stands for κ_Z or κ_W, or without additional BSM contributions to the Higgs boson width, i.e. $\mathrm{BR}_{\mathrm{BSM}} = 0$. The measured results for the combination of ATLAS and CMS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



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

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

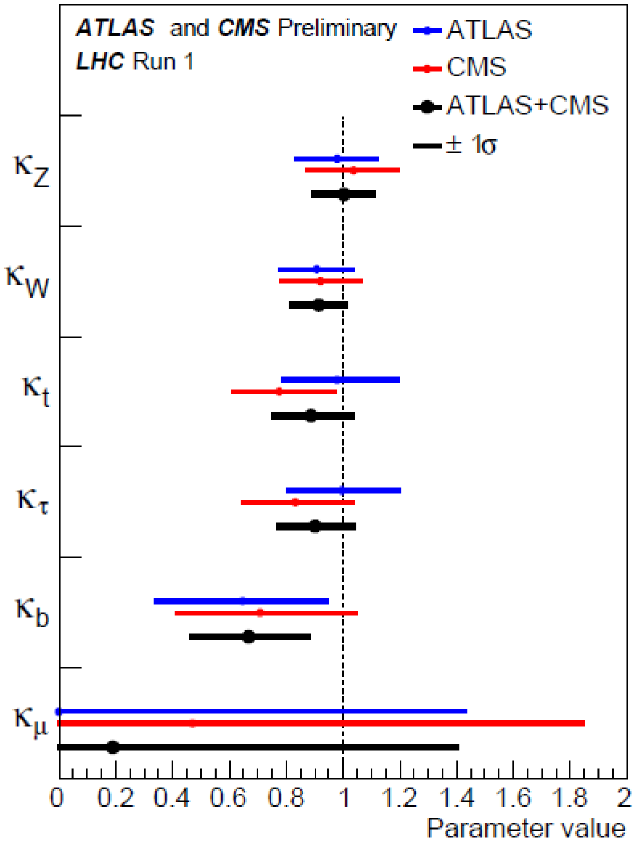


Table 15: Fit results for the parameterisation assuming the absence of BSM particles in the loops, $\mathrm{BR}_{\mathrm{BSM}} = 0$, and $\kappa_j \geq 0$. The measured results with their measured and expected uncertainties are reported for the combination of ATLAS and CMS, together with the measured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

Then, is SMEFT enough?

Can’t we drop the chiral loops?

- It will depend on whether

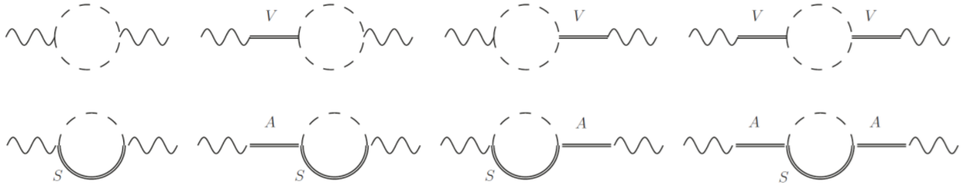
“tiny” *[O(p^4) 1-loop]* << “tiny” *[O(p^4) tree coupling]*

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

---

* Brivio,Corbett,Éboli,Gavela,Gonzalez-Fraile,Gonzalez-Garcia,Merlo,Rigolin JHEP 1403 (2014) 024
* Brivio,Gonzalez-Fraile,Gonzalez-Garcia,Merlo, EPJC76 (2016) no.7, 416

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



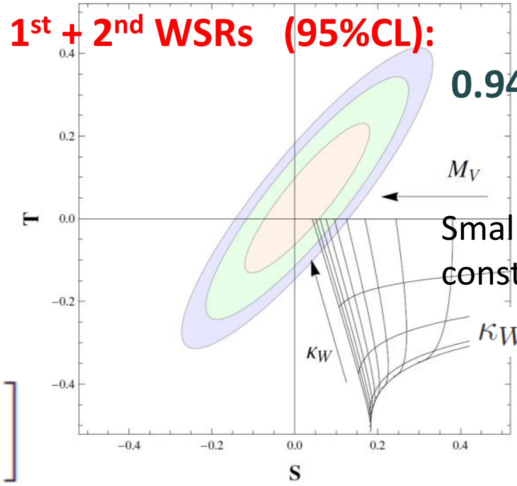
V,A resonances + 1-loop + 2 WSRs

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

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

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

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



$M_V > 4$ TeV

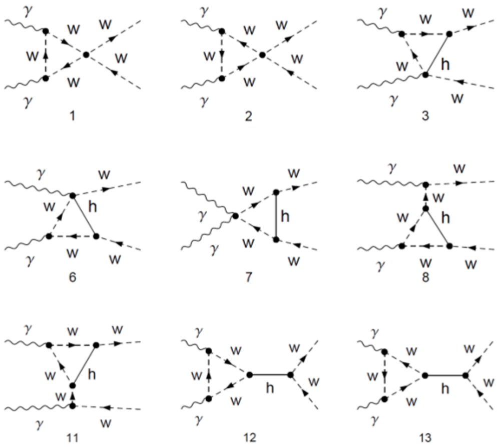
$0.94 < a=\kappa_W < 1$

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

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

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

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

* 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

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

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

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

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

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

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

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

SUMMARY: NAÏVE `CHIRAL' COUNTING

- "Chiral" counting *

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

and for the building blocks,

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

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

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

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

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

- Assignment of the 'chiral' dimension: *

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

* Manohar,Georgi, NPB234 (1984) 189
* Hirn,Stern '05
* Buchalla,Catà,Krause '13
* Pich,Rosell,Santos,SC, forthcoming

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

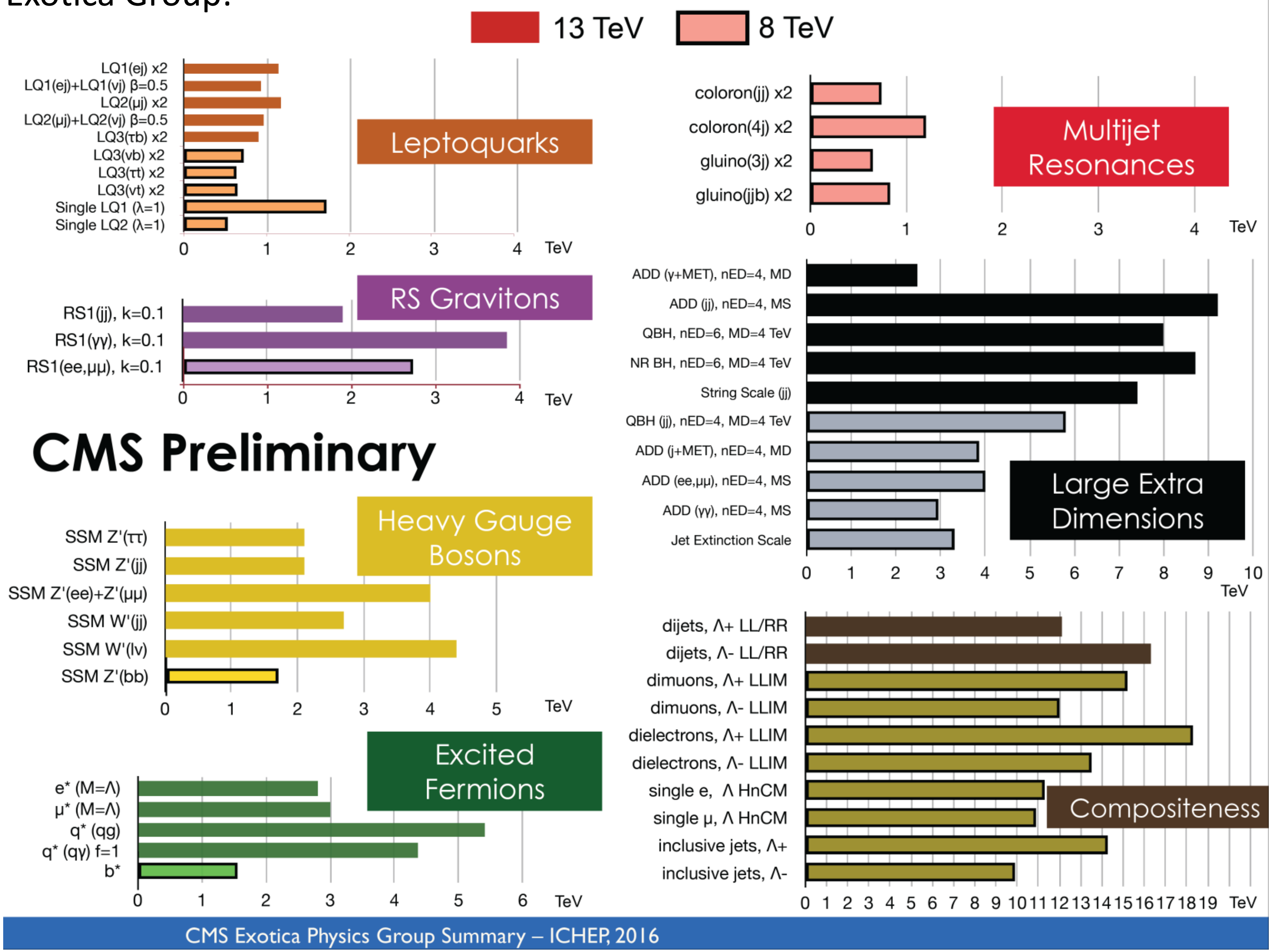
$$|\mathcal{F}_j^{\psi^4}| = 2\pi/\Lambda^2$$

