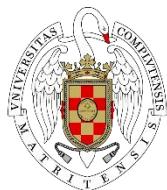


Suppression of fermionic operators in the HEFT

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F. Alvarado, A. Guevara, SC, arXiv:1909.00875 [hep-ph]; Acta Phys.Polon.B 50 (2019) 1937-1953; in preparation

Outline

- 1.) BSM searches & NP scale: high-mass bounds vs low-mass bounds
- 2.) A simple scenario: naturally suppressing SM fermion interactions
- 3.) Conclusions: possibility of NP states at 1 – 2 TeV

1.) Limits on NP-scale:

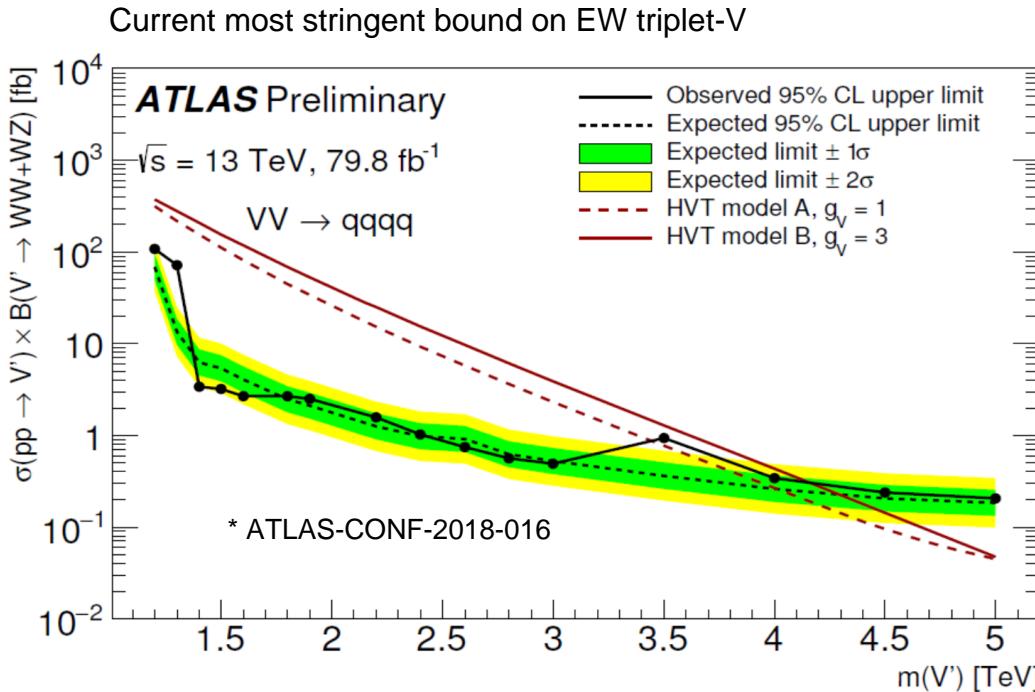
high-mass bounds

vs

low-mass bounds

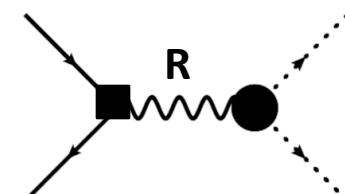
1.) R mass bounds: diboson resonance searches* “have established” $M_R \gtrsim 4$ TeV

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



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

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



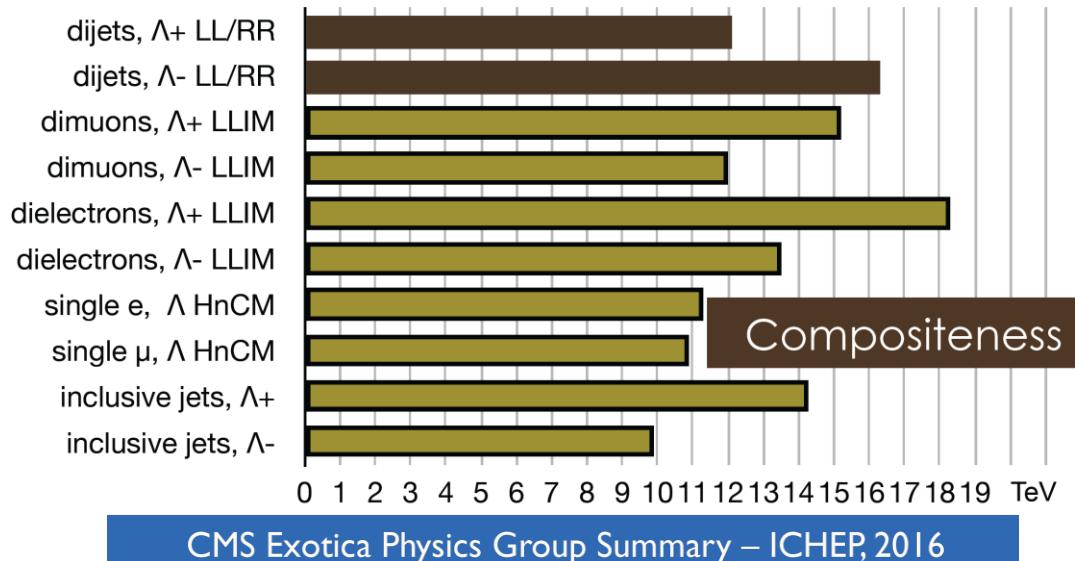
(x) Pappadopulo, Thamm, Torre, Wulzer, JHEP 1409 (2014) 060

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

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

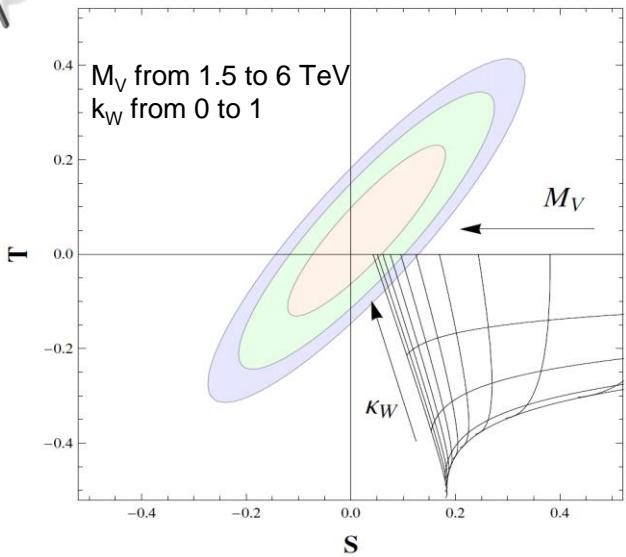
* Aguilar-Saavedra et al, arXiv:1802.07237 [hep-ph]

* Isidori, arXiv:1302.0661 [hep-ph]

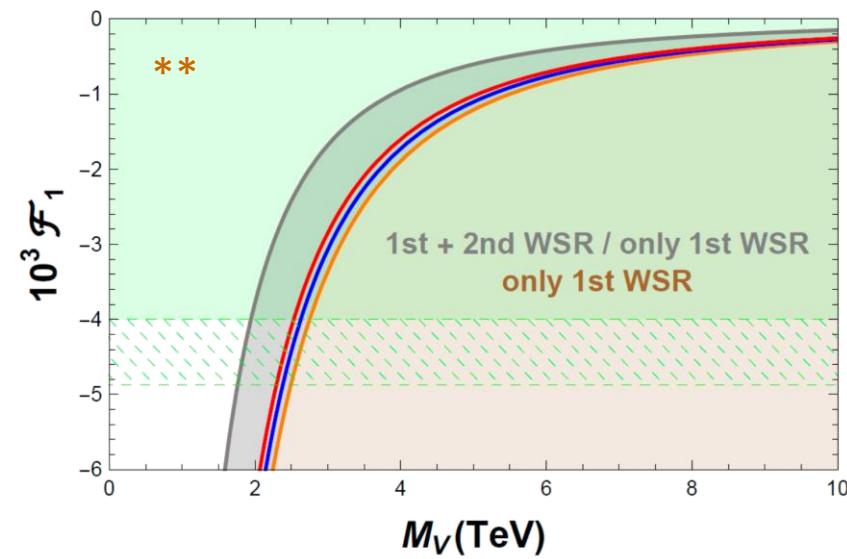
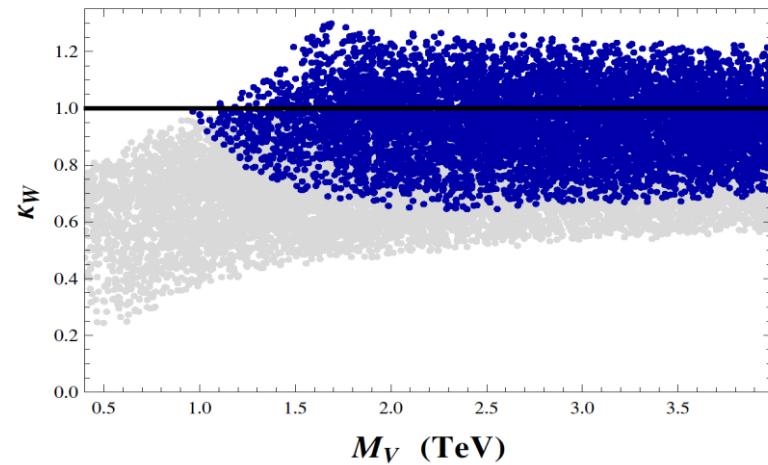
* Jung,Straub, arXiv:1801.01112 [hep-ph].

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

Scenario 1+2-WSR *



Scenario 1-WSR *



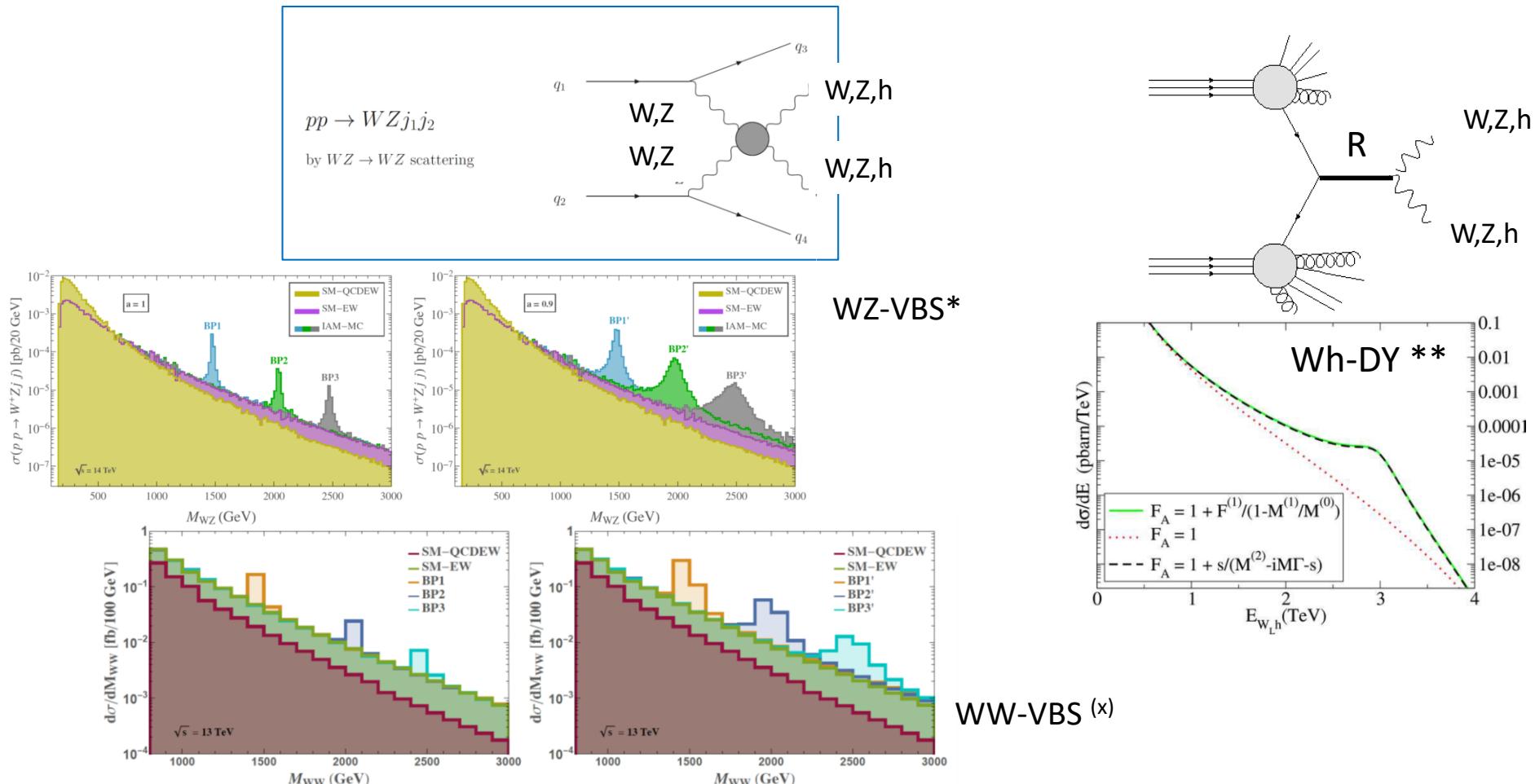
[** Pich,Rosell,SC, 2004.02827 [hep-ph].

See I. Rosell's talk on Thu 30th July]

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

4.) Likewise, VBS and DY production searches on few-TeV Resonances yields:

- $M_R \sim 1 - 3 \text{ TeV} \rightarrow \text{LHC clearly not yet sensitive}$
- $M_R \sim 1 - 2 \text{ TeV} \rightarrow \text{might be seen at HL-LHC (3 } ab^{-1} \text{ & } \Gamma_R > 40 \text{ GeV)}$



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

(x) Delgado,Garcia-Garcia,Herrero, JHEP 11 (2019) 065

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

2.) Suppressing fermionic EFT operators

(x) F. Alvarado, A. Guevara, SC, arXiv:1909.00875 [hep-ph]; Acta Phys.Polon.B 50 (2019) 1937-1953; in preparation
Further details: <https://drive.google.com/file/d/1zPuZs4bqBwbw2Bq17s2uiiPYh3UOKmHz/view>

- Is it possible to conciliate these results?

