Low-energy signals of strongly-coupled EW symmetry-breaking scenarios

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PRL 110 (**2013**) 181801 [arXiv:1212.6769]
JHEP 01 (**2014**) 157 [arXiv:1310.3121]
[arXiv:1510.03114 [hep-ph]]

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CURRENT SITUATION

$M > 1$ TeV

Mass gap

t

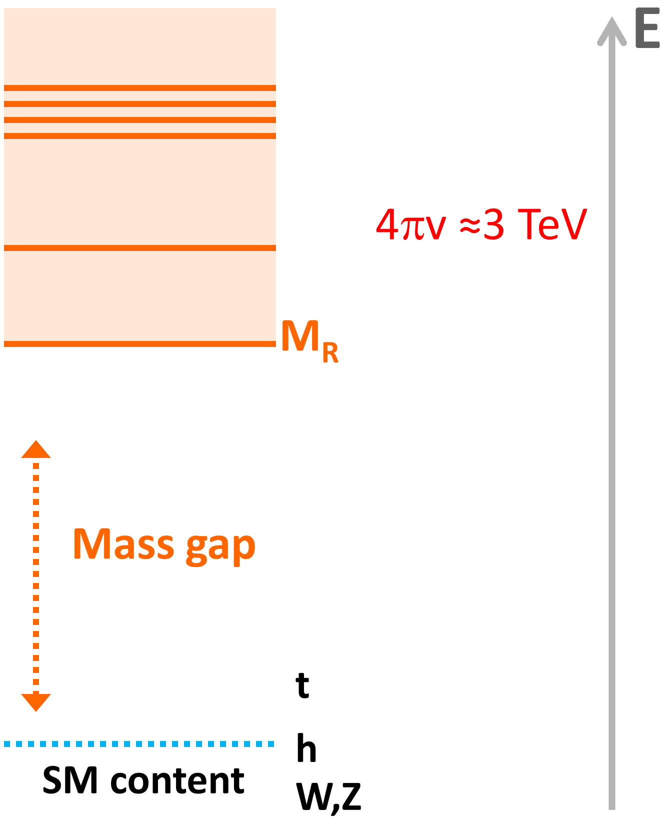
h

W,Z

SM content

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

the Resonance + EFT program



SM content

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

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

+

Resonance Lagrangian — V,A,S,P singlet & triplet

+

UV completion hypothesis — Sum-rules

THIS WORK

Resonance contributions to the NLO low-energy couplings

Prediction for low-energy observables

Low-energy chiral expansion

- If Higgs (pseudo) Goldstone boson ➔ **Non-linearity for h + ωᵃ**
- **Expansion** in non-linear EFT's: *

Finite pieces from loops (amplitude dependent) (+)

$$\mathcal{M}(2\to 2) \approx \frac{p^2}{v^2}\left[\underbrace{1}_{\text{LO (tree)}} + \left(\underbrace{\frac{c_k^r\, p^2}{v^2}}_{\text{NLO (tree)}} - \underbrace{\frac{\Gamma_k\, p^2}{16\pi^2 v^2}\ln\frac{p}{\mu} + \ldots}_{\text{NLO (1-loop)}}\right) + \mathcal{O}(p^4)\right]$$

Related to suppression $\sim 1/M_R^2$ (other states)

Typical <u>loop</u> suppression $\sim 1/(16\pi^2 v^2)$ (non-linearity)

THIS WORK

** 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
(x) Contino,Salvarezza, [1504.02750]
(x) Contino,Marzocca,Pappadopulo,Rattazzi, JHEP 1110 (2011) 081

100% determined by $\mathcal{L}_{LO}$
[Guo,Ruiz-Femenia,SC,[1506.04204]

- 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, J.Exp.Theor.Phys. 120 (2015) 354

* Weinberg '79
* Manohar,Georgi, NPB234 (1984) 189
* Urech '95
* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149
* Pich,Rosell,Santos,SC, forthcoming FTUAM-15-20