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

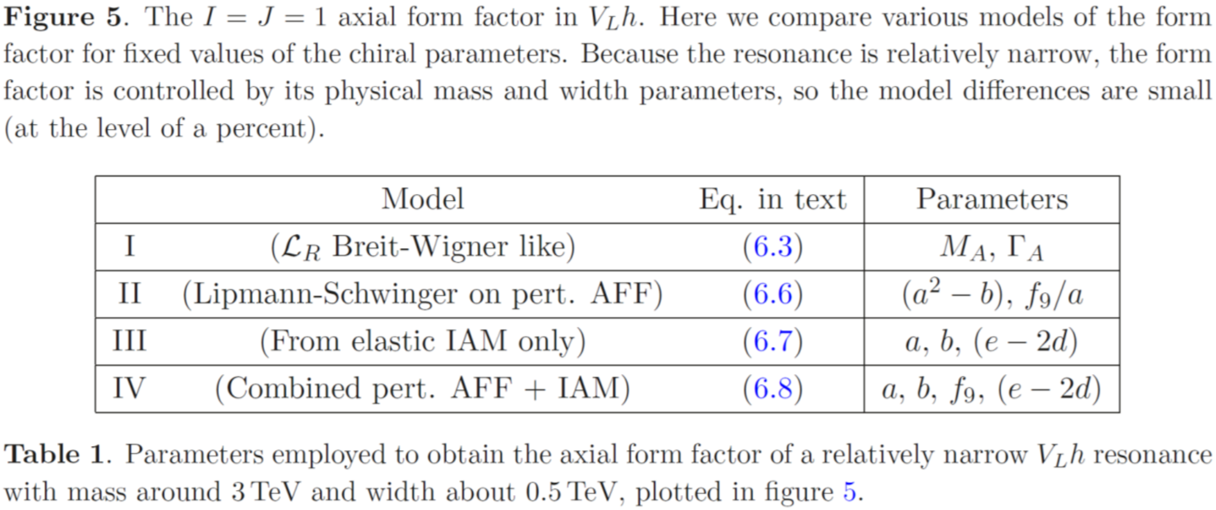


Figure 5. The $I = J = 1$ axial form factor in $V_L h$. Here we compare various models of the form factor for fixed values of the chiral parameters. Because the resonance is relatively narrow, the form factor is controlled by its physical mass and width parameters, so the model differences are small (at the level of a percent).

	Model	Eq. in text	Parameters
I	($\mathcal{L}_R$ Breit-Wigner like)	(6.3)	M_A, Γ_A
II	(Lipmann-Schwinger on pert. AFF)	(6.6)	$(a^2 - b)$, f_9/a
III	(From elastic IAM only)	(6.7)	a, b, $(e - 2d)$
IV	(Combined pert. AFF + IAM)	(6.8)	a, b, f_9, $(e - 2d)$

Table 1. Parameters employed to obtain the axial form factor of a relatively narrow $V_L h$ resonance with mass around 3 TeV and width about 0.5 TeV, plotted in figure 5.

- 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) :

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

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

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

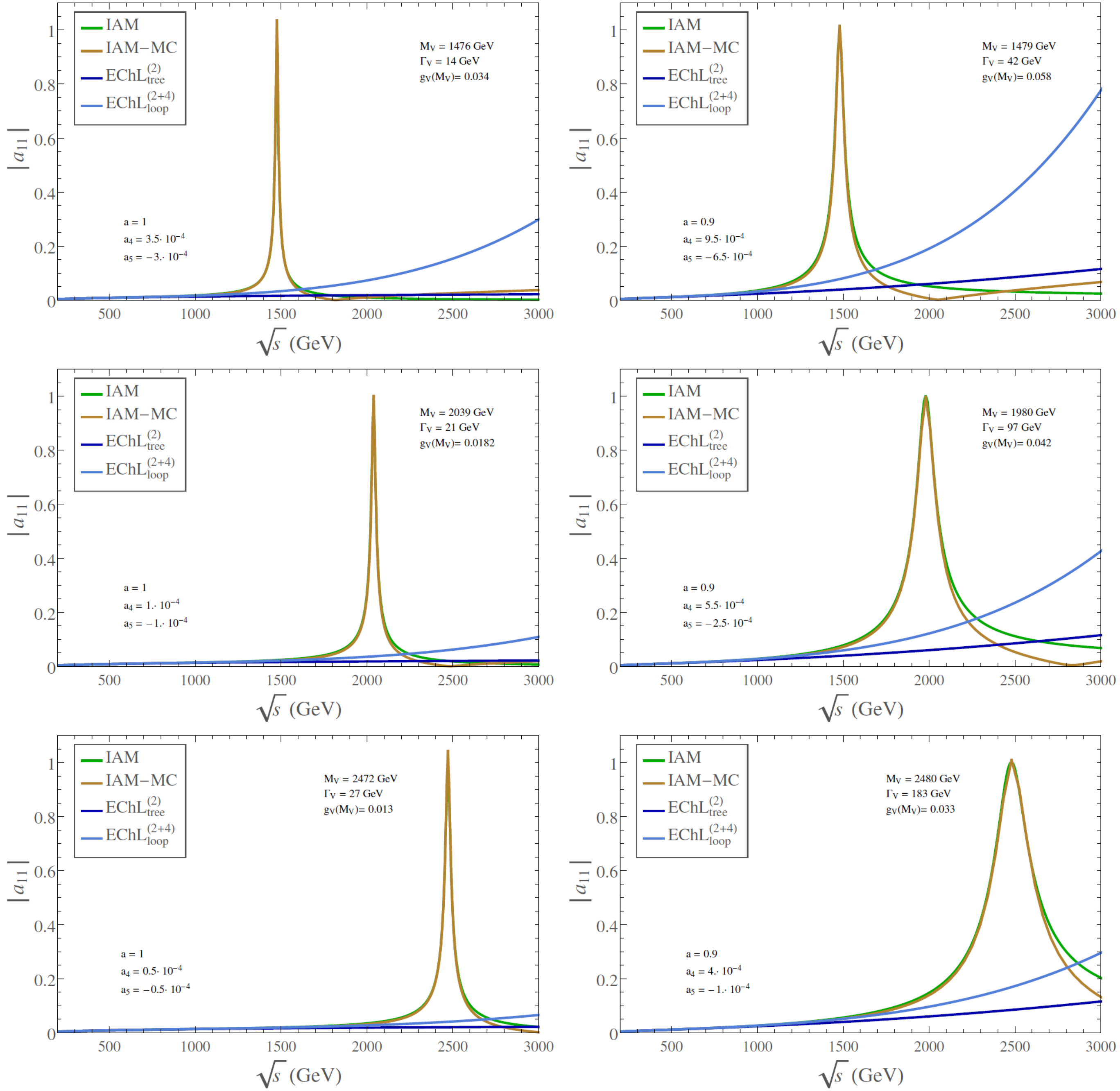
$$u(\varphi) \;=\; \exp\{i\vec\sigma\,\vec\varphi/(2v)\}$$