Four fermion operators very suppressed

LHC exp searches exclude low M_R

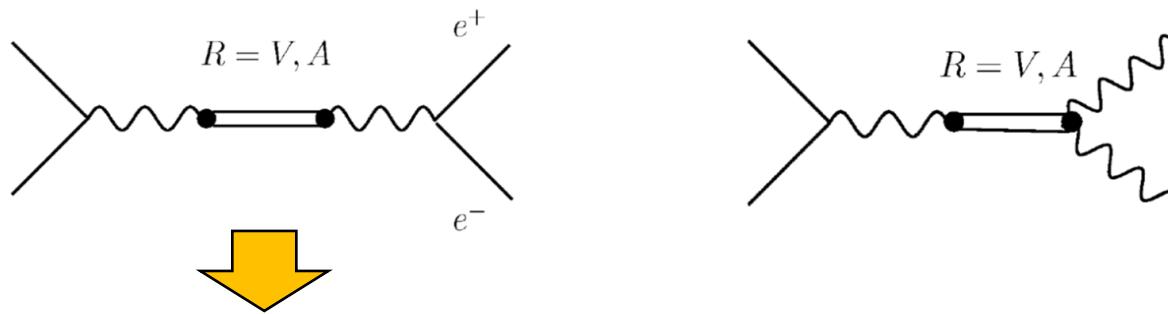
VBS → tiny σ even for $M_R \sim 1 - 3$ TeV

DY → tiny σ even for $M_R \sim 3$ TeV

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

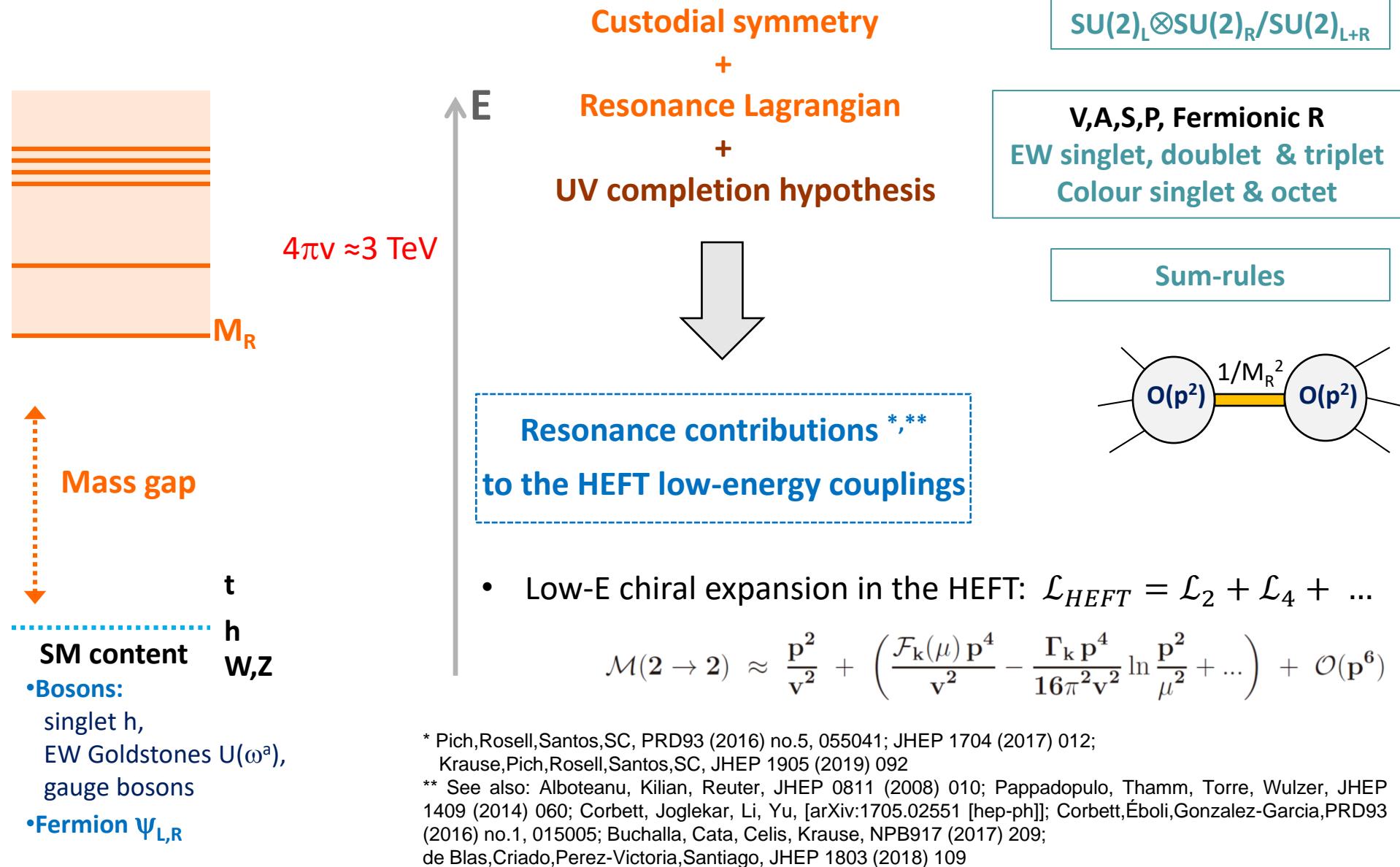
- A simple scenario solution motivated by the DY analysis [Cata,Isidori,Kamenik, NPB822 (2009) 230-244]:

SM fermions couple to R via EW gauge bosons



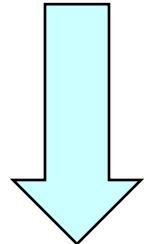
- **Low-E HEFT if no direct interactions between NP \Leftrightarrow SM fermions?**

R contributions to low-E HEFT *



Impact of this “Resonance – gauge-boson mixing” in the HEFT?

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



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

(similar for A)

$$\mathcal{L}^{\text{EWET}} = \mathcal{L} \Big|_{R \rightarrow R^{c\ell}} = \mathcal{L}_2^{\text{EWET}} + \mathcal{L}_4^{\text{EWET}} + \mathcal{L}_6^{\text{EWET}} + \dots$$

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

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

- \mathcal{L}_4 EFT fermionic operators: absent
- \mathcal{L}_4 EFT custodial breaking ops: absent

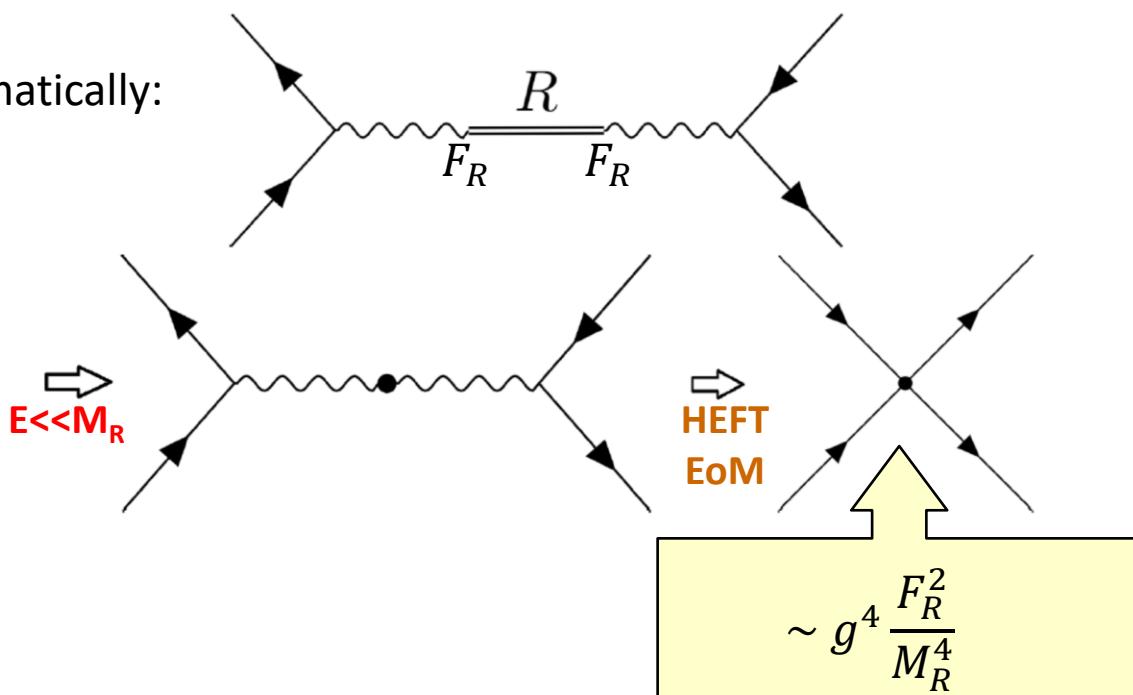
(*) Pich,Rosell,Santos,SC, PRD93 (2016) no.5, 055041; JHEP 1704 (2017) 012; Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

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

- **Resonance – gauge boson mixing:** terms in the HEFT with the structure of \mathcal{L}_4 (*but the suppression of \mathcal{L}_6*)

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

- Diagrammatically:



(x) F. Alvarado, A. Guevara, SC, arXiv:1909.00875 [hep-ph]; Acta Phys.Polon.B 50 (2019) 1937-1953; in preparation
Further details: <https://drive.google.com/file/d/1zPuZs4bqBwbw2Bg17s2uiiPYh3UOKmHz/view>

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

→ Usual experimental parametrization:

$$\mathcal{L}_{EWET} \supset \mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2} \left(\eta_{\ell\ell} J_\mu^\ell J^{\ell,\mu} + \eta_{rr} J_\mu^r J^{r,\mu} + 2\eta_{r\ell} J_\mu^r J^{\ell,\mu} \right) \quad [\text{combinations of } \mathfrak{F}_j^{\psi^4} \text{ couplings in } \mathcal{L}_4]$$

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

→ Our prediction:

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

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

* Two Weinberg SR employed:

$$F_V^2 - F_A^2 - v^2 = 0 \text{ and } F_V^2 M_V^2 - F_A^2 M_A^2 = 0.$$

$$\Lambda \geq 20 \text{ TeV}$$

$r = M_A^2/M_V^2$	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) F. Alvarado, A. Guevara, SC, arXiv:1909.00875 [hep-ph];

Acta Phys.Polon.B 50 (2019) 1937-1953; in preparation. Further details: <https://drive.google.com/file/d/1zPuZs4bqBwbw2Bg17s2uiiPYh3UOKmHz/view>

• \mathcal{L}_4 EFT custodial breaking ops:

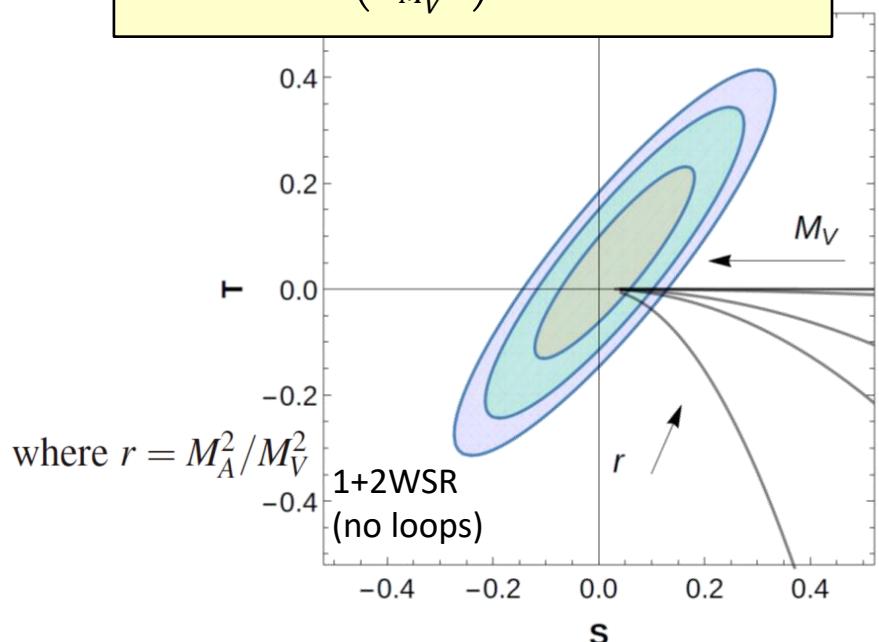
present [$O(p^6)$ suppressed]

→ Our prediction [caveat, loops* neglected]:

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

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

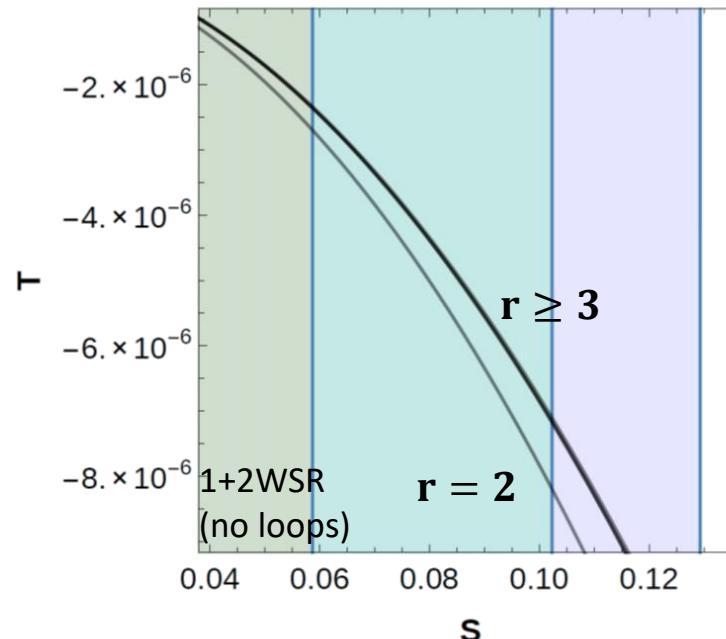
$$-4.5 \cdot 10^{-4} \left(\frac{1 \text{ TeV}^4}{M_V^4} \right) \sim 0 \quad (\text{in practice})$$



* Two Weinberg SR employed:

$$F_V^2 - F_A^2 - v^2 = 0 \text{ and } F_V^2 M_V^2 - F_A^2 M_A^2 = 0.$$

$r = M_A^2/M_V^2$	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



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

(x) F. Alvarado, A. Guevara, SC, arXiv:1909.00875 [hep-ph];

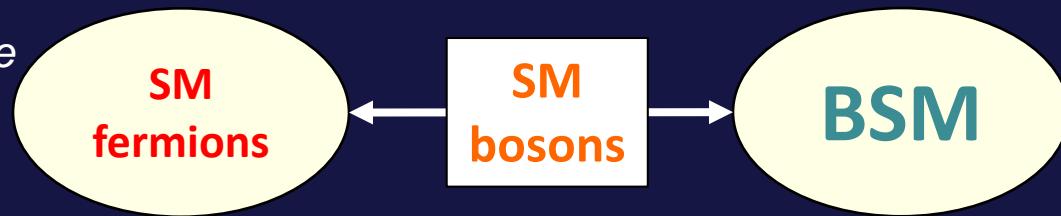
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3.) Conclusions



Optimistic message:

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



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



Resonances with $M_R \sim 1 - 2$ TeV perfectly allowed

- **LHC searches:** R production, WW scat: naturally small (*difficult; long term*)
4-fermion ops. (“compositeness”) (*not very sensitive*)
- **Low-E searches:** deviations in low-E bosonic EW precision observables
(*low $E \leq$ EW scale*) (*maybe better; there’s place to exp.improve; long-term*)

BACKUP

Low-energy chiral expansion in the HEFT

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

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

$$\mathcal{M}(2 \rightarrow 2) \approx \frac{\mathbf{p}^2}{\mathbf{v}^2} + \left(\frac{\mathcal{F}_k(\mu) \mathbf{p}^4}{\mathbf{v}^2} - \frac{\Gamma_k \mathbf{p}^4}{16\pi^2 \mathbf{v}^2} \ln \frac{\mathbf{p}^2}{\mu^2} + \dots \right) + \mathcal{O}(\mathbf{p}^6)$$

LO (tree)
NLO (tree)
NLO (1-loop)

 suppression
 $\sim 1/M^2 + \dots$

 (heavier states)

Finite pieces from loops
 (amplitude dependent) ⁽⁺⁾

↑
 ** 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

[See C. Quezada & I. Rosell's
 talks on Thursday]

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_μ^a, B_μ (and QCD)
+ EW Goldstones ω^\pm, z [non-linearly realized via $U(\omega^a)$ ^(x)]
- Fermions ψ : (t,b)-type doublets

(ii) Symmetries:

- **SM symmetry:** **Gauge sym. group** $G_{\text{SM}} = SU(2)_L \times U(1)_Y$ (and QCD)
Spont. Breaking (EWSB) $G_{\text{SM}} \rightarrow H_{\text{SM}} = U(1)_{\text{EM}}$

- **Symmetry of the SM scalar sector:**

Global CHIRAL sym. $G = SU(2)_L \times SU(2)_R \times U(1)_{B-L} \supset G_{\text{SM}}$

Sp.S.Breaking to Cust.sym. $G \rightarrow H = SU(2)_{L+R} \times U(1)_{B-L} \supset H_{\text{SM}}$

Explicit Breaking: L \rightleftharpoons R asymmetry of the gauge sector ($g, g' \neq 0$)
t \rightleftharpoons b splitting ($\lambda_t \neq \lambda_b$)

(iii) Chiral power counting:

	[boson]	\rightleftharpoons	order 0	($\sim p^0$)
$[g W^\mu] = [g' B^\mu] = [d_\mu] = [g] = [\lambda_\psi] = [m_{\chi, \psi}] = [\cancel{\psi \psi}]$		\rightleftharpoons	order 1	($\sim p^1$)
weak SM fermion coupling $[\psi \psi]$		\rightleftharpoons	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

- EW Effective Theory ($EWET = EW\chi L = HEFT$):

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

$$U(\varphi) \equiv u(\varphi)^2$$

- **Chiral expansion:** $\mathcal{L}_{EWET} = \sum_{\hat{d} \geq 2} \mathcal{L}_{EWET}^{(\hat{d})}$
- **$O(p^2)$, LO** ($\supseteq SM$): $\mathcal{L}_{EWET}^{(2)} = \sum_{\xi} [i \bar{\xi} \gamma^\mu d_\mu \xi - v (\bar{\xi}_L \gamma \xi_R + h.c.)]$
 $- \frac{1}{2g^2} \langle \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \rangle_2 - \frac{1}{2g'^2} \langle \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \rangle_2 - \frac{1}{2g_s^2} \langle \hat{G}_{\mu\nu} \hat{G}^{\mu\nu} \rangle_3$
 $+ \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - V(h/v) + \frac{v^2}{4} \mathcal{F}_u(h/v) \langle u_\mu u^\mu \rangle_2$
with $\mathcal{F}_u = 1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \mathcal{O}(h^3)$, **being** $a_{SM} = b_{SM} = 1$