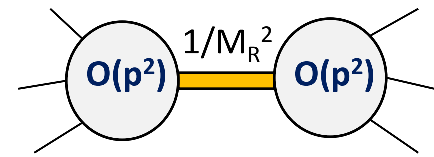
R contributions to the NLO EFT couplings [i.e., $O(p^4)$]

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

  General $\Delta\mathcal{L}_R$ `up to $O(p^2)$' **

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

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



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

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

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

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

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

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

$$\mathcal{L}_{ECLh} = \mathcal{L}_{p^2} + \boxed{\mathcal{L}_{p^4}} + \ldots$$

$$\supset \mathcal{L}^{\rm SM}$$

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

- Impose UV-completion assumptions on $\mathcal{L}_R$, (sum-rules,unitarity...)

  ➔ **EFT predictions ****

* Weinberg, 79; Manohar,Georgi, NPB234 (1984) 189
* Gasser,Leutwyler '84 '85
* Hirn,Stern '05
* Buchalla,Catà,Krause '13
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

* Apelquist,Bernard '80
* Longhitano '80, '81
* Alonso,Gavela,Merlo,Rigolin,Yepes '12
* Brivio,Corbett,Eboli,Gavela,Gonzalez–Fraile,Gonzalez–Garcia,Merlo,Rigolin '13

(x) Catà, EPJC74 (2014) 8, 2991

** Ecker et al. '89
** Cirigliano et al., NPB753 (2006) 139
** Pich,Rosell,Santos,SC, [1501.07249]; forthcoming FTUAM-15-20

Resonance Lagrangian (purely bosonic part)

$$\mathcal{L} = \mathcal{L}_2[\chi,\psi] + \mathcal{L}_R[R,\chi,\psi]$$

- A piece without resonances

$$\mathcal{L}_2 = \frac{v^2}{4}\left(1+\frac{2\kappa_W h}{v}+\dots\right)\langle u_\mu u^\mu\rangle$$

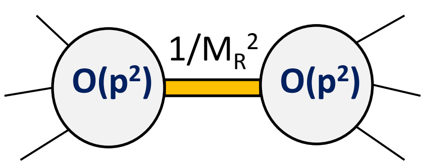
- And resonance operators (+kinetic terms)

$$\mathcal{L}_R = \langle V_{\mu\nu}\,\chi_V^{\mu\nu}\rangle + \langle A_{\mu\nu}\,\chi_A^{\mu\nu}\rangle + \langle P\,\chi_P\rangle + S_1\,\chi_{S_1}$$

$$\begin{aligned}
\chi_V^{\mu\nu} &= \frac{F_V}{2\sqrt{2}}\,f_+^{\mu\nu} + \frac{i\,G_V}{2\sqrt{2}}\,[u^\mu,u^\nu] + \frac{\widetilde{F}_V}{2\sqrt{2}}\,f_-^{\mu\nu} + \frac{\widetilde{\lambda}_1^{hV}}{\sqrt{2}}\,[(\partial^\mu h)\,u^\nu - (\partial^\nu h)\,u^\mu]\,,\\
\chi_A^{\mu\nu} &= \frac{F_A}{2\sqrt{2}}\,f_-^{\mu\nu} + \frac{\lambda_1^{hA}}{\sqrt{2}}\,[(\partial^\mu h)\,u^\nu - (\partial^\nu h)\,u^\mu] + \frac{\widetilde{F}_A}{2\sqrt{2}}\,f_+^{\mu\nu} + \frac{i\,\widetilde{G}_A}{2\sqrt{2}}\,[u^\mu,u^\nu]\,,\\
\chi_{S_1} &= \frac{c_d}{\sqrt{2}}\langle u_\mu u^\mu\rangle\,,\\
\chi_P &= d_P u_\mu \partial^\mu h/v\,,\\
\chi_{V_1}^{\mu\nu} = \chi_{A_1}^{\mu\nu} = \chi_S = \chi_{P_1} &= 0
\end{aligned}$$

O(p⁴) low-energy EFT from $\mathcal{L}_R$ (purely bosonic part)