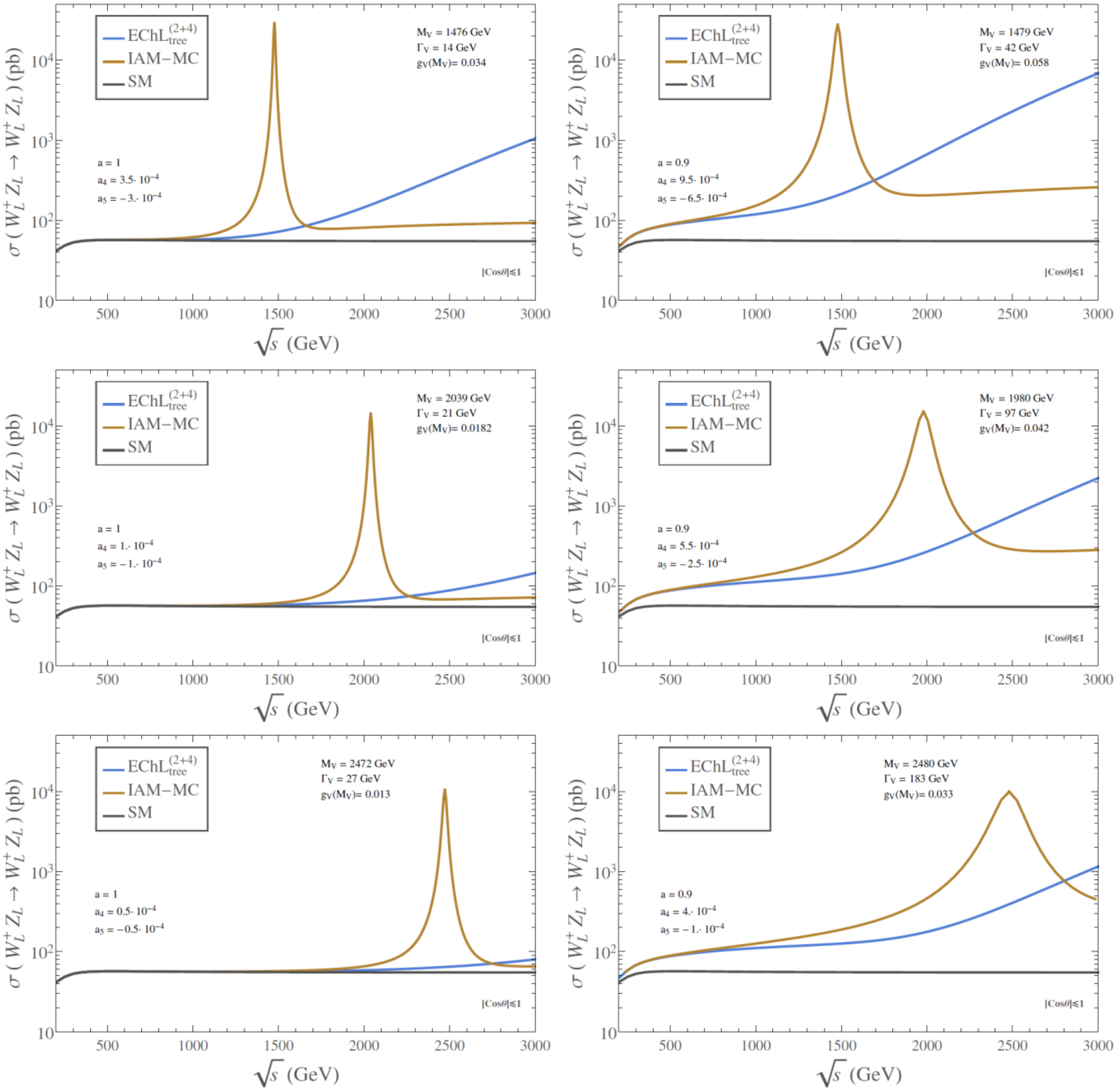
$$u(\varphi) \quad\longrightarrow\quad g_L\,u(\varphi)\,g_h^\dagger \;=\; g_h\,u(\varphi)\,g_R^\dagger\,,$$

$$U(\varphi) \,\equiv\, u(\varphi)^2 \quad\longrightarrow\quad g_L\,U(\varphi)\,g_R^\dagger\,,$$

$$\begin{aligned}v\,,\,\varphi^i\,,\,u(\varphi/v)\,,\,U(\varphi/v)\,,\,h\,,\,W^i_\mu\,,\,B_\mu\,,\,G^a_\mu \;&\sim\; \mathcal{O}\left(p^0\right)\,, \\ \xi\,,\,\bar\xi,\,\psi\,,\,\bar\psi\,,\,D_\mu U\,,\,u_\mu\,,\,\partial_\mu\,,\,D_\mu\,,\,d_\mu\,,\,\nabla_\mu\,,\,\hat W_\mu\,,\,\hat B_\mu\,,\,\hat X_\mu\,,\,\hat G_\mu\,, & \\ m_h\,,\,m_W\,,\,m_Z\,,\,m_\psi\,,\,g\,,\,g'\,,g_S,\,\mathcal{T}\,,\,\mathcal{Y} \;&\sim\; \mathcal{O}\left(p\right)\,, \\ \hat W_{\mu\nu}\,,\,\hat B_{\mu\nu}\,,\,\hat X_{\mu\nu}\,,\,\hat G_{\mu\nu}\,,\,f_{\pm\,\mu\nu}\,,\,c_n^{(V)}\,,\,\bar\eta\,\Gamma\,\zeta \;&\sim\; \mathcal{O}\left(p^2\right)\,, \\ \partial_{\mu_1}\partial_{\mu_2}...\partial_{\mu_n}\,\mathcal{F}(h/v) \;&\sim\; \mathcal{O}\left(p^n\right)\,,\end{aligned}$$