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

$$\begin{aligned} \mathcal{L}_{EWET}^{(4)} &= \sum_{i=1}^{12} \mathcal{F}_i(h/v) \mathcal{O}_i + \sum_{i=1}^3 \tilde{\mathcal{F}}_i(h/v) \tilde{\mathcal{O}}_i + \sum_{i=1}^8 \mathcal{F}_i^{\psi^2}(h/v) \mathcal{O}_i^{\psi^2} + \sum_{i=1}^3 \tilde{\mathcal{F}}_i^{\psi^2}(h/v) \tilde{\mathcal{O}}_i^{\psi^2} \\ &\quad + \sum_{i=1}^{10} \mathcal{F}_i^{\psi^4}(h/v) \mathcal{O}_i^{\psi^4} + \sum_{i=1}^2 \tilde{\mathcal{F}}_i^{\psi^4}(h/v) \tilde{\mathcal{O}}_i^{\psi^4}. \end{aligned}$$

(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; 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	$\tilde{\mathcal{O}}_i$	$\tilde{\mathcal{O}}_i^{\psi^2}$	$\tilde{\mathcal{O}}_i^{\psi^4}$
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	$\frac{(\partial_\mu h)}{v} \langle f_+^{\mu\nu} u_\nu \rangle_2$	$\langle J_V^\mu \rangle_2 \langle u_\mu \mathcal{T} \rangle_2$	—

Low-energy chiral expansion in the HEFT

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

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

$$\mathcal{M}(2 \rightarrow 2) \approx \frac{\mathbf{p}^2}{\mathbf{v}^2} + \left(\frac{\mathcal{F}_k(\mu) \mathbf{p}^4}{\mathbf{v}^2} - \frac{\Gamma_k \mathbf{p}^4}{16\pi^2 \mathbf{v}^2} \ln \frac{\mathbf{p}^2}{\mu^2} + \dots \right) + \mathcal{O}(\mathbf{p}^6)$$

LO (tree)
NLO (tree)
NLO (1-loop)

 suppression

 $\sim 1/M^2 + \dots$

 (heavier states)
 Typical loop suppression

 $\sim \Gamma_k / (16\pi^2 v^2)$

(non-linearity)

↑
** Catà, EPJC74 (2014) 8, 2991

** Pich,Rosell,Santos,SC, [1501.07249]; ‘forthcoming FTUAM-15-20

*** Pich,Rosell and SC, JHEP 1208 (2012) 106;
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[Guo,Ruiz-Femenia,SC,
PRD92 (2015) 074005]

*** Alonso,Jenkins,Manohar, PLB 754 (2016) 335-342

*** Alonso,Kanshin,Saa, PRD 97 (2018) no.3, 035010

*** Buchalla,Cata,Celis,Knecht,Krause, NPB 928 (2018) 93-106

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

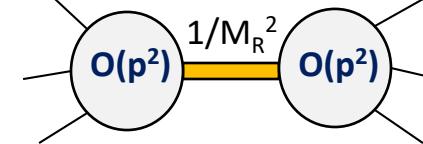


High-energy Lagrangian

$$\mathcal{L}^{\text{HE}}[\mathbf{R}, \text{light}] = \mathcal{L}_2[\text{light}] + \mathcal{L}_{\mathbf{R}}[\mathbf{R}, \text{light}] + \mathcal{L}_4^{\text{HE}}[\text{light}]$$

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

$$\mathcal{L}_{\mathbf{R}} = \mathcal{L}_{\mathbf{R}}^{\text{Kin}}[\mathbf{R}] + \mathbf{R} \chi_{\mathbf{R}}[\text{light}] + \mathcal{O}(\mathbf{R}^2)$$



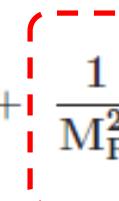
Low-energy Lagrangian (tree-level)

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

- Solve R eom at low energies: $R_{\text{cl.}}[\text{light}] \sim \frac{1}{M_R^2} \chi_{\mathbf{R}}[\text{light}] + \mathcal{O}\left(\frac{p^4}{M_R^4}\right)$



- Evaluate $\mathcal{L}^{\text{EFT}}[\text{light}] = \mathcal{L}^{\text{HE}}[R_{\text{cl.}}[\text{light}], \text{light}] \sim \mathcal{L}_2[\text{light}] + \frac{1}{M_R^2} (\chi_{\mathbf{R}}[\text{light}])^2 + \dots$



* 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

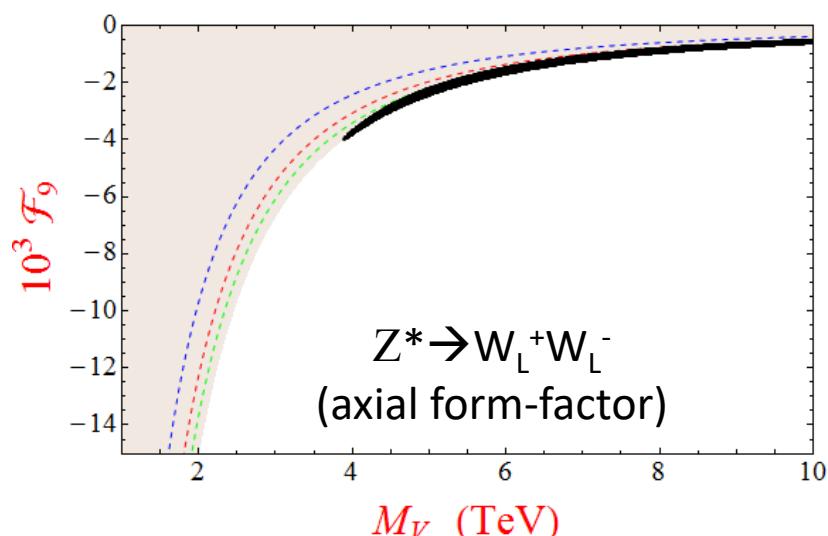
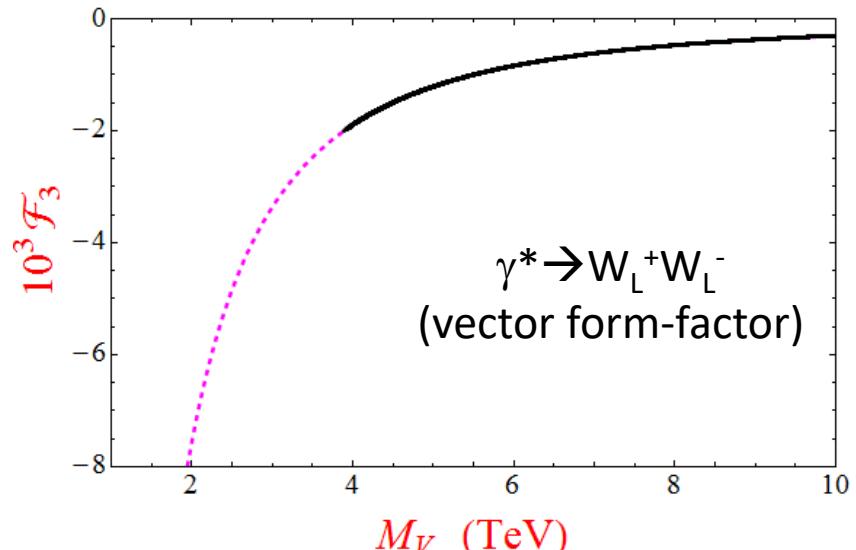
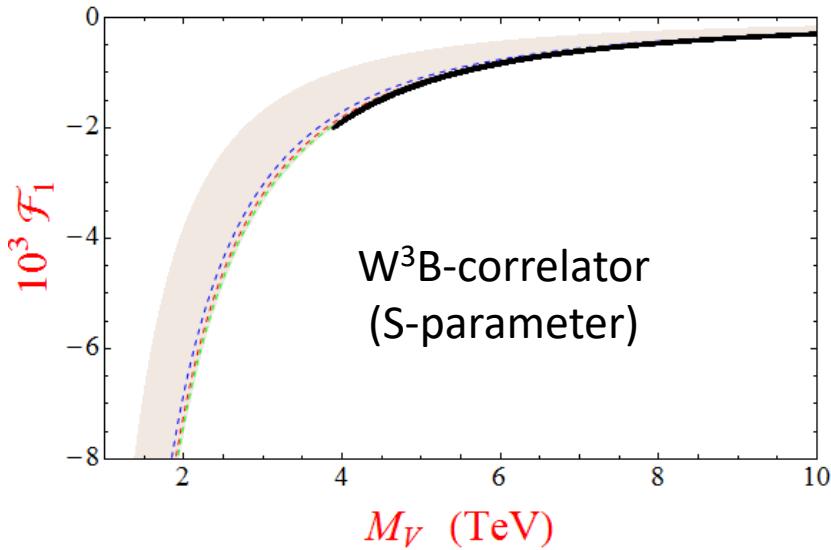
i	$\Delta\mathcal{F}_i$	$\Delta\tilde{\mathcal{F}}_i$	i	$\Delta\mathcal{F}_i$
1	$-\frac{F_V^2 - \tilde{F}_V^2}{4M_{V_3^1}^2} + \frac{F_A^2 - \tilde{F}_A^2}{4M_{A_3^1}^2}$	$-\frac{\tilde{F}_V G_V}{2M_{V_3^1}^2} - \frac{F_A \tilde{G}_A}{2M_{A_3^1}^2}$	7	$\frac{d_P^2}{2M_{P_3^1}^2} + \frac{\lambda_1^{hA}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

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

[Relation with Longhitano'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

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



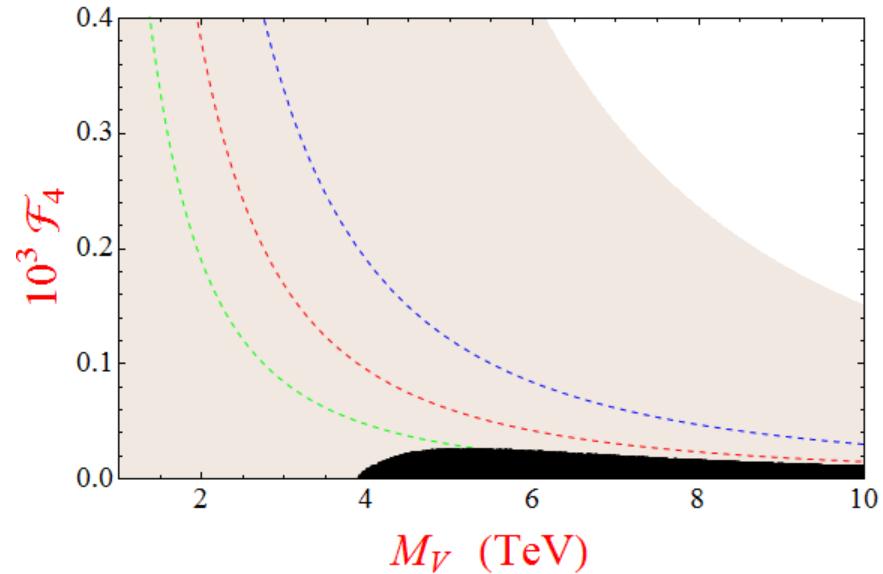
* Pich, Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801

* Pich, Rosell, Santos, SC, PRD 93 (2016) no.5, 055041

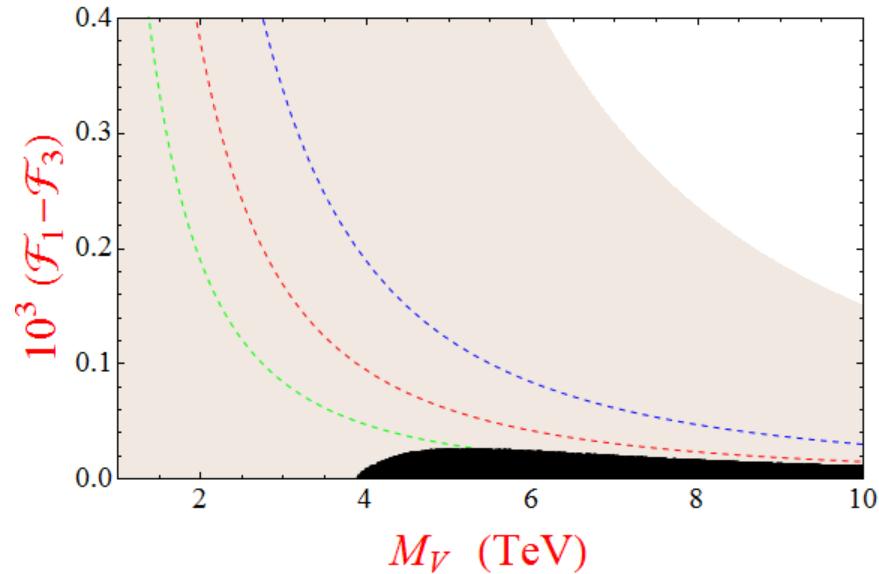
Theory:

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

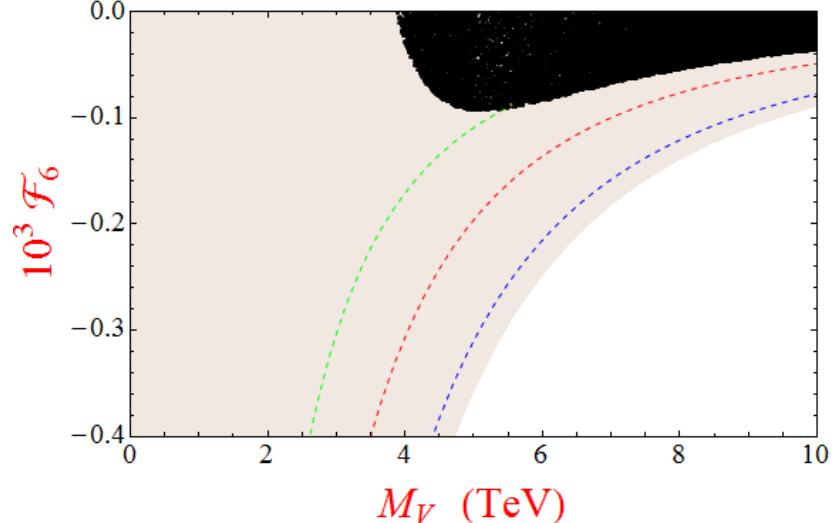
- $w^a w^b \rightarrow w^c w^d$ scattering