$\mathcal{O}_1 = \frac{1}{4}\langle f_+^{\mu\nu} f_{+\,\mu\nu} - f_-^{\mu\nu} f_{-\,\mu\nu}\rangle$	$\mathcal{O}_6 = \frac{1}{v^2}(\partial_\mu h)(\partial^\mu h)\langle u_\nu u^\nu\rangle$
$\mathcal{O}_2 = \frac{1}{2}\langle f_+^{\mu\nu} f_{+\,\mu\nu} + f_-^{\mu\nu} f_{-\,\mu\nu}\rangle$	$\mathcal{O}_7 = \frac{1}{v^2}(\partial_\mu h)(\partial_\nu h)\langle u^\mu u^\nu\rangle$
$\mathcal{O}_3 = \frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle$	$\mathcal{O}_8 = \frac{1}{v^4}(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)$
$\mathcal{O}_4 = \langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle$	$\mathcal{O}_9 = \frac{1}{v}(\partial_\mu h)\langle f_-^{\mu\nu} u_\nu\rangle$
$\mathcal{O}_5 = \langle u_\mu u^\mu\rangle^2$	



$$\Delta\mathcal{L}_R^{\mathcal{O}(p^4)} = \sum_{R=V,A}\frac{1}{M_R^2}\left(\frac{1}{2}\langle\chi_R^{\mu\nu}\rangle\langle\chi_{R\,\mu\nu}\rangle - \langle\chi_R^{\mu\nu}\chi_{R\,\mu\nu}\rangle\right)$$

$$+\frac{1}{2M_P^2}\left(\langle\chi_P\chi_P\rangle - \frac{1}{2}\langle\chi_P\rangle^2\right) + \frac{\chi_{S_1}^2}{2M_{S_1}^2}$$

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

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

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

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

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

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

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

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

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

$$\begin{aligned}
\mathcal{F}_1 &= \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2}\\
\mathcal{F}_2 &= -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2}\\
\mathcal{F}_3 &= -\frac{F_V G_V}{2M_V^2}\\
\mathcal{F}_4 &= \frac{G_V^2}{4M_V^2}\\
\mathcal{F}_5 &= \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2}\\
\mathcal{F}_6 &= -\frac{(\lambda_1^{hA})^2 v^2}{M_A^2}\\
\mathcal{F}_7 &= \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2 v^2}{M_A^2}\\
\mathcal{F}_8 &= 0\\
\mathcal{F}_9 &= -\frac{F_A \lambda_1^{hA} v}{M_A^2}
\end{aligned}$$

* Pich,Rosell,Santos,SC, [arXiv:1510.03114 [hep-ph]]

High-energy constraints on $\mathcal{L}_R$ (purely bosonic part)

• Form-factors into ωω & hω

$$F^V_{\omega\omega}(s) = 1 + \frac{F_V G_V}{v^2}\frac{s}{M_V^2 - s} \qquad\qquad F_V G_V = v^2$$

$$F^A_{h\omega}(s) = \kappa_W \left(1 + \frac{F_A \lambda_1^{hA}}{\kappa_W v}\frac{s}{M_A^2 - s}\right) \qquad\qquad F_A\lambda_1^{hA} = \kappa_W v$$

They contribute to the LR-correlator (W[3]B correlator -order-parameter of the EW sym. breaking-)

➔In particular, in the Peskin-Takeuchi sum-rule for S **

•Moreover, asymptotically-free strongly-coupled theories (QCD-like) ➔ 2 WSRs

$$\Pi_{VV}(s) - \Pi_{AA}(s) \to 1/s^3 \qquad \left\{ \begin{array}{ll} F_V^2 - F_A^2 = v^2\,, \qquad F_V^2\, M_V^2 - F_A^2\, M_A^2 = 0 & \text{(tree)} \\ \kappa_W = M_V^2/M_A^2 & \text{(1-loop)} \end{array} \right.$$