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


IAM
IAM−MC
$\mathrm{EChL}^{(2)}_{\mathrm{tree}}$
$\mathrm{EChL}^{(2+4)}_{\mathrm{loop}}$
$|a_{11}|$
$\sqrt{s}$ (GeV)
0
0.2
0.4
0.6
0.8
1
500
1000
1500
2000
2500
3000
M_V = 1476 GeV
Γ_V = 14 GeV
$g_V(M_V)$= 0.034
a = 1
$a_4 = 3.5\cdot 10^{-4}$
$a_5 = -3.\cdot 10^{-4}$
M_V = 1479 GeV
Γ_V = 42 GeV
$g_V(M_V)$= 0.058
a = 0.9
$a_4 = 9.5\cdot 10^{-4}$
$a_5 = -6.5\cdot 10^{-4}$
M_V = 2039 GeV
Γ_V = 21 GeV
$g_V(M_V)$= 0.0182
a = 1
$a_4 = 1.\cdot 10^{-4}$
$a_5 = -1.\cdot 10^{-4}$
M_V = 1980 GeV
Γ_V = 97 GeV
$g_V(M_V)$= 0.042
a = 0.9
$a_4 = 5.5\cdot 10^{-4}$
$a_5 = -2.5\cdot 10^{-4}$
M_V = 2472 GeV
Γ_V = 27 GeV
$g_V(M_V)$= 0.013
a = 1
$a_4 = 0.5\cdot 10^{-4}$
$a_5 = -0.5\cdot 10^{-4}$
M_V = 2480 GeV
Γ_V = 183 GeV
$g_V(M_V)$= 0.033
a = 0.9
$a_4 = 4.\cdot 10^{-4}$
$a_5 = -1.\cdot 10^{-4}$


EChL$^{(2+4)}_{\rm tree}$
IAM−MC
SM
M_V = 1476 GeV
Γ_V = 14 GeV
$g_V(M_V)$= 0.034
a = 1
$a_4 = 3.5\cdot 10^{-4}$
$a_5 = -3.\cdot 10^{-4}$
M_V = 1479 GeV
Γ_V = 42 GeV
$g_V(M_V)$= 0.058
a = 0.9
$a_4 = 9.5\cdot 10^{-4}$
$a_5 = -6.5\cdot 10^{-4}$
M_V = 2039 GeV
Γ_V = 21 GeV
$g_V(M_V)$= 0.0182
a = 1
$a_4 = 1.\cdot 10^{-4}$
$a_5 = -1.\cdot 10^{-4}$
M_V = 1980 GeV
Γ_V = 97 GeV
$g_V(M_V)$= 0.042
a = 0.9
$a_4 = 5.5\cdot 10^{-4}$
$a_5 = -2.5\cdot 10^{-4}$
M_V = 2472 GeV
Γ_V = 27 GeV
$g_V(M_V)$= 0.013
a = 1
$a_4 = 0.5\cdot 10^{-4}$
$a_5 = -0.5\cdot 10^{-4}$
M_V = 2480 GeV
Γ_V = 183 GeV
$g_V(M_V)$= 0.033
a = 0.9
$a_4 = 4.\cdot 10^{-4}$
$a_5 = -1.\cdot 10^{-4}$
$|\cos\theta|\leq 1$
$\sigma\,(W_L^+ Z_L \to W_L^+ Z_L)$ (pb)
10
10^2
10^3
10^4
500
1000
1500
2000
2500
3000
$\sqrt{s}$ (GeV)

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

- SMEFT → EWχL :*

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

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

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

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

- Non-linear scenarios: e.g., dilaton models (x) $\longrightarrow \boxed{\Delta(\mathrm{a}^2) = \Delta\mathrm{b}}$

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 … : $^{(x), (+), *}$

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

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

- Amplitudes organized according to chiral exp.: $^{(x), \;*}$

  - **Dominant corrections:** Deviations from SM in $O(p^2)$ operators
  - **Subdominant corrections:** $\underbrace{O(p^4)\text{ operators}}_{\textit{(heavier states)}} \; + \; \underbrace{O(p^2)\text{ loops}}_{\textit{(non-linearity)}}$

- 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).

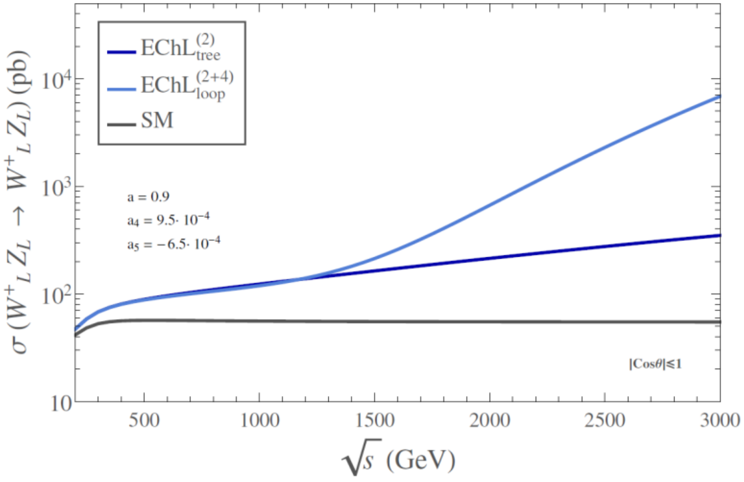
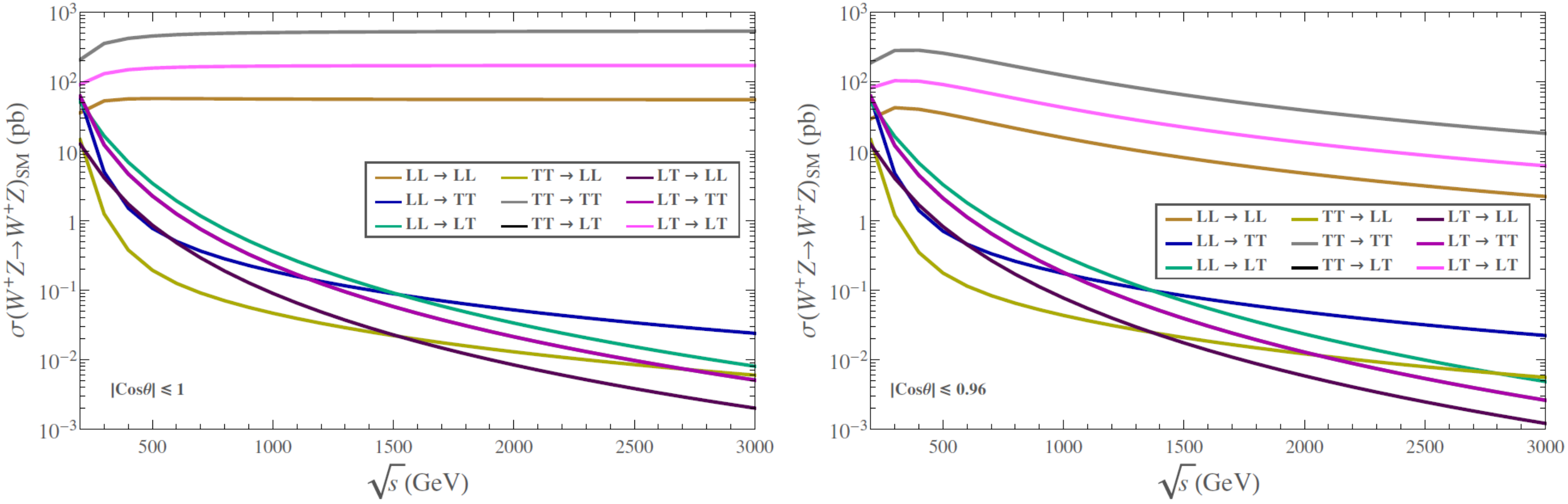
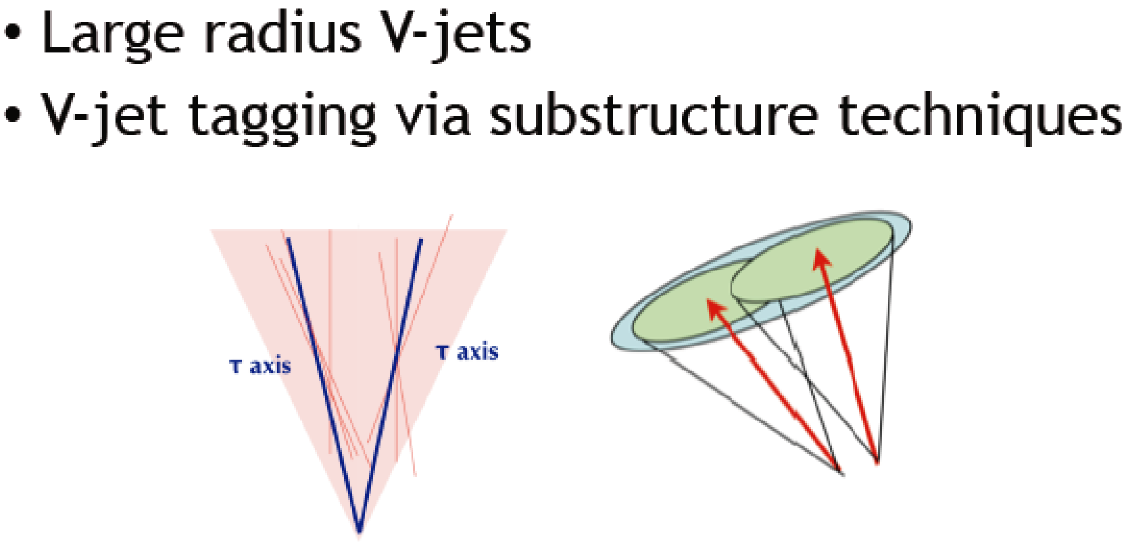