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



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



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

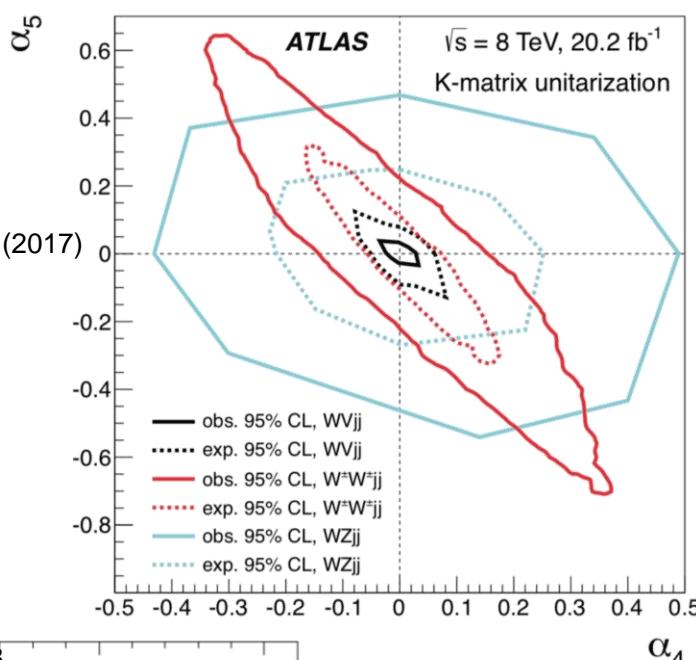
→ HEFT couplings in the range

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

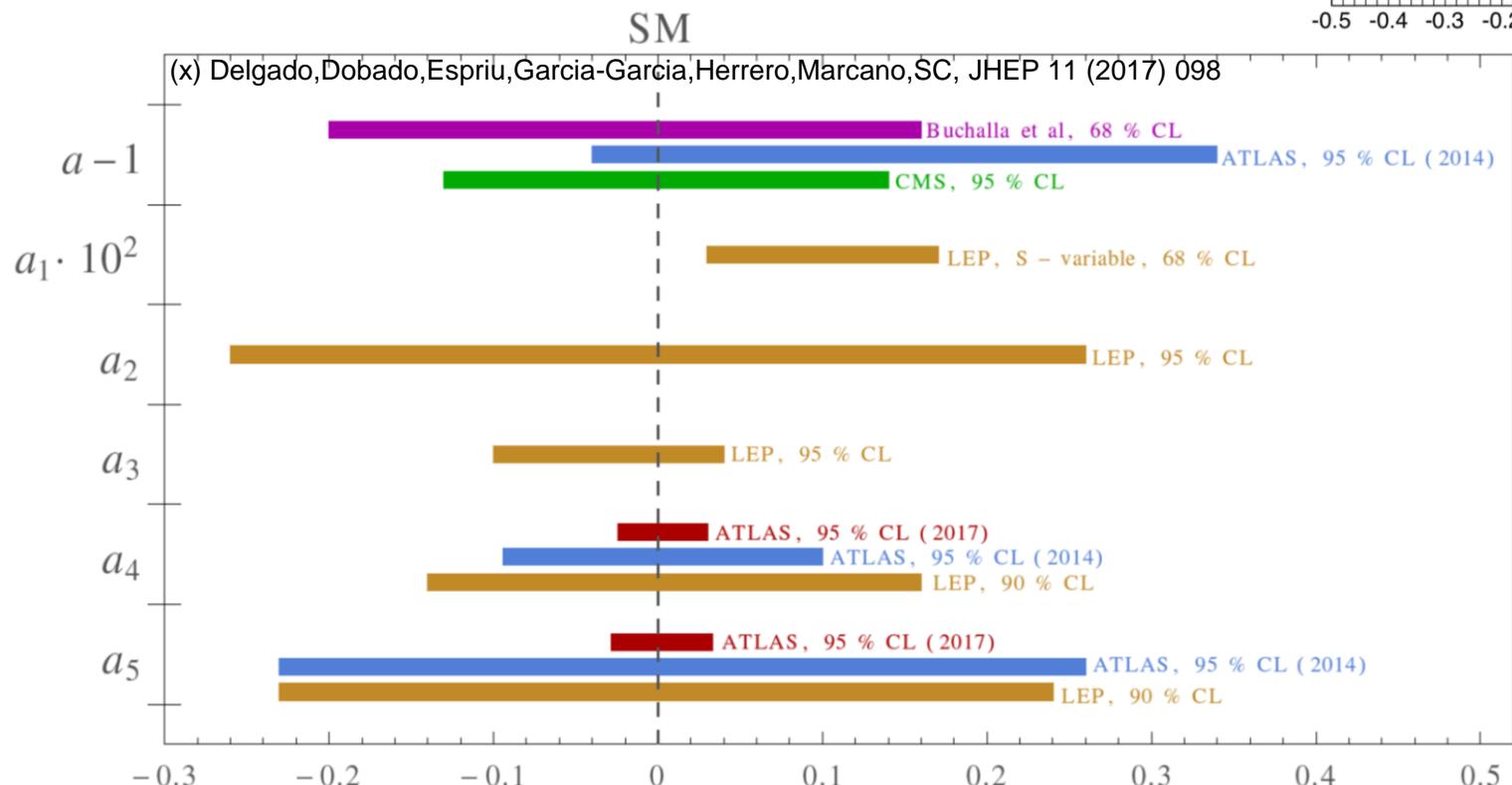
* Pich,Rosell and SC, JHEP 1208 (2012) 106; PRL 110 (2013) 181801
 * Pich,Rosell,Santos,SC, PRD 93 (2016) no.5, 055041

- Still far from current experimental precision,
although recent important improvements from VBS:

[ATLAS], PRD 95 032001 (2017)

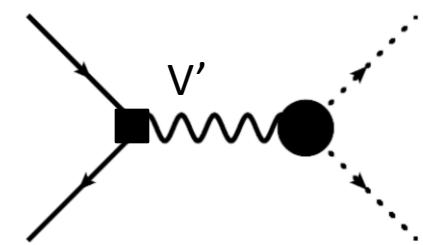


- Useful to observe the summary: ^(x)



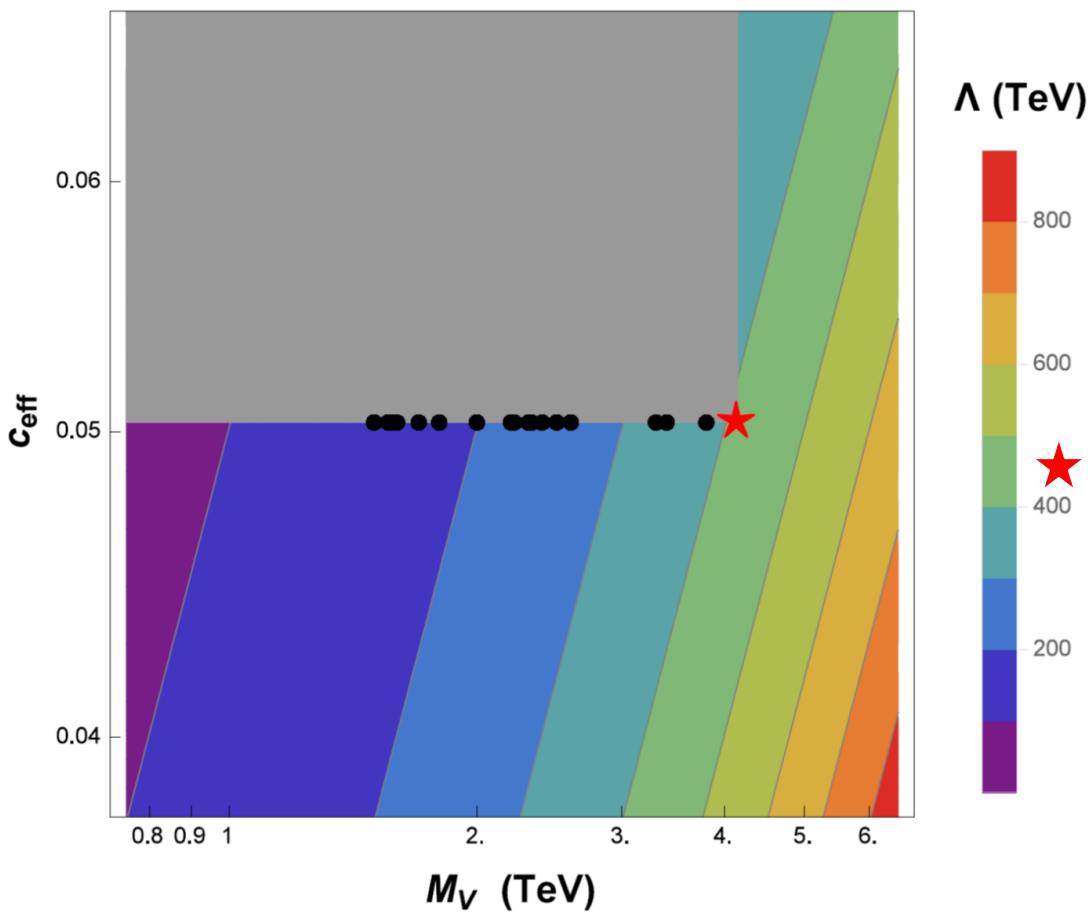
- HVT diboson searches: in practice, **DY dominated**

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



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

→ Exclusion in the (m_V, c_{eff}) plane and the $O_j^{\psi^4}$ scale Λ ^(*)



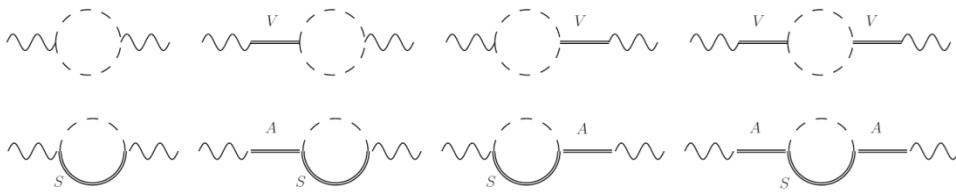
$$\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2} [\eta_{LL}(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L) + \eta_{RR}(\bar{q}_R \gamma^\mu q_R)(\bar{q}_R \gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R \gamma^\mu q_R)(\bar{q}_L \gamma_\mu q_L)],$$

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

$\star \rightarrow \Lambda = 410 \text{ TeV}$

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

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



V,A resonances + 1-loop + 2 WSRs

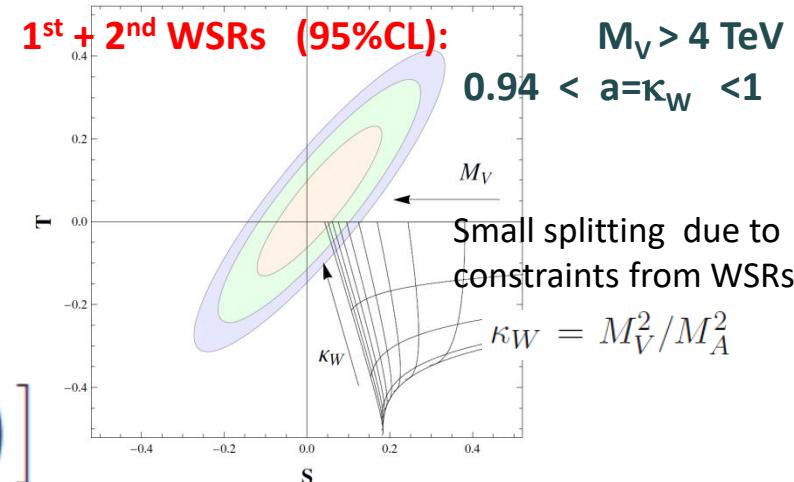
$$S = -16\pi \left[\underbrace{a_1^r(M_V)}_{\sim -2 \times 10^{-3}} + \underbrace{\frac{a^2 - 1}{192\pi^2} \left(\ln \frac{M_V^2}{m_h^2} + \frac{5}{6} \right)}_{\sim -6 \times 10^{-5}} \right]$$

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

$$\Lambda^{-2} \sim (5 \text{ TeV})^{-2}$$

$$\Lambda^{-2} \sim (30 \text{ TeV})^{-2}$$

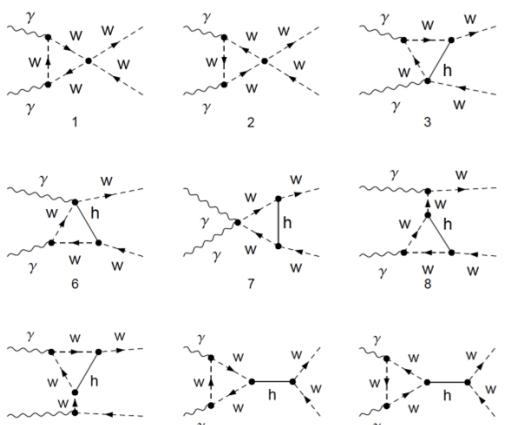
$$- \mathcal{R}_4 / 192\pi^2$$



EXAMPLE 2: *, (x), (+)

$\gamma\gamma \rightarrow W_L^+ W_L^-$

(only charged shown here)



+30
more

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

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

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

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

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

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

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

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

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

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

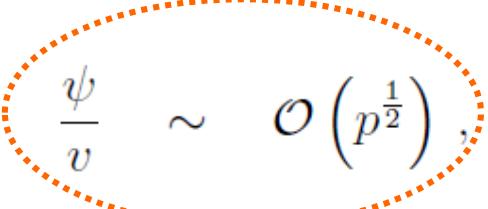
$$f_+^{\mu\nu} = - \left(u^\dagger \hat{W}^{\mu\nu} u + u \hat{B}^{\mu\nu} u^\dagger \right) ,$$

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

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

SUMMARY: NAÏVE ‘CHIRAL’ COUNTING

- “Chiral” counting *

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


and for the building blocks,

$$u(\varphi/v), U(\varphi/v), \frac{h}{v}, \frac{W_\mu^a}{v}, \frac{B_\mu}{v} \sim \mathcal{O}(p^0),$$

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

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

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

- Assignment of the ‘chiral’ dimension: *

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



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

* 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

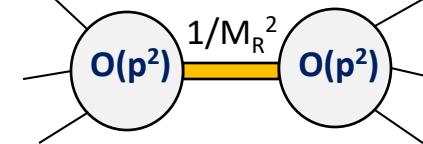
* Krause,Pich,Rosell,Santos,SC, JHEP 1905 (2019) 092

High-energy Lagrangian

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

with the most general linear resonance $\mathcal{O}(p^2)$ operators (chiral + CP invariance)

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



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

Low-energy Lagrangian (tree-level)

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

(e.g., for a vector triplet) $\mathbf{V}_{\text{cl}}^{\mu\nu} = -\frac{2}{M_V^2} \left(\chi_V^{\mu\nu} - \frac{1}{2} \langle \chi_V^{\mu\nu} \rangle \right) + \mathcal{O}\left(\frac{p^4}{M_V^4}\right)$

- Evaluate $\mathcal{L}^{\text{EFT}}[\ell\text{ight}] = \mathcal{L}^{\text{HE}}[\mathbf{R}_{\text{cl}}[\ell\text{ight}], \ell\text{ight}] \sim \mathcal{L}_2[\ell\text{ight}] + \boxed{\frac{1}{M_{\mathbf{R}}^2} (\chi_{\mathbf{R}}[\ell\text{ight}])^2} + \dots$

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

[Relation with Longhitano's couplings $\mathcal{F}_j = a_j + O(h)$; notice: $a_{j \geq 5}$ 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	$\frac{c_d c^{S_1^1}}{2M_{S_1^1}^2} + \frac{\tilde{\lambda}_1^2 - \lambda_1^2}{2M_\Psi}$	5	$\frac{d_P c^{P_3^1}}{M_{P_3^1}^2} + \frac{2(\lambda_1 \lambda_2 - \tilde{\lambda}_1 \tilde{\lambda}_2)}{M_\Psi}$
2	$-\frac{G_V C_0^{V_3^1}}{\sqrt{2} M_{V_3^1}^2} - \frac{\tilde{C}_A \tilde{C}_0^{A_3^1}}{\sqrt{2} M_{A_3^1}^2} - \frac{\tilde{\lambda}_1^2 - \lambda_1^2}{2M_\Psi}$	6	$-\frac{\tilde{c}_T \tilde{c}^{\hat{V}_1^1}}{\sqrt{2} M_{V_1^1}^2} - \frac{c_T c^{\hat{A}_1^1}}{\sqrt{2} M_{A_1^1}^2} + \frac{(\lambda_0 \lambda_1 + \tilde{\lambda}_0 \tilde{\lambda}_1)}{M_\Psi}$
3	$-\frac{F_V C_0^{V_3^1}}{\sqrt{2} M_{V_3^1}^2} - \frac{\tilde{F}_A \tilde{C}_0^{A_3^1}}{\sqrt{2} M_{A_3^1}^2}$	7	$\frac{\lambda_2^2 - \tilde{\lambda}_2^2}{M_\Psi}$
4	$-\frac{\sqrt{2} F_X C_0^{V_1^1}}{M_{V_1^1}^2} - \frac{\sqrt{2} \tilde{F}_X \tilde{C}_0^{A_1^1}}{M_{A_1^1}^2}$	8	$-\frac{C_G C_0^{V_1^8}}{\sqrt{2} M_{V_1^8}^2} - \frac{\tilde{C}_G \tilde{C}_0^{A_1^8}}{\sqrt{2} M_{A_1^8}^2}$

+ ψ^4 ops. (more tedious)

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

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

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

(*) 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 $O_j^{\psi^4}$:

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].