** Peskin,Takeuchi, PRD 46 (1992) 381; PRL 65 (1990) 964.

*Pich,Rosell, SC, PRL 110 (2013) 181801; JHEP 01 (2014) 157

*Orgogozo, Rychkov, JHEP 1203 (2012) 046; 1306 (2013) 014

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

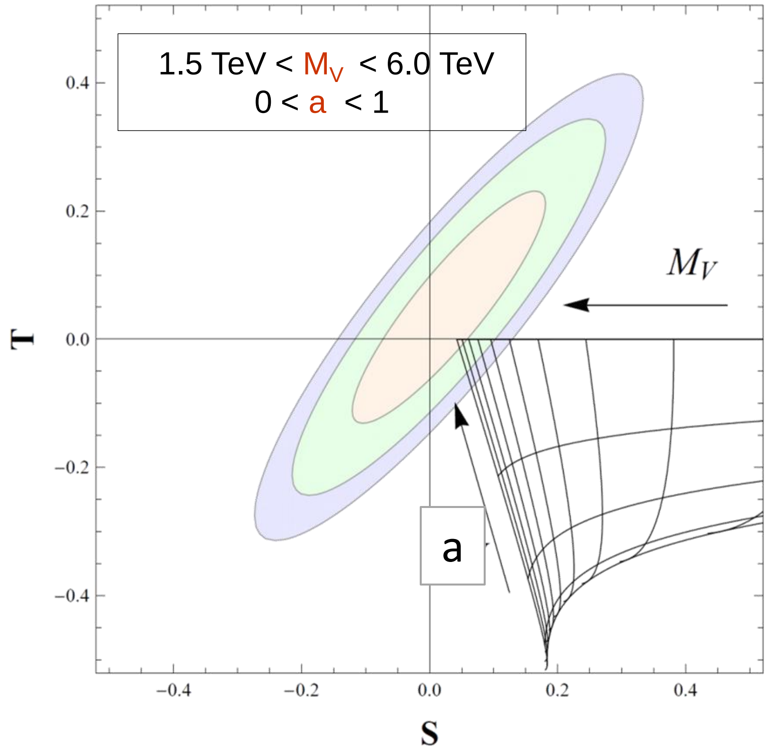
* Pich,Rosell,Santos,SC, [arXiv:1510.03114 [hep-ph]]

(S , T) oblique parameters:
ONE-LOOP results + UV-constraint

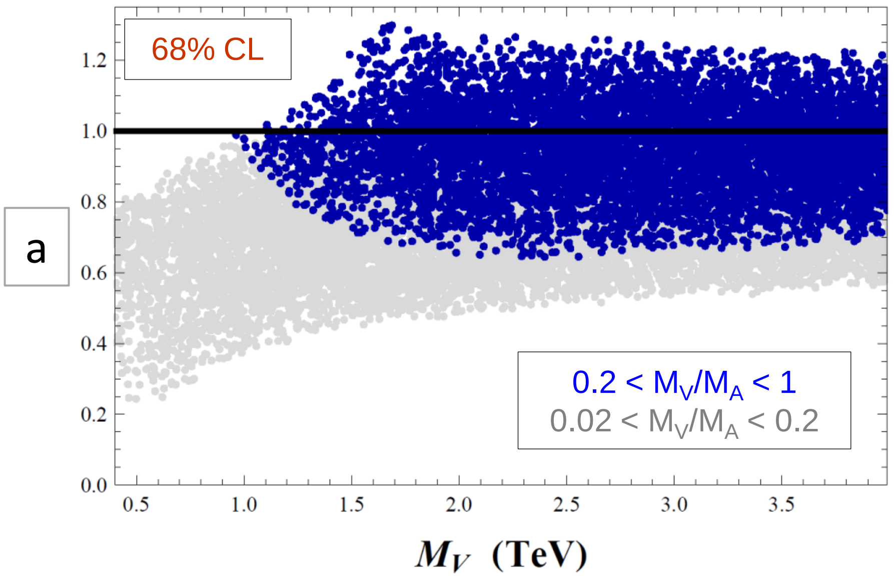
C & P-even

ii) NLO results: 1st and 2nd WSRs*

1 > a > 0.97
$M_A \approx M_V$ > 5 TeV
(68%CL)