Figure 2. Predictions of the cross section $\sigma(W_L Z_L \to W_L Z_L)$ as a function of the center of mass energy $\sqrt{s}$ from the EChL. The predictions at leading order, $\text{EChL}^{(2)}_{\text{tree}}$, and next to leading order, $\text{EChL}^{(2+4)}_{\text{loop}}$, are displayed separately. The EChL coefficients are set here to $a = 0.9$, $b = a^2$, $a_4 = 9.5\times10^{-4}$ and $a_5 = -6.5\times10^{-4}$. 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:



- Fat jets:
  - See Apyan’s talk

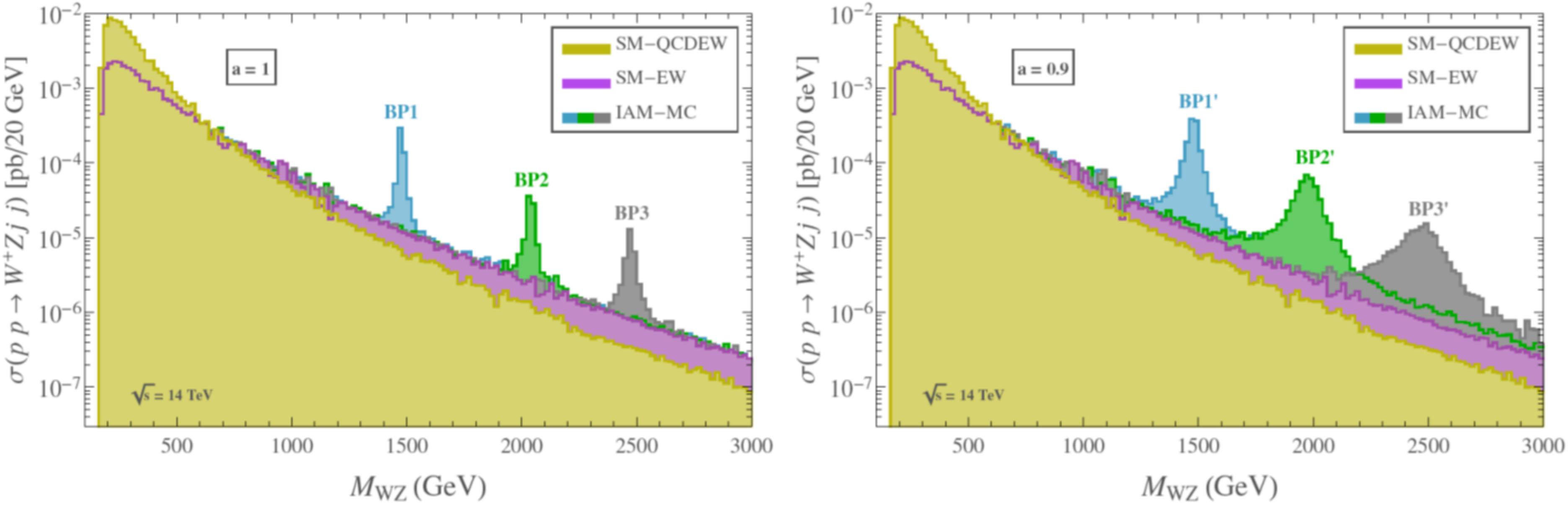


- Large radius V-jets
- V-jet tagging via substructure techniques

Sirunyan et al [CMS], PRL 120 (2018) no.7, 071802

- Optimal VBS cuts: (MG5_aMC + IAM-MC UFO; no detector sim)

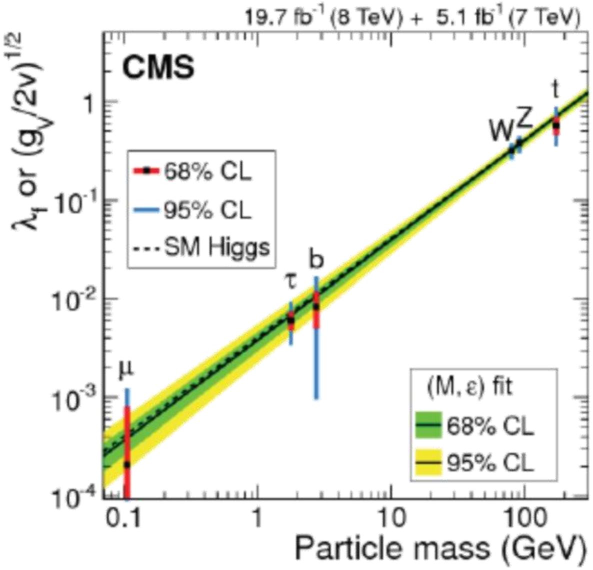
$$
\begin{aligned}
2 < |\eta_{j_1,j_2}| &< 5\,, \\
\eta_{j_1}\cdot\eta_{j_2} &< 0, \\
p_T^{j_1,j_2} &> 20\,\mathrm{GeV}\,, \\
M_{jj} &> 500\,\mathrm{GeV}\,, \\
|\eta_{W,Z}| &< 2\,.
\end{aligned}
$$



- MG5_aMC: generate pp > W+ Z j j , Z > l+ l- ,W+ > l+ vl

(Onshell, Madspin OFF, Madevent ON)

Motivation for “non-linear” EFTs



1) “We are so close to SM, so why not

simply using SMEFT with the ϕ Higgs doublet?

Isn’t this enough?”

2) “Aren’t BSM loops essentially negligible?