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

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

1. From high-energy collider studies.-

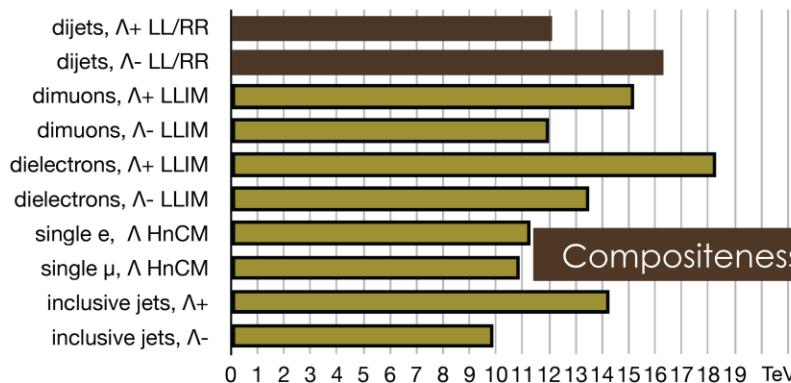
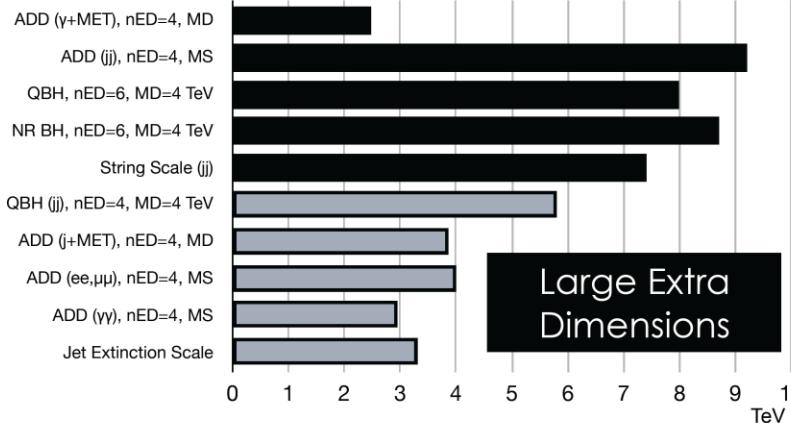
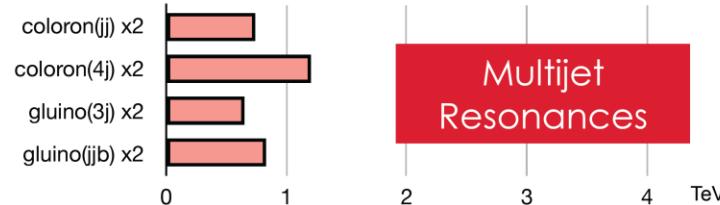
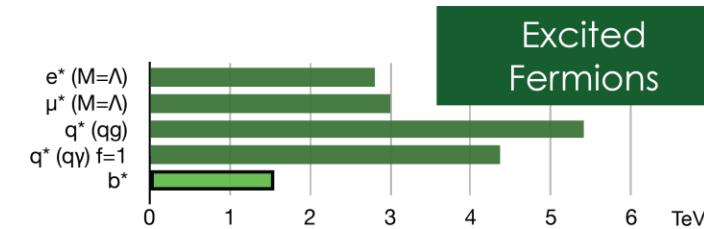
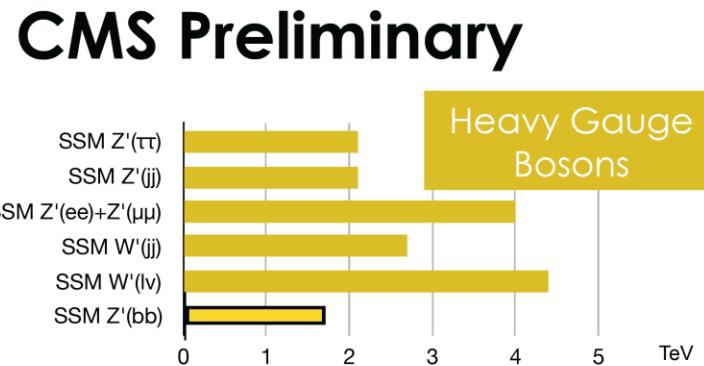
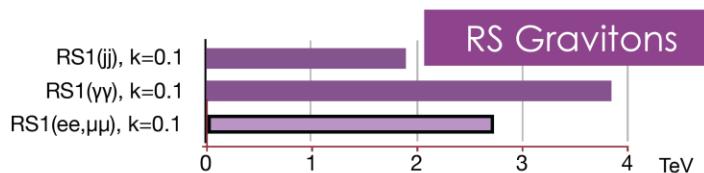
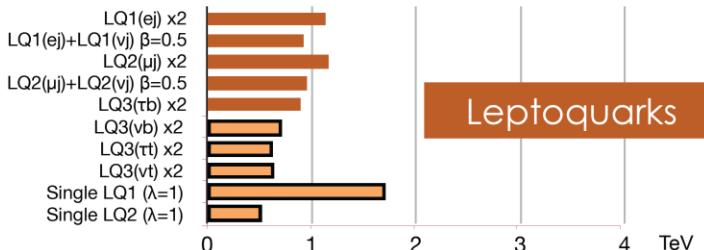
- $\Lambda \geq 1.5$ TeV from multi-top production at LHC and Tevatron [69],
- $\Lambda \geq 2.3$ TeV from t and $t\bar{t}$ production at LHC and Tevatron [70],
- $\Lambda \geq 4.7$ TeV from dilepton production at LHC [71].

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:

13 TeV 8 TeV



CMS Exotica Physics Group Summary – ICHEP, 2016

- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>

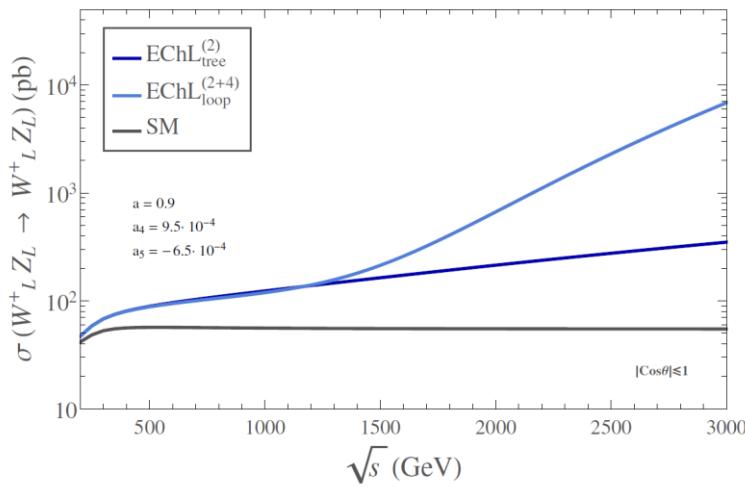
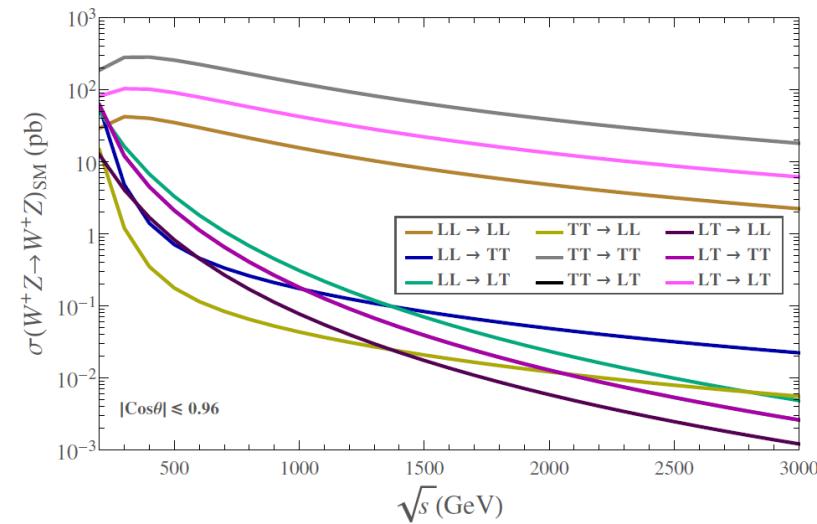
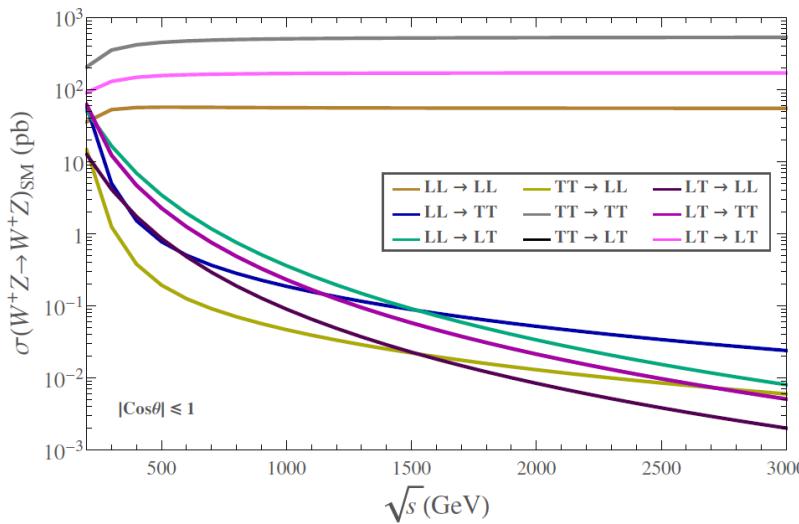


Figure 2. Predictions of the cross section $\sigma(W_L Z_L \rightarrow W_L Z_L)$ as a function of the center of mass energy \sqrt{s} from the EChL. The predictions at leading order, EChL_{tree}, and next to leading order, EChL_{loop}⁽²⁺⁴⁾, are displayed separately. The EChL coefficients are set here 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.

- Hierarchies in the SM for the subprocess $WZ \rightarrow WZ$:

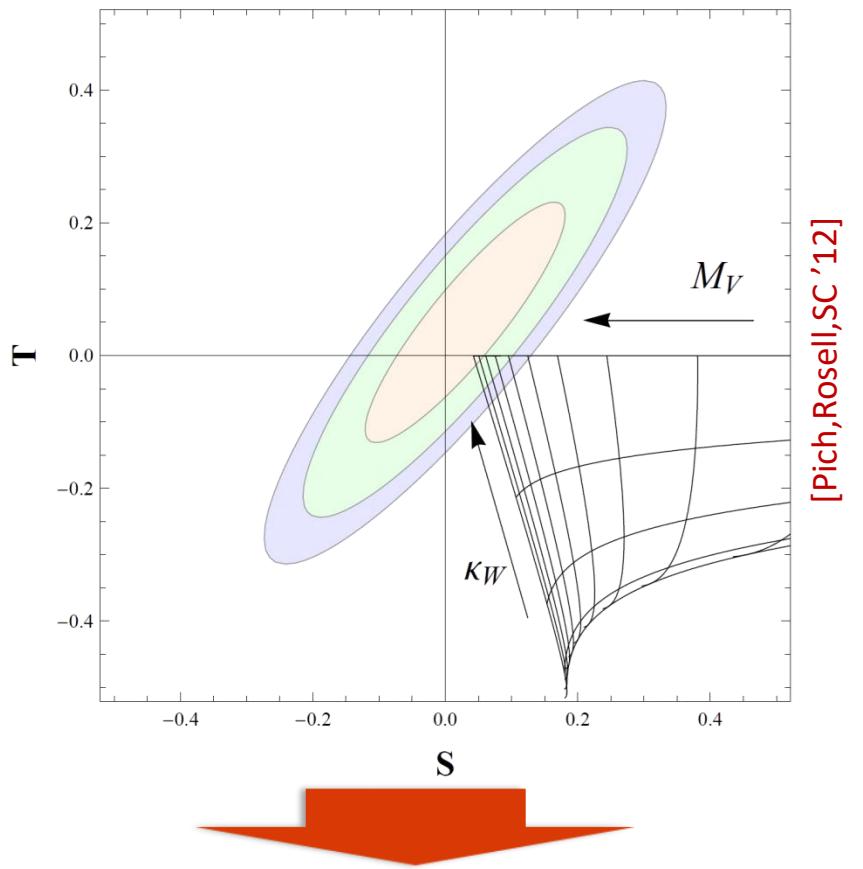


$$c_{\text{eff}}^2 \equiv (\hat{c}^{V_3^1})^2 + (\tilde{c}^{V_3^1})^2 + \frac{1}{2}(C_0^{V_3^1})^2 = \frac{24\pi}{N_C} \frac{\gamma_{q\bar{q}}}{\mathcal{B}_{V^0 \rightarrow \text{dibos}}} \geq \frac{24\pi}{N_C} \gamma_{q\bar{q}} \equiv (c_{\text{eff}}^{\text{bound}})^2$$

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

NLO results: 1st and 2nd WSRs

(asymptotically-free theories)



[Pich,Rosell,SC '12]

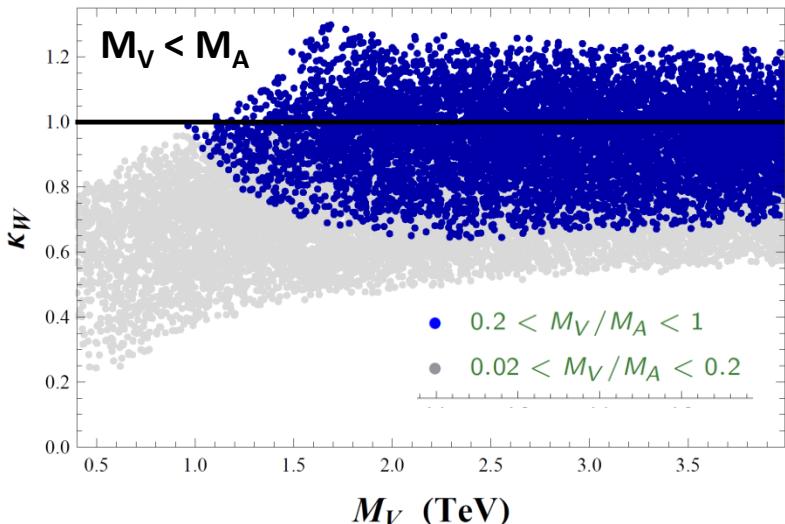
At NLO with the 1st and 2nd WSRs

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

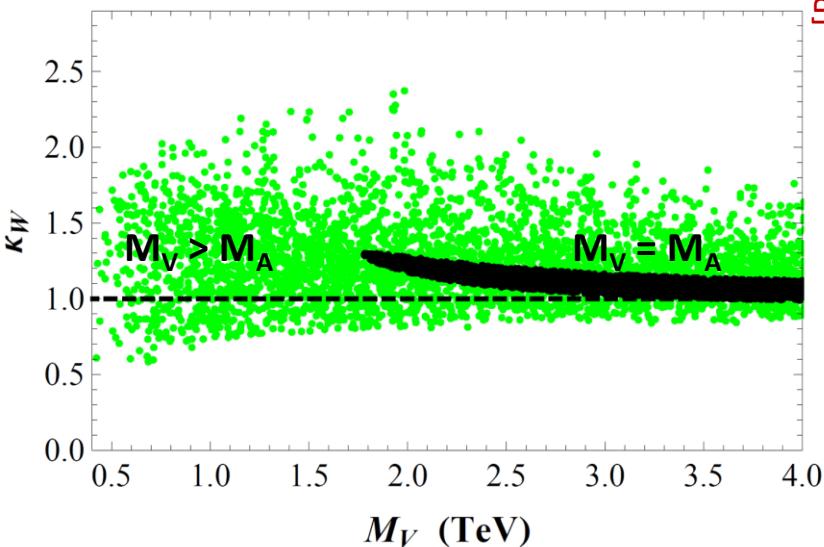
Small splitting $(M_V/M_A)^2 = \kappa_W$

NLO results: only 1st WSR

(walking & conformal TC, extra dimensions,...)