iii) NLO results: 1st WSR and $M_V < M_A$*



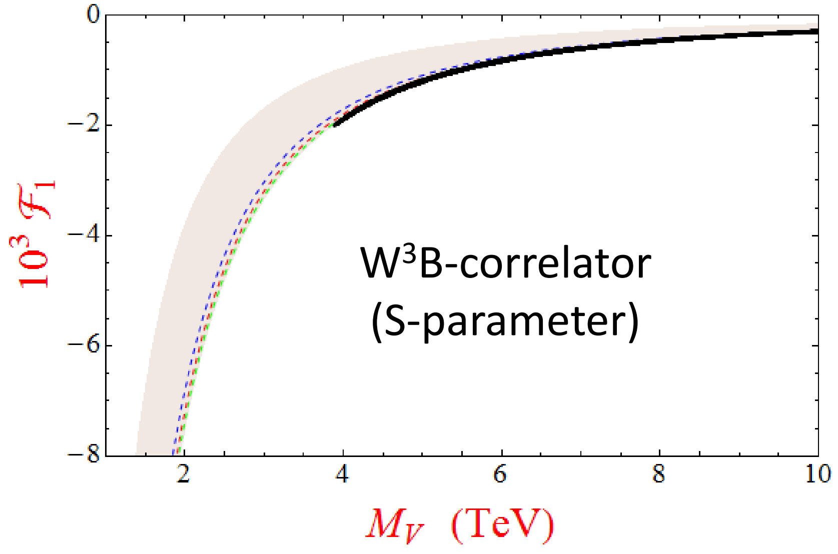
Similar conclusions, but softened

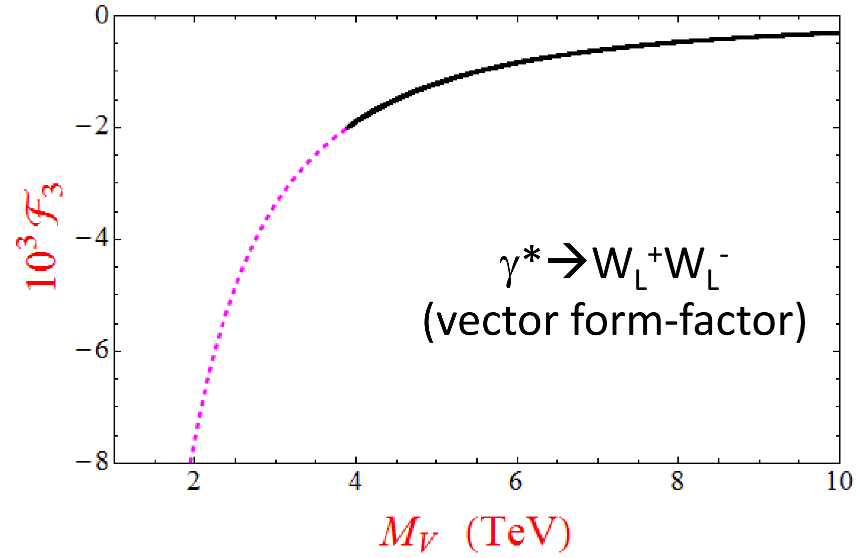
For M_V<M_A:

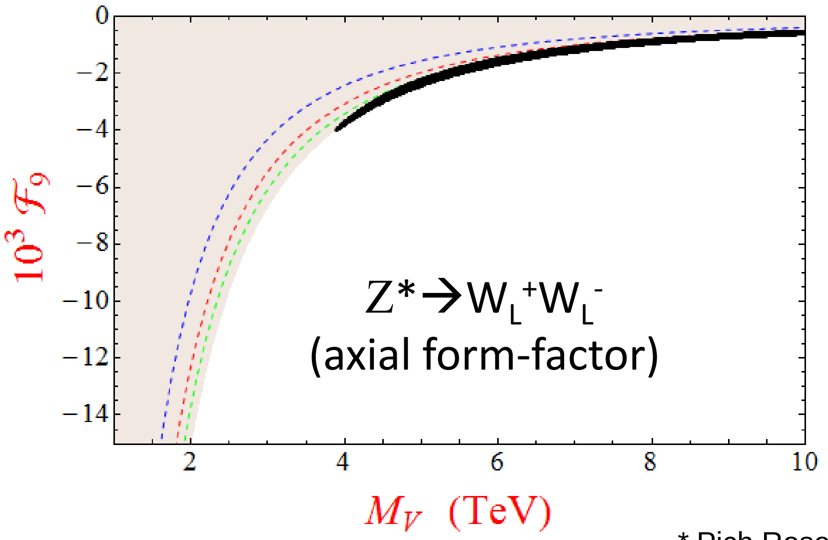
✓ M_R > 1 TeV at 68% CL.