In general NO, only true if “tiny” << “tiny”

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

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

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

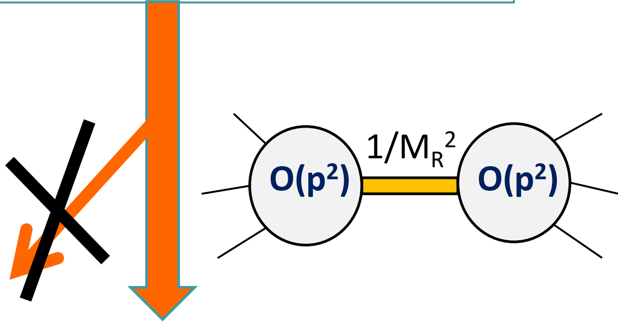
R contributions to the NLO EFT couplings *[i.e., $O(p^4)$]*

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

  General ΔL_R `up to $O(p^2)$' **

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

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



$$\mathcal{L}_{ECLh} = \underset{\supset\ \mathcal{L}^{\rm SM}}{\mathcal{L}_{p^2}} + \mathcal{L}_{p^4} + \ \ldots$$

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

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

$$\Delta\mathcal{L}_{p^4}^{\rm EFT} = \frac{1}{2M_R^2}\left(\langle \mathcal{O}_R\,\mathcal{O}_R\rangle - \frac{1}{N}\langle\mathcal{O}_R\rangle^2\right) \qquad (R=S,\,P)\,,$$

$$\Delta\mathcal{L}_{p^4}^{\rm EFT} = -\frac{1}{M_R^2}\left(\langle \mathcal{O}_R^{\mu\nu}\,\mathcal{O}_{R\,\mu\nu}\rangle - \frac{1}{N}\langle\mathcal{O}_R^{\mu\nu}\rangle^2\right) \qquad (R=V,\,A)\,,$$

$$\Delta\mathcal{L}_{p^4}^{\rm EFT} = \frac{1}{2M_{R_1}^2}\,(\mathcal{O}_{R_1})^2 \qquad (R_1=S_1,\,P_1)\,,$$

$$\Delta\mathcal{L}_{p^4}^{\rm EFT} = -\frac{1}{M_{R_1}^2}\,(\mathcal{O}_{R_1}^{\mu\nu}\,\mathcal{O}_{R_1\,\mu\nu}) \qquad (R_1=V_1,\,A_1)\,.$$

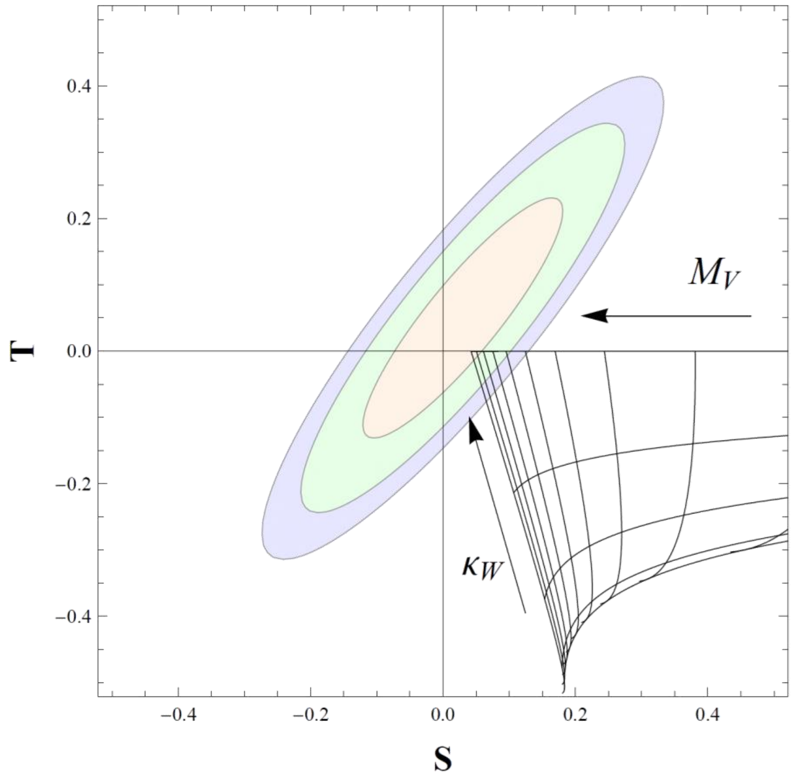
(classification of the operators according to `chiral' dimension)

- Impose UV-completion assumptions on L_R, (sum-rules,unitarity...)

  ➔ **EFT predictions ****

NLO results: 1st and 2nd WSRs

(*asymptotically-free theories*)



[Pich,Rosell,SC'12]

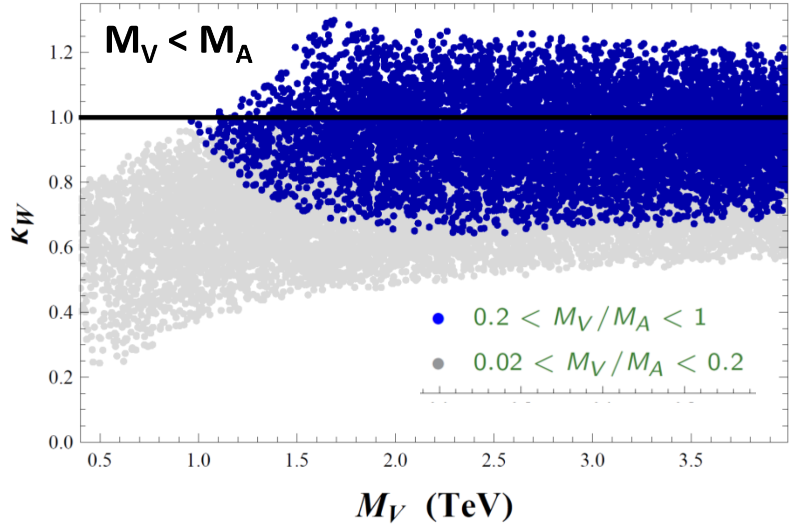
At NLO with the 1st and 2nd WSRs

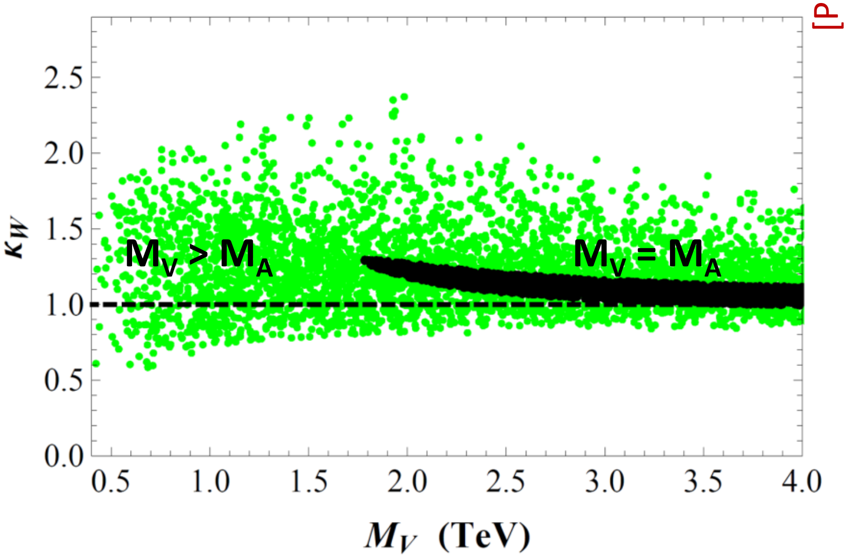
$M_V > 5.4$ TeV, $0.97 < \kappa_W < 1$ at 68% CL

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

NLO results: only 1st WSR

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





[Pich,Rosell,SC'12]