[Pich,Rosell,SC '12]



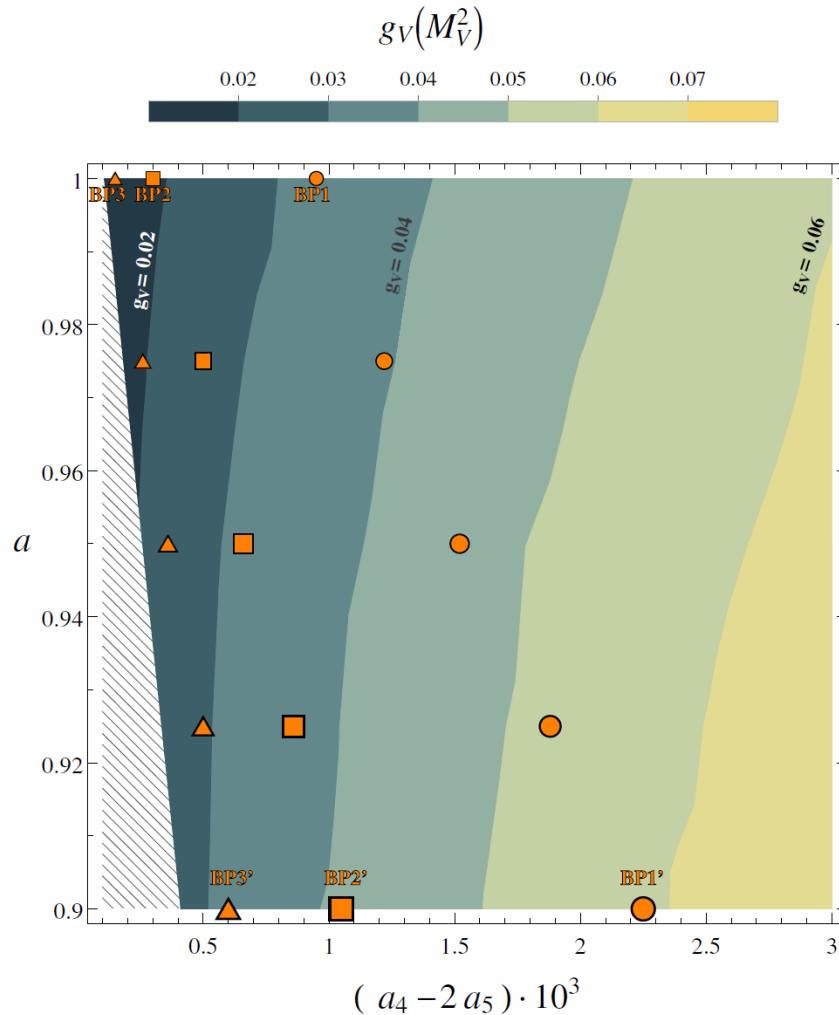
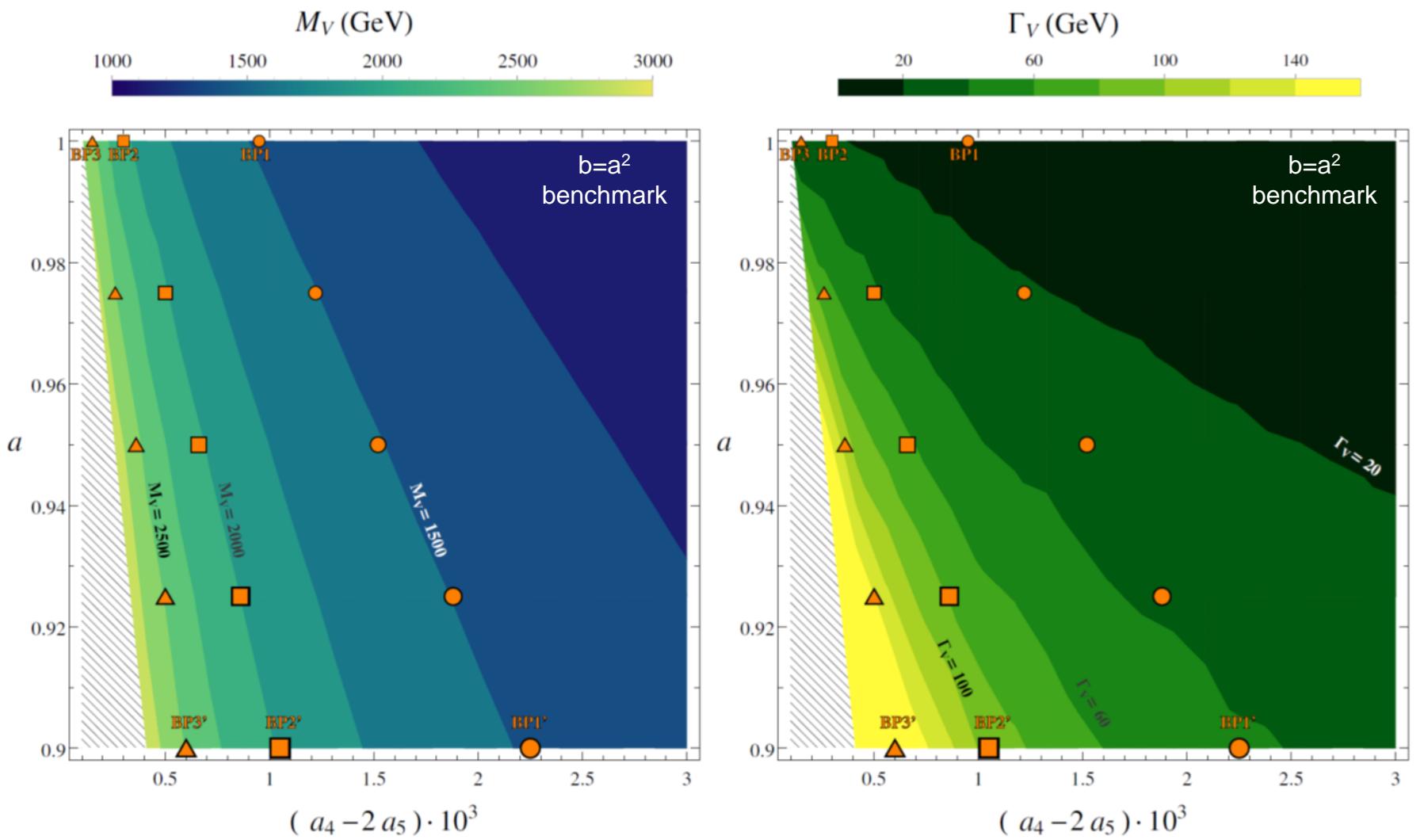


Figure 6. Predictions of $g_V(M_V^2)$ as a function of a and $(a_4 - 2a_5)$ computed from eq. (4.10), as discussed in the text. The benchmark points specified with geometric symbols correspond respectively to those in figure 4.

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



- Analytical expressions in the Equiv.Theor. Limit:

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

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

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

- Sensitivity with perfect WZ reconstruction efficiency:

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

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

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

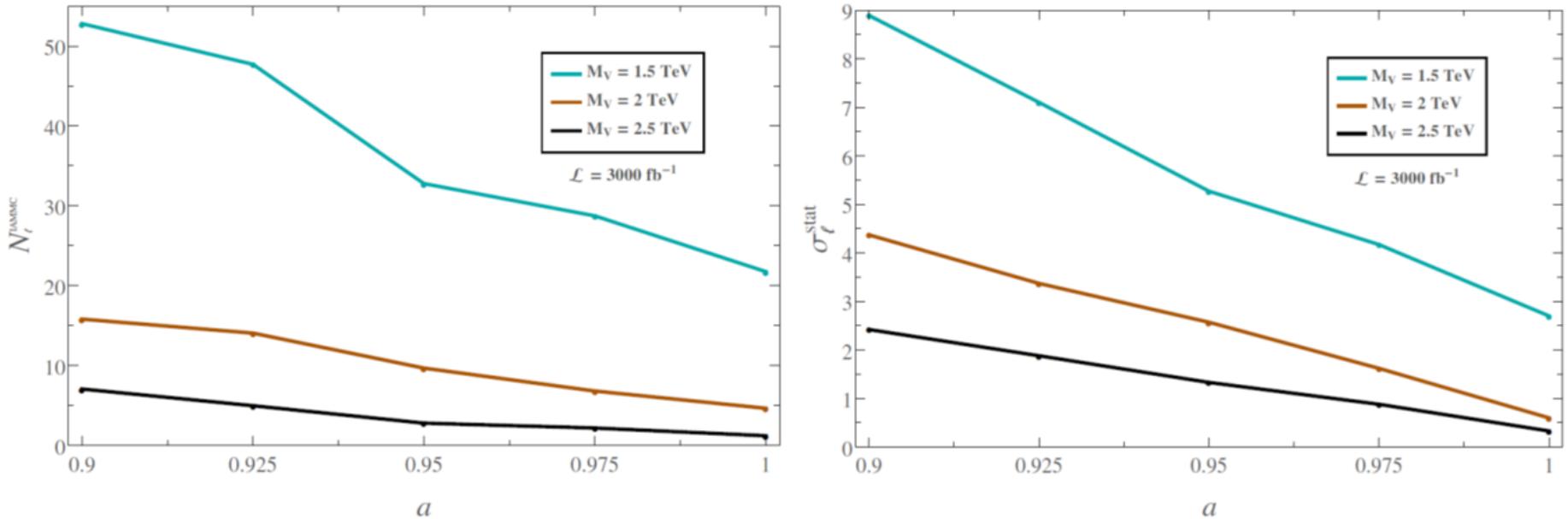
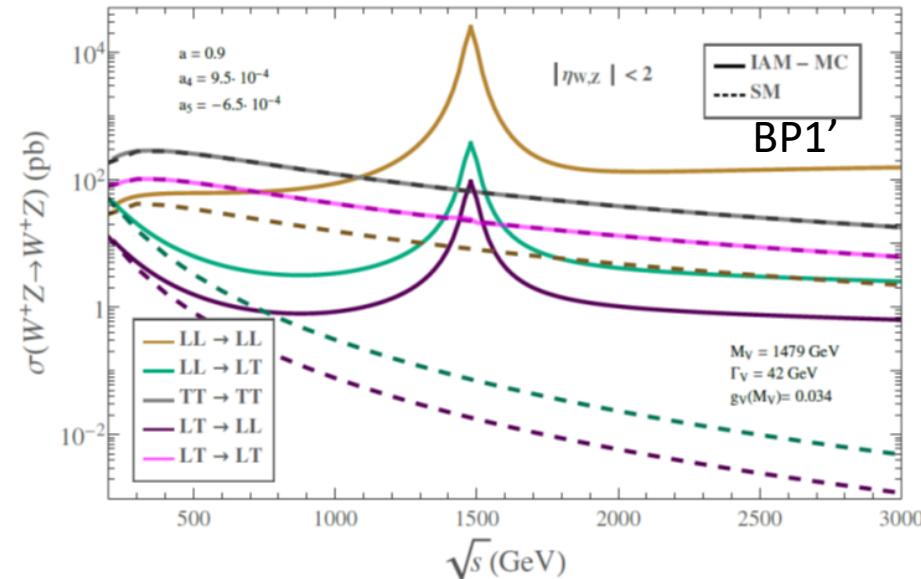
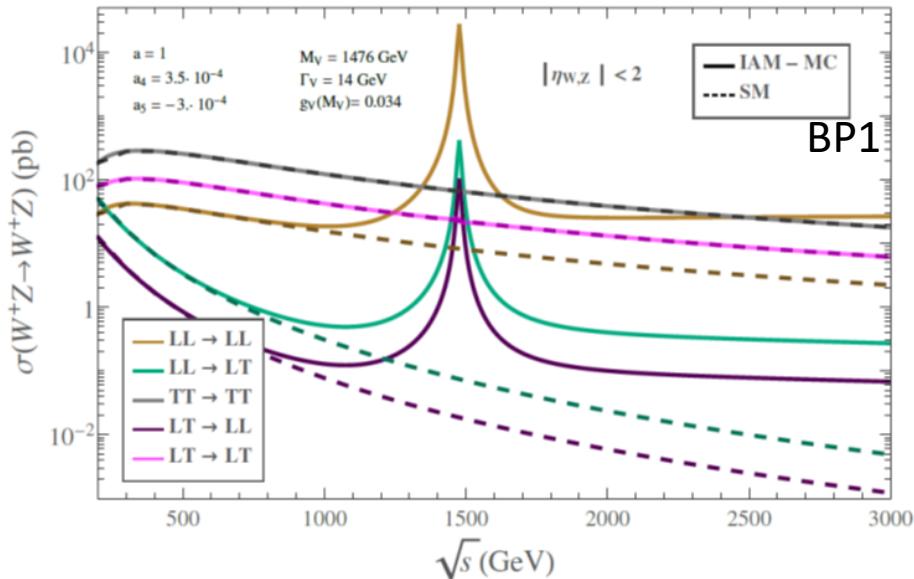


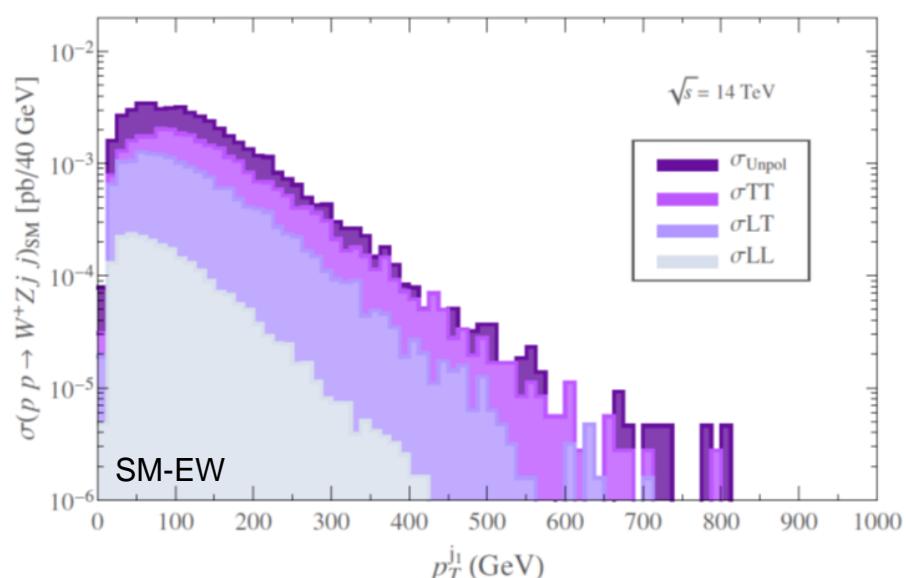
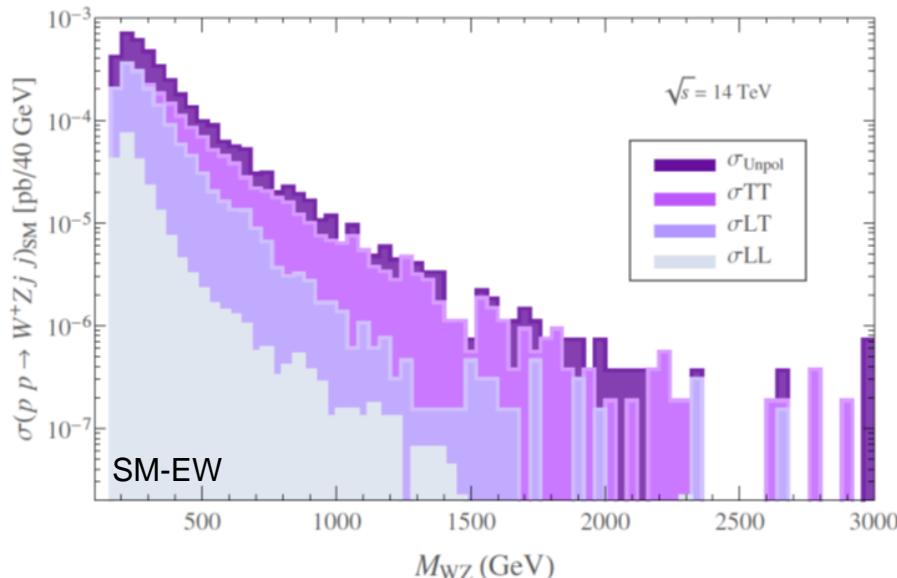
Figure 17. Predictions for the number of $pp \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \nu jj$ events, $N_\ell^{\text{IAM-MC}}$, (left panel) and the statistical significance, $\sigma_\ell^{\text{stat}}$, (right panel) as a function of the parameter a for $\mathcal{L} = 3000 \text{ fb}^{-1}$. Marked points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

- $WZ \rightarrow WZ$ subprocess: polarizations (in the WZ rest frame)

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

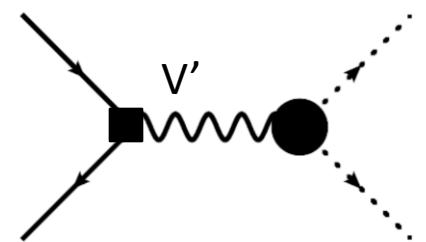


- $pp \rightarrow jjWZ$ at LHC: SM backgrounds and polarizations (in the WZ rest frame)