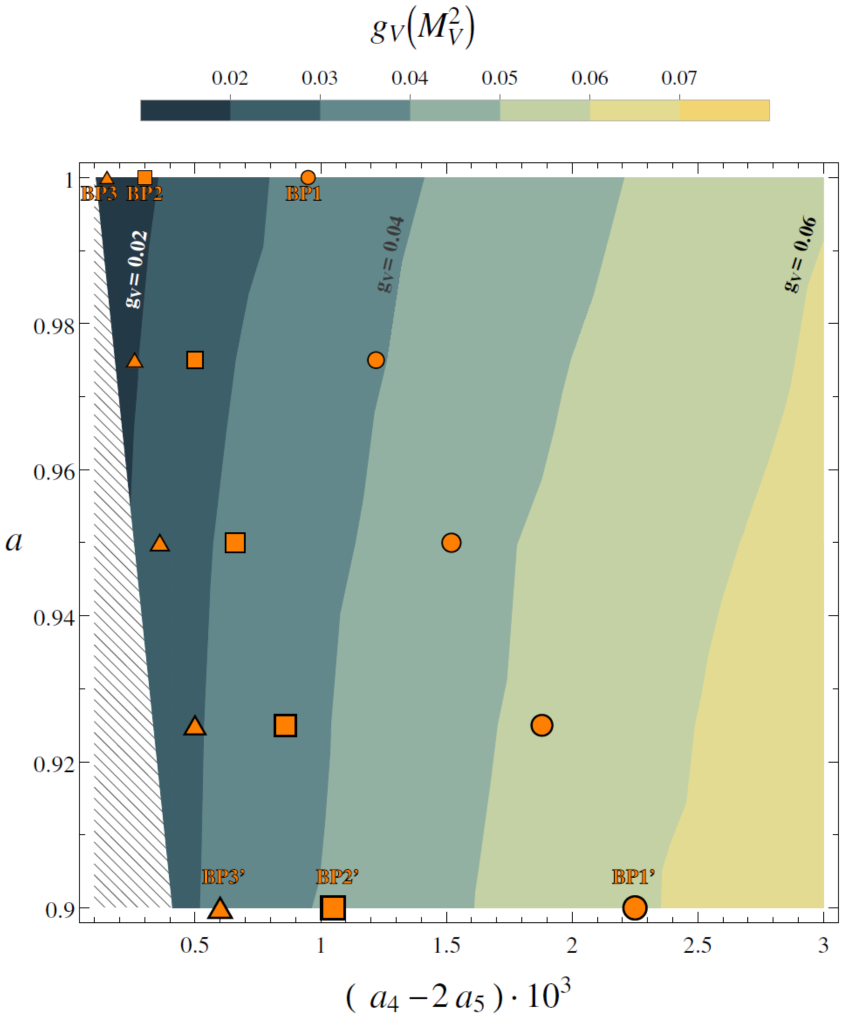
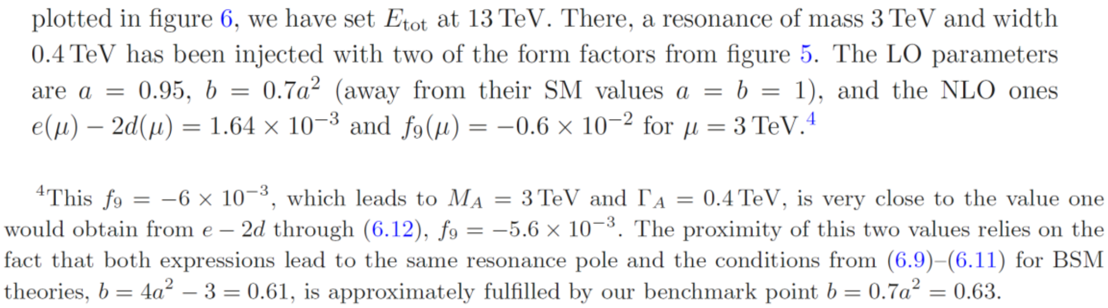


Figure 6. Predictions of $g_V(M_V^2)$ as a function of a and $(a_4 - 2a_5)$ computed from eq. (4.10), as discussed in the text. The benchmark points specified with geometric symbols correspond respectively to those in figure 4.

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

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

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



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 $b = 0.7a^2 = 0.63$.

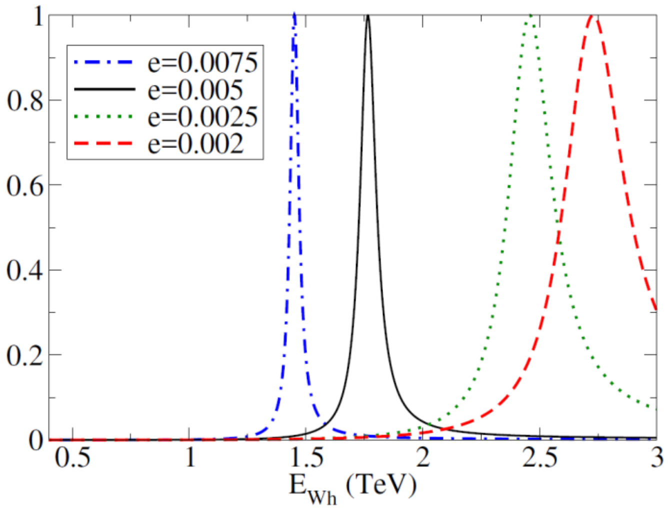


Figure 2. The $I = J = 1$ axial resonance generated in $V_L h$ scattering by the e counterterm in the NLO HEFT Lagrangian, with values of the constant at $\mu = 3\,\text{TeV}$ as indicated in the legend. Here, $d = 0$, $a = 0.95$ and $b = 0.7a^2$ are fixed.

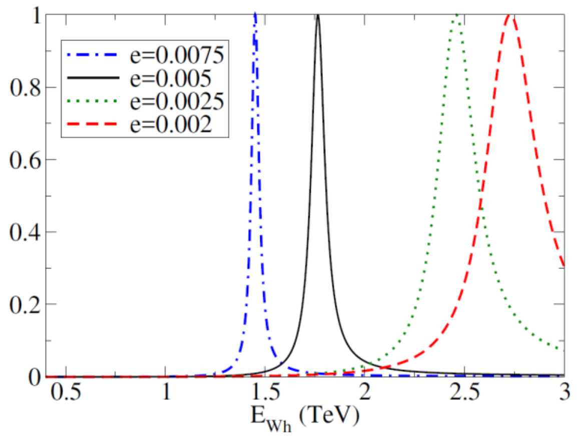


Figure 4. The $I = J = 1$ axial resonance generated in $V_L h$ scattering with $a = 0.95$. Here we have fixed $2a^2 - b = 1$ which is a characteristic prediction of Minimally CHM. We set $d = 0$.

$$\tilde{M}_{11}(s) = \frac{M_{11}^{(0)}(s)^2}{M_{11}^{(0)}(s) - M_{11}^{(1)}(s)}$$

$$M_{11}(s) = M_{11}^{(0)}(s) + M_{11}^{(1)}(s) = K s + s^2 \left[B(\mu) + D \log \frac{s}{\mu^2} + E \log \frac{-s}{\mu^2} \right]$$

$$\begin{aligned} K &= \frac{a^2 - b}{96\pi v^2} \\ B(\mu) &= \frac{e^r(\mu) - 2d^r(\mu)}{96\pi v^4} - \frac{a^2 - b}{110592\pi^3 v^4} \left(150(1 - a^2) - 83(a^2 - b)\right) \\ D &= \frac{a^2 - b}{4608\pi^3 v^4} \left(3(1 - a^2) - (a^2 - b)\right) \\ E &= -\frac{(a^2 - b)^2}{9216\pi^3 v^4} \, . \end{aligned}$$

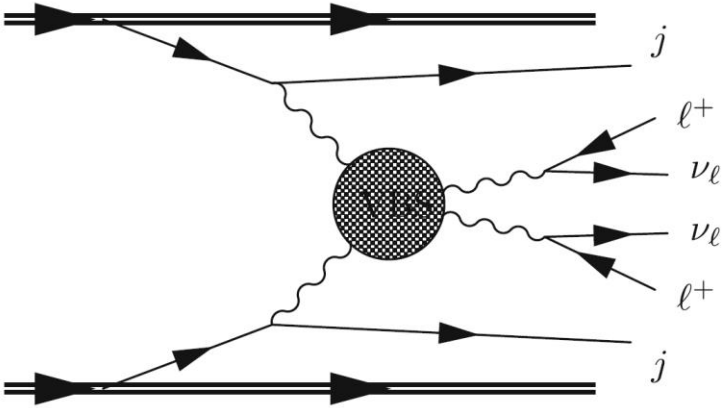
$$M_A^2 = \frac{K}{B} = v^2 \frac{a^2 - b}{e - 2d + \frac{a^2 - b}{1152\pi^2}[150(a^2 - 1) + 83(a^2 - b)]}$$

$$\gamma_A = \frac{K^2}{B + D + E} = \frac{\gamma_A^0}{1 - \frac{3}{\pi}\gamma_A^0 \left(1 + 2\frac{a^2 - 1}{a^2 - b}\right)}$$

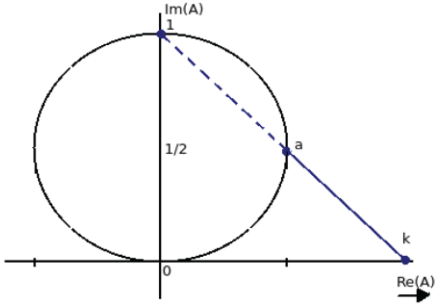
$$\Gamma_A^0 = M_A \gamma_A^0 = \frac{a^2 - b}{96\pi v^2} M_A^3$$

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

VBFNLO analysis



K-matrix (or T-matrix)



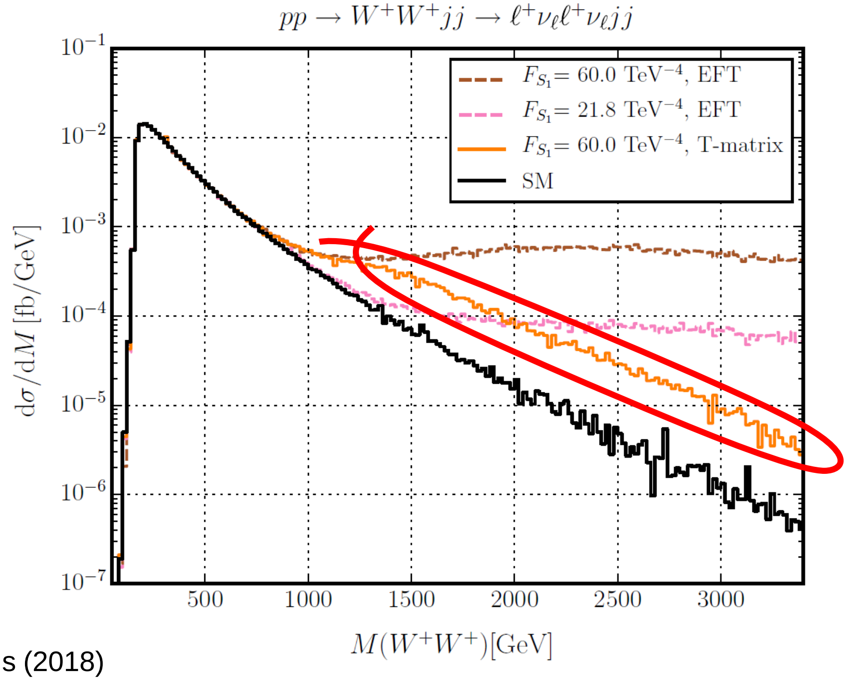
$$T = \mathrm{Re}(T_o)\left(\mathbb{1} - \frac{i}{2}T_o^\dagger\right)^{-1}$$

- (Linear) SMEFT dim=8:

$$\mathcal{O}_{S_0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right],$$
$$\mathcal{O}_{S_1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S_2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right].$$

$$\mathcal{O}_{M_0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_2} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_3} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi\right] \times \widehat{B}^{\beta\nu},$$
$$\mathcal{O}_{M_5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi\right] \times \widehat{B}^{\beta\mu},$$
$$\mathcal{O}_{M_5'} = \left[(D_\mu\Phi)^\dagger \widehat{W}^{\beta\mu} D^\nu\Phi\right] \times \widehat{B}_{\beta\nu},$$
$$\mathcal{O}_{M_7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu} D^\nu\Phi\right].$$

$$\mathcal{O}_{T_0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right],$$
$$\mathcal{O}_{T_1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right],$$
$$\mathcal{O}_{T_2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right],$$
$$\mathcal{O}_{T_5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta},$$
$$\mathcal{O}_{T_6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu},$$
$$\mathcal{O}_{T_7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha},$$
$$\mathcal{O}_{T_8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta},$$
$$\mathcal{O}_{T_9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}.$$



* VBFNLO: Perez,Sekulla,Zeppenfeld, EPJC78 (2018) no.9, 759; Perez, PhD Thesis (2018)

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.

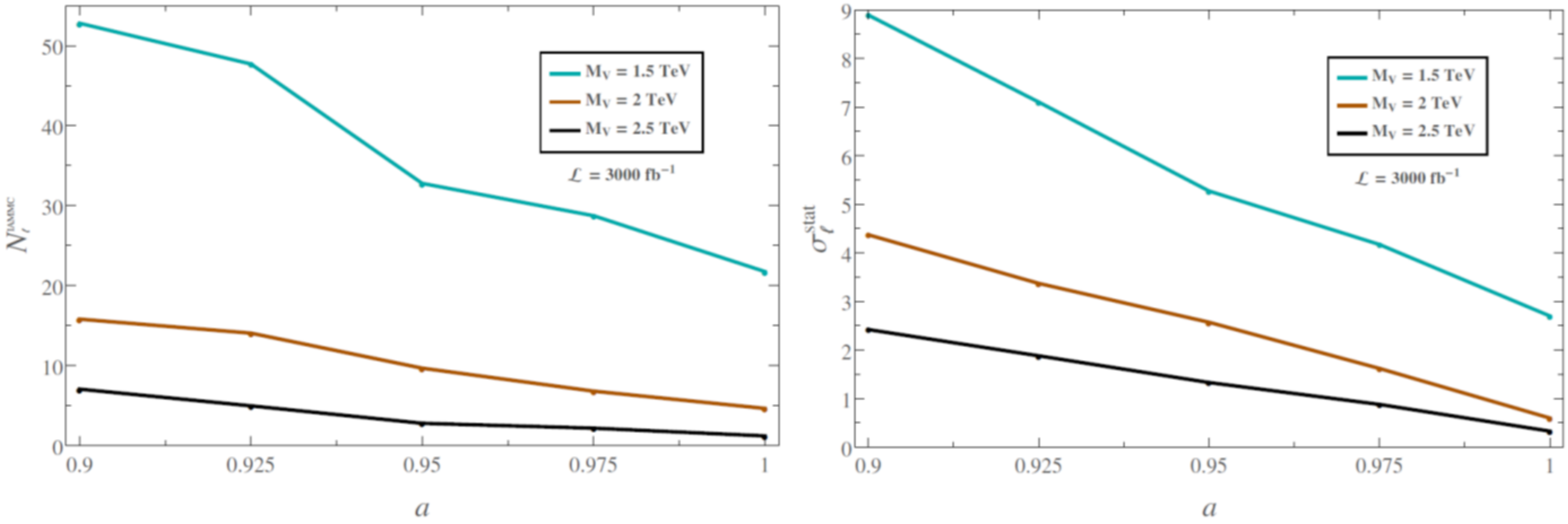


Figure 17. Predictions for the number of $pp \to \ell_1^+ \ell_1^- \ell_2^+ \nu jj$ events, $\mathrm{N}_\ell^{\mathrm{IAM-MC}}$, (left panel) and the statistical significance, $\sigma_\ell^{\rm stat}$, (right panel) as a function of the parameter a for $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$. Marked points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