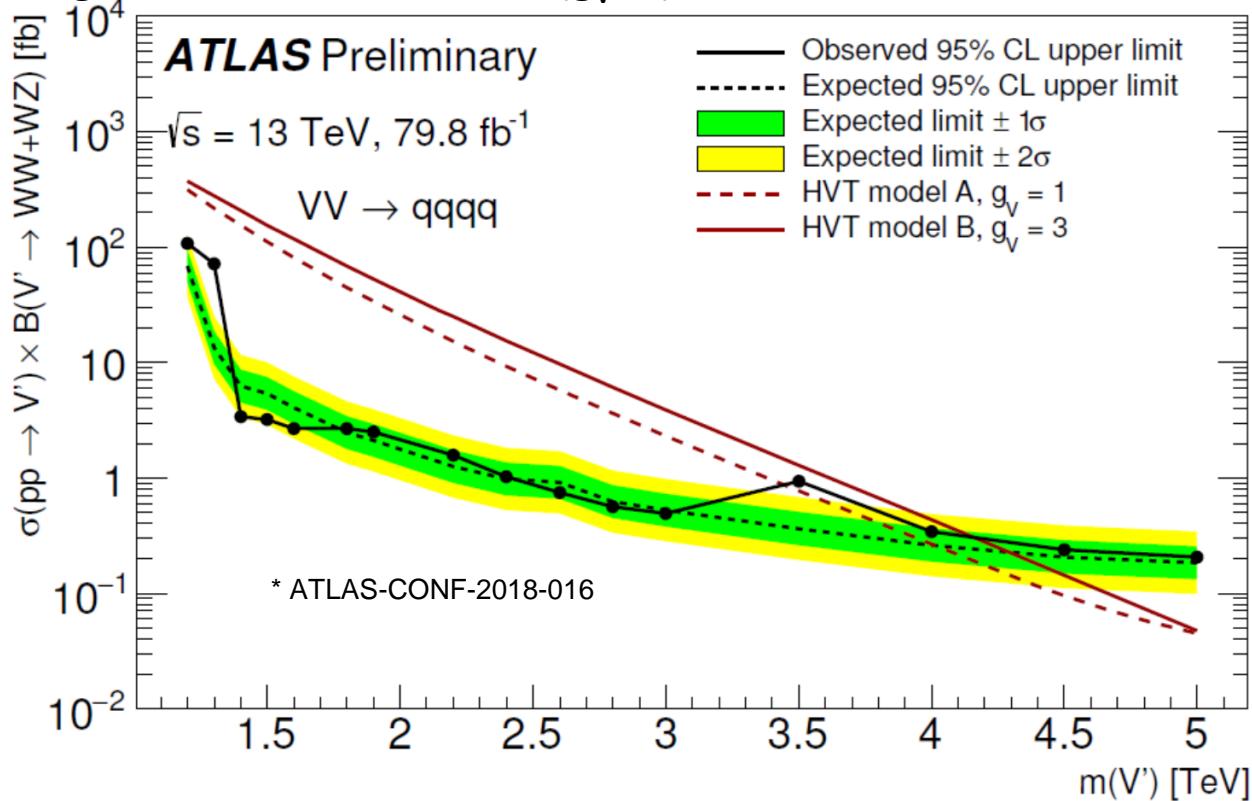


- HVT diboson searches: in practice, **DY dominated**

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



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

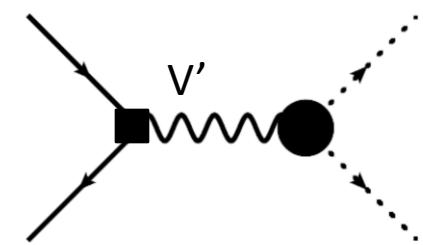


(a) HVT $V' \rightarrow WW + WZ$

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

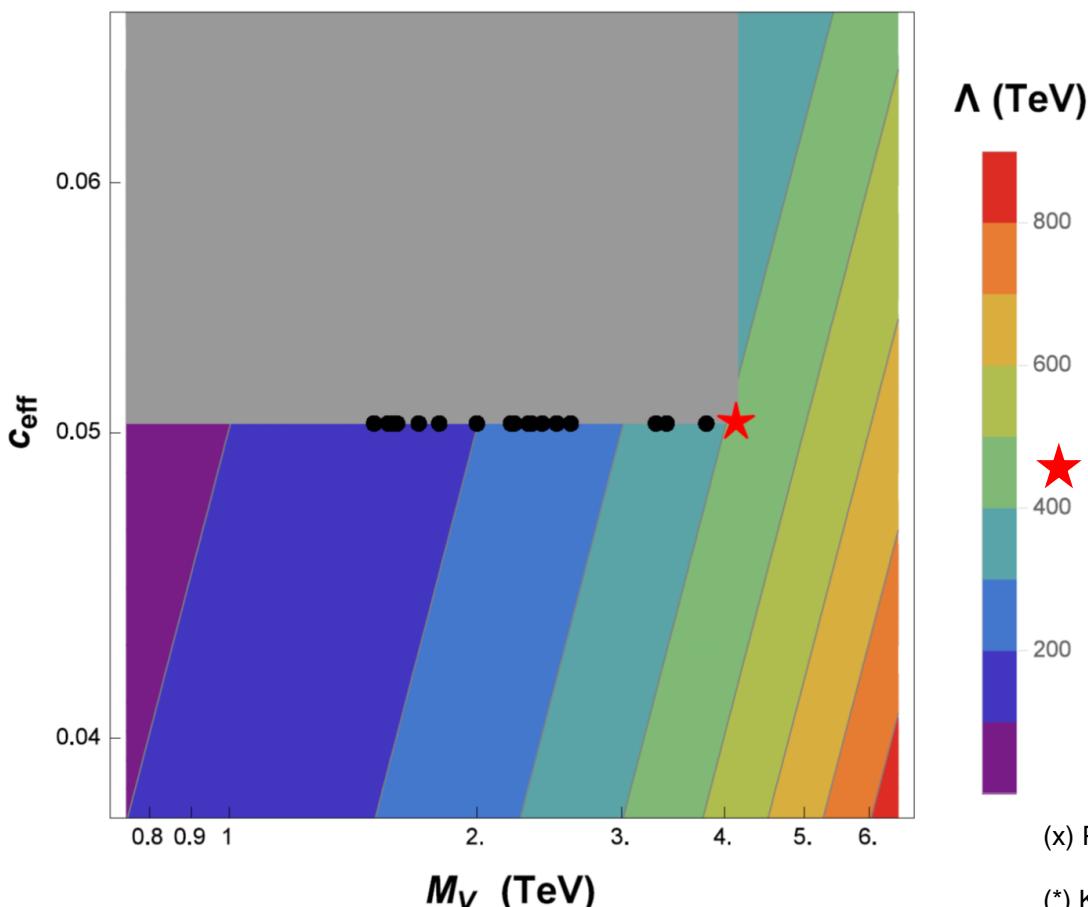
- HVT diboson searches: in practice, **DY dominated**

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



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

→ Exclusion in the (m_V, c_{eff}) plane and the $O_j^{\psi^4}$ scale Λ ^(*)



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

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

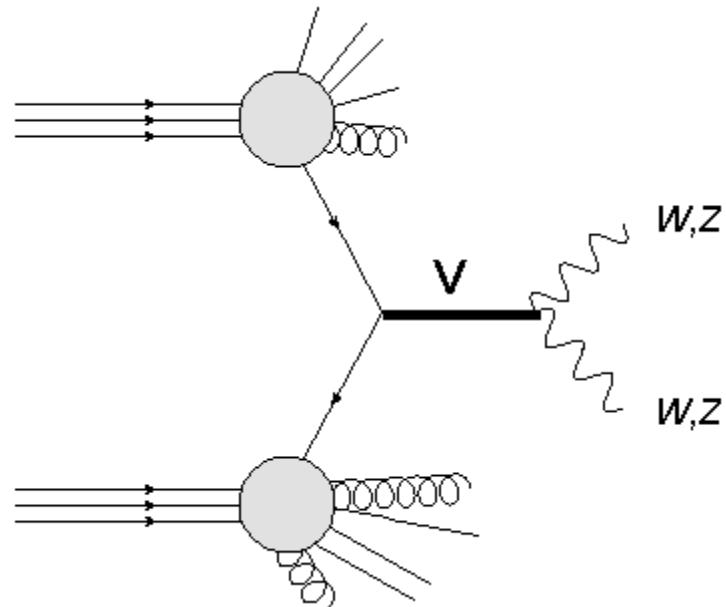
★ → $\Lambda = 410 \text{ TeV}$

*(a reanalysis for several
 $\gamma_{q\bar{q}}$ is advised,
to enlarge the exclusion region)*

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

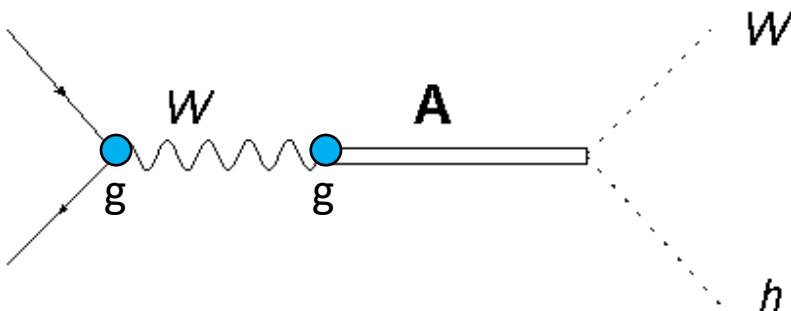
(*) Krause, Pich, Rosell, Santos, SC, JHEP 1905 (2019) 092

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



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

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



- In the HEFT case,

1) DY produces the gauge bosons

[with a weak coupling suppression]

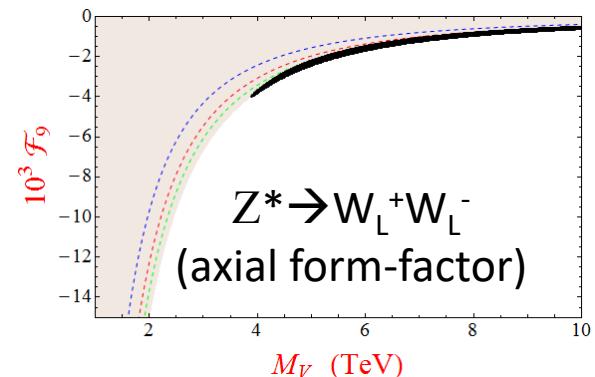
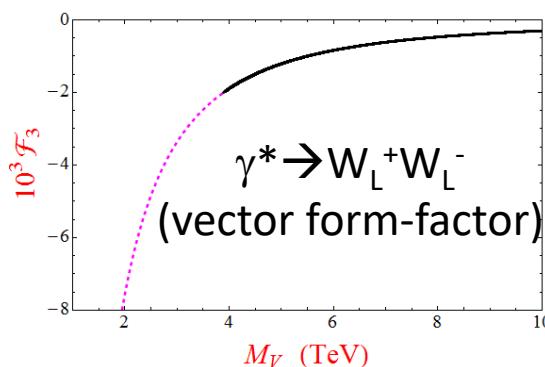
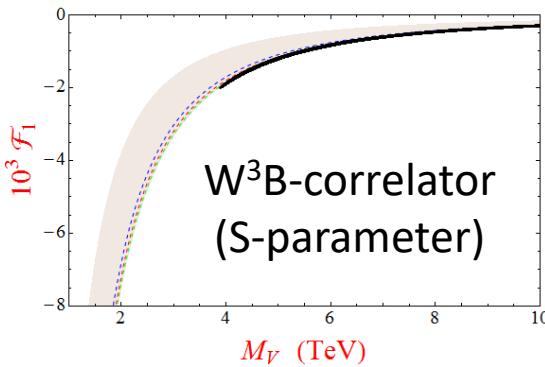
2) Then, the strong BSM interactions generate A, coupled to W

[with a weak coupling suppression]

- Implications: additional chiral suppression → Much more suppressed experimentally:

Resonances with $M_R \sim 3$ TeV perfectly allowed

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



- An estimate of these bosonic observable gives,

$$T = -1.1 \cdot 10^{-5} \left(\frac{3 \text{ TeV}}{M_V} \right)^4 \quad \text{Large suppression}$$

$$U = 0,$$

$$S = 0.13 \left(\frac{3 \text{ TeV}}{M_V} \right)^2,$$

$$\Delta g_1^Z = g_1^Z - 1 = -0.92 \cdot 10^{-3} \left(\frac{3 \text{ TeV}}{M_V} \right)^2,$$

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

$$\Delta \kappa_\gamma = \kappa_\gamma - 1 = -0.36 \cdot 10^{-3} \left(\frac{3 \text{ TeV}}{M_V} \right)^2,$$

$$\Delta \kappa_Z = \kappa_Z - 1 = -0.82 \cdot 10^{-3} \left(\frac{3 \text{ TeV}}{M_V} \right)^2.$$

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

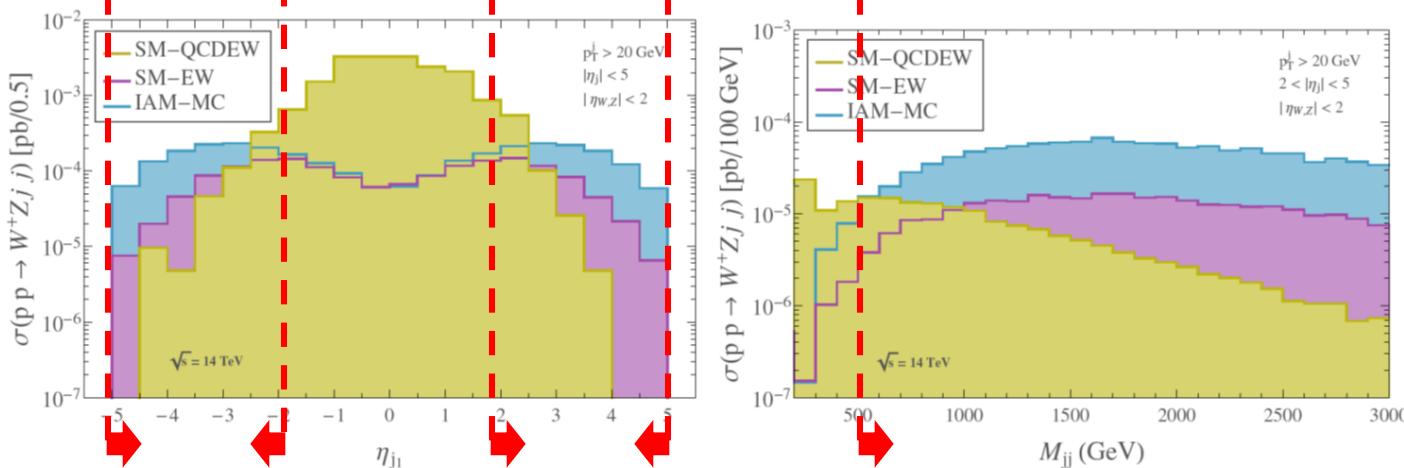
Dobado,Llanes-Estrada,SC, JHEP 1803 (2018) 159

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

- Benchmark points of this study:

BP	$M_V(\text{GeV})$	$\Gamma_V(\text{GeV})$	$g_V(M_V^2)$	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

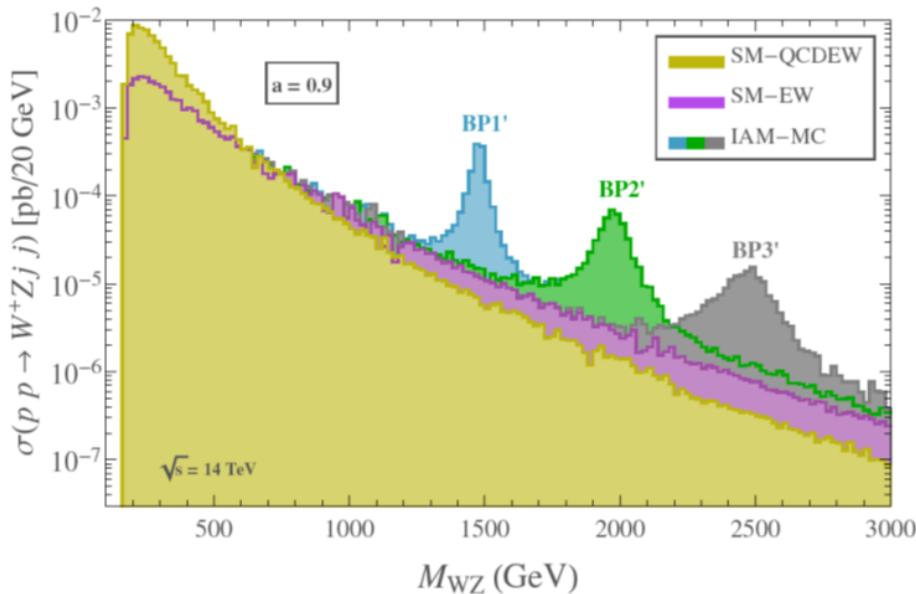
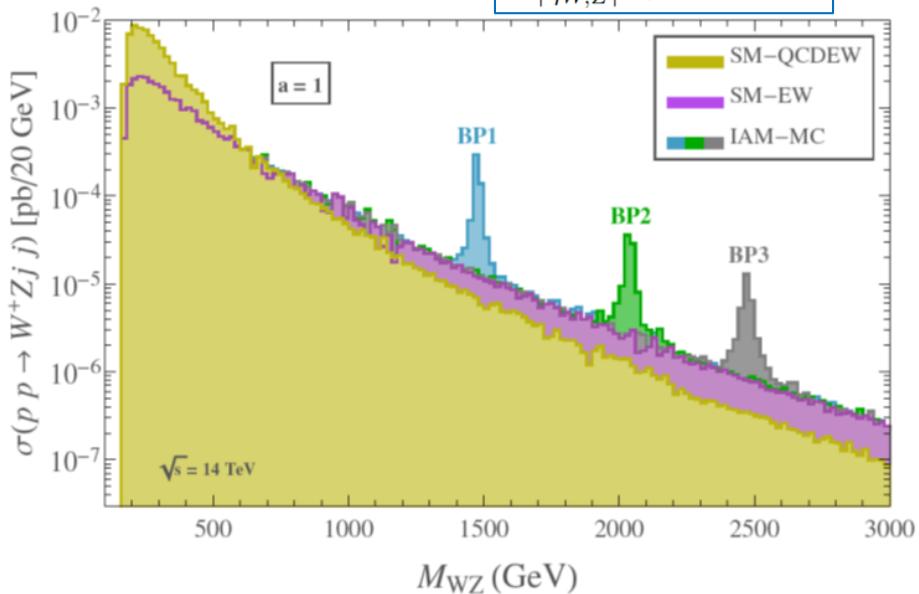
• Backgrounds:



• Optimal VBS cuts: (*)

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

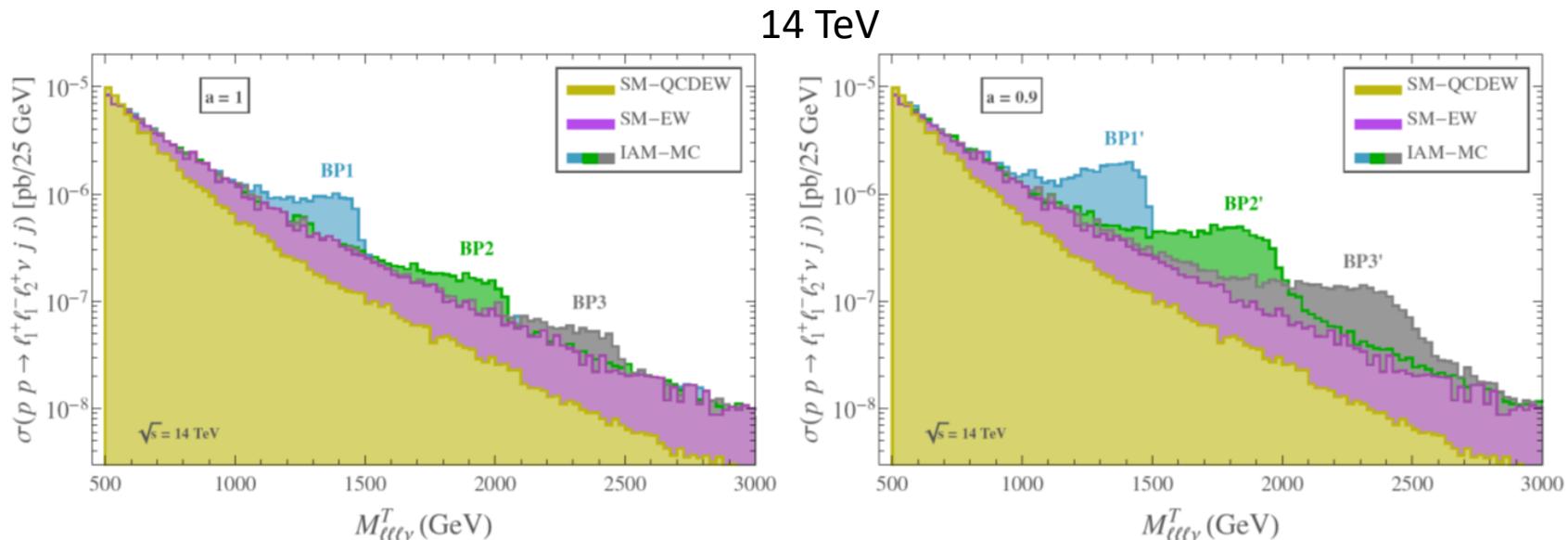
*[MG5_aMC + IAM-MC UFO;
NO detector sim;
NO polarization discriminant cuts (x)]*



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

(x) Fabbrichesi,Pinamonti,Tonero,Urbano, PRD 93 (2016) 015004

- Fully leptonic decays:



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

$$2 < |\eta_{j_{1,2}}| < 5 ,$$

$$\eta_{j_1} \cdot \eta_{j_2} < 0 ,$$

$$p_T^{j_1, j_2} > 20 \text{ GeV} ,$$

$$M_{jj} > 500 \text{ GeV} ,$$

$$M_Z - 10 \text{ GeV} < M_{\ell_Z^+ \ell_Z^-} < M_Z + 10 \text{ GeV} ,$$

$$M_{WZ}^T \equiv M_{\ell\ell\nu}^T > 500 \text{ GeV} ,$$

$$\not{p}_T > 75 \text{ GeV} ,$$

$$p_T^\ell > 100 \text{ GeV} ,$$

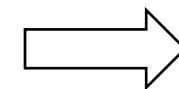
ranges of $M_{\ell\ell\nu}^T$:

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

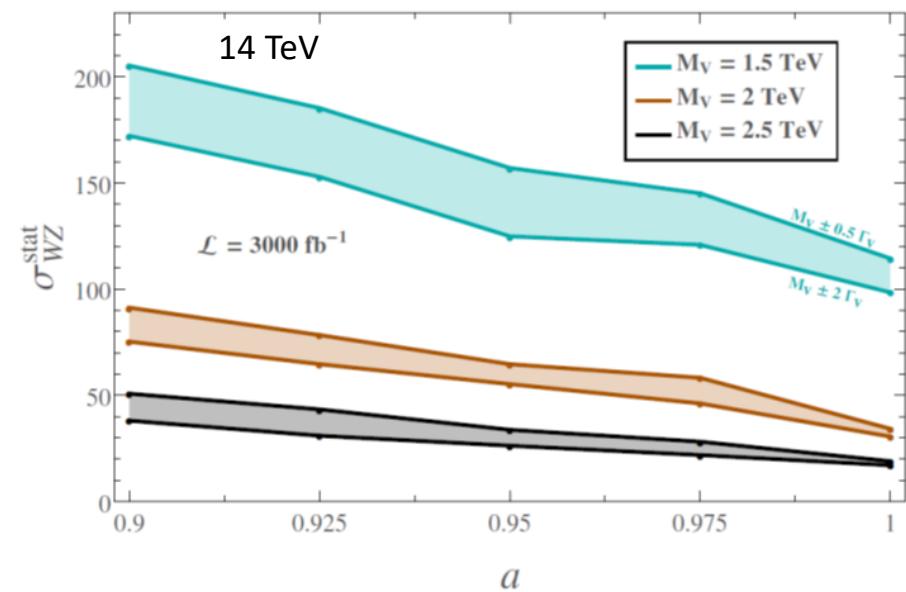
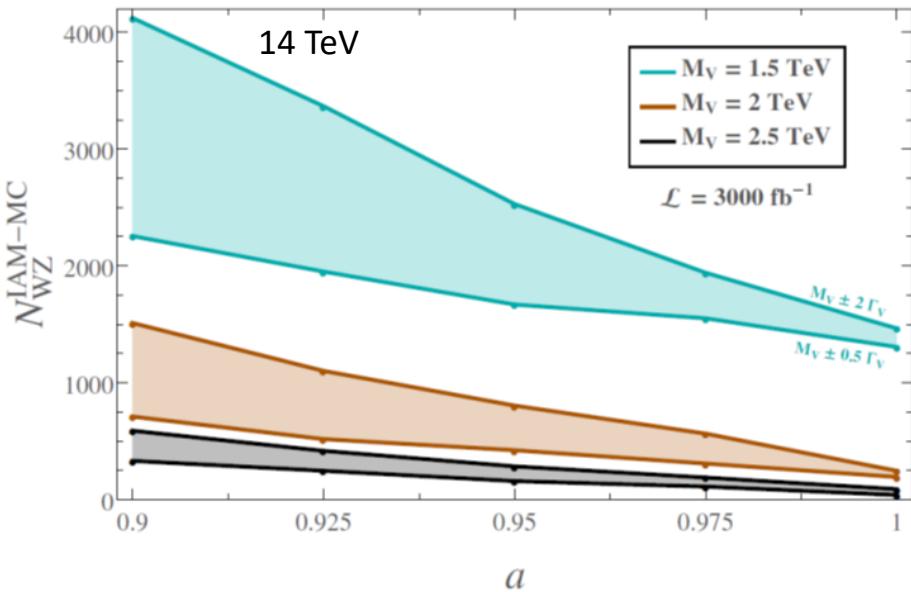
BP1 : 1325–1450 GeV ,	BP2 : 1875–2025 GeV ,	BP3 : 2300–2425 GeV ,
BP1' : 1250–1475 GeV ,	BP2' : 1675–2000 GeV ,	BP3' : 2050–2475 GeV .

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

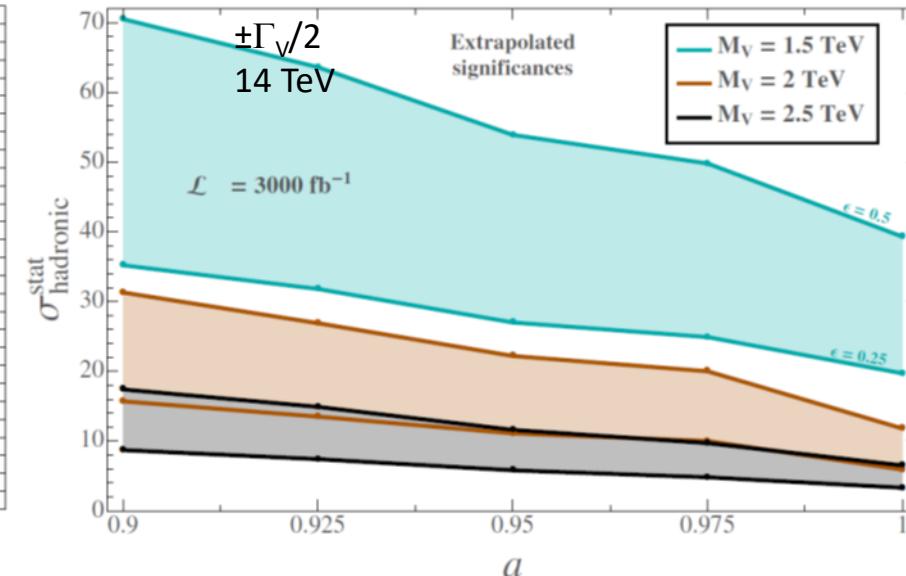
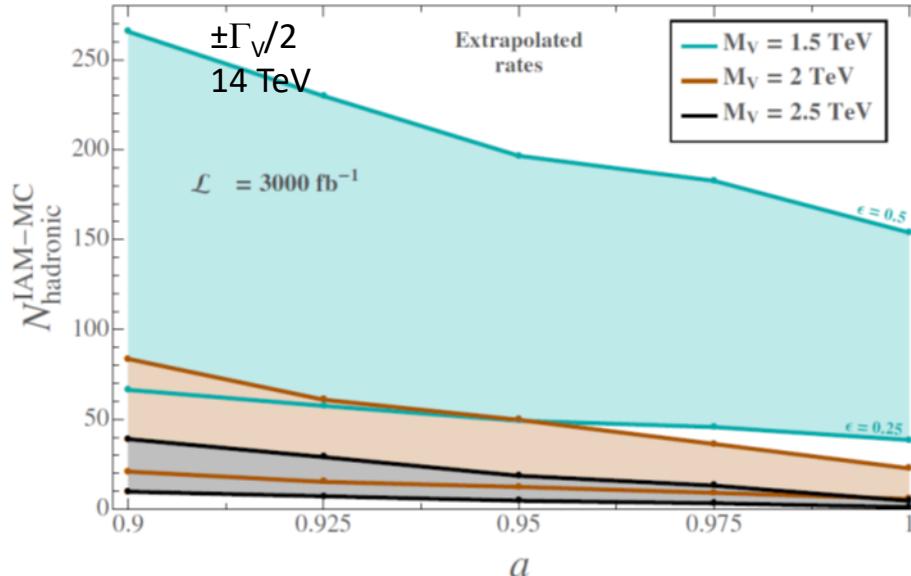
- Important improvements through fat-jet reconstruction techniques



- Sensitivity with 100% WZ efficiency reconstruction:



- Sensitivity estimate with “fat” jets:



BENCHMARK point

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

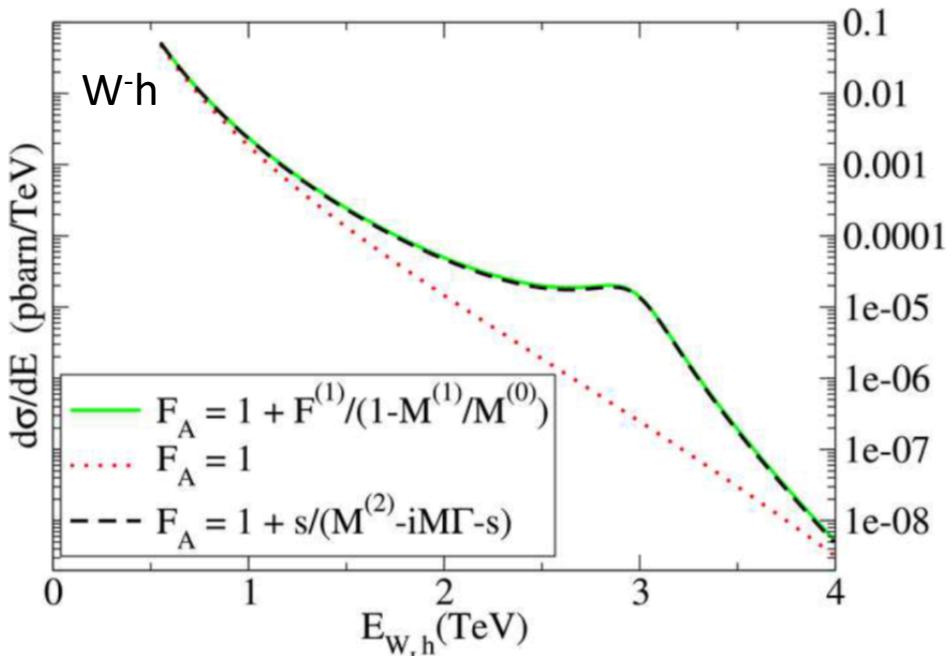
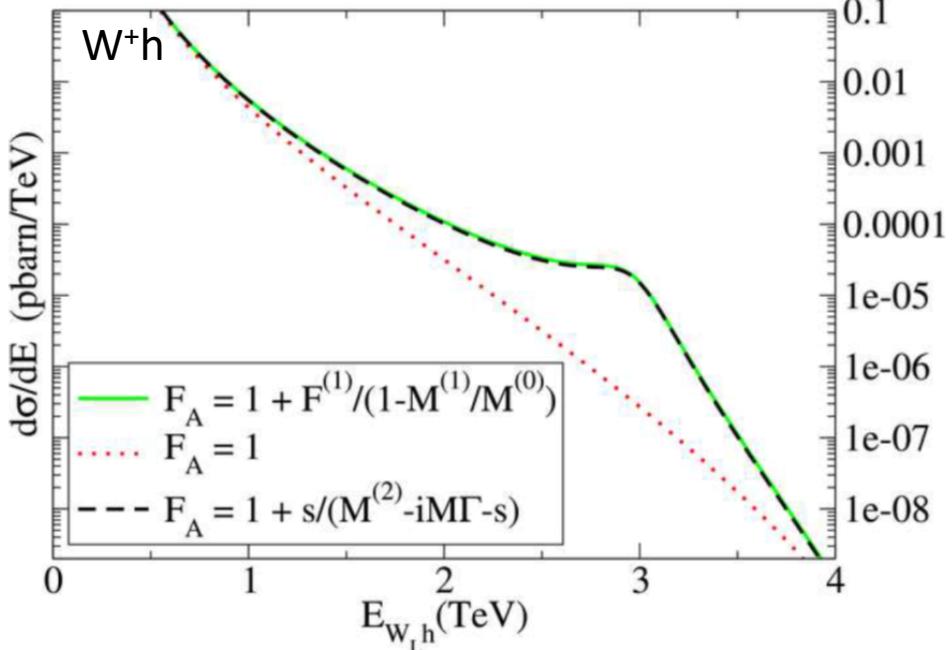
$\mathcal{M}_{11}(s)$ PWA $\rightarrow e(\mu) - 2d(\mu) = 1.64 \cdot 10^{-3}$

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



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

HEFT predict: BSM excess $\sim 10^{-2} \text{ fb}$



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