* Pich,Rosell, SC, PRL 110 (2013) 181801; JHEP 01 (2014) 157

S-parameter and form-factor couplings
(affected by S+T + 2WSRs bounds)



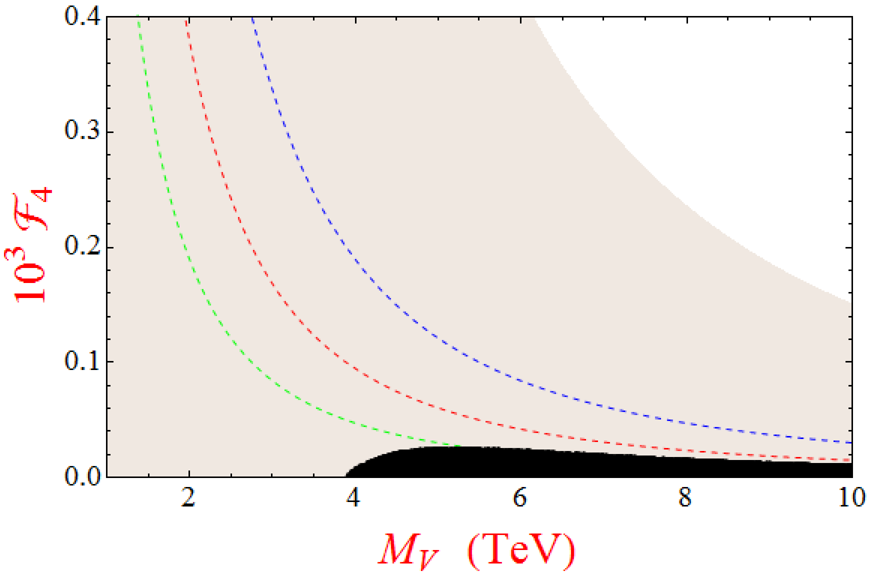




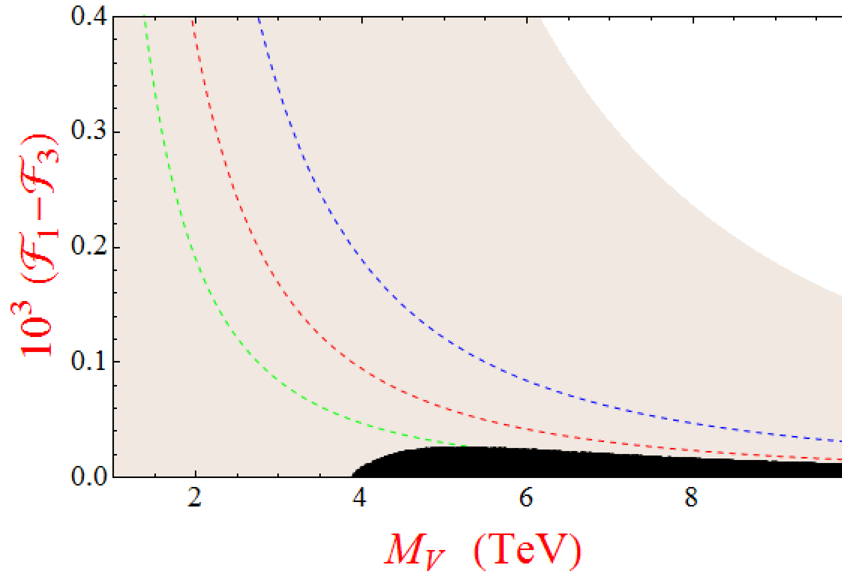
* Pich,Rosell,Santos,SC, [arXiv:1510.03114 [hep-ph]]

Scattering couplings
(affected by S+T + 2WSRs bounds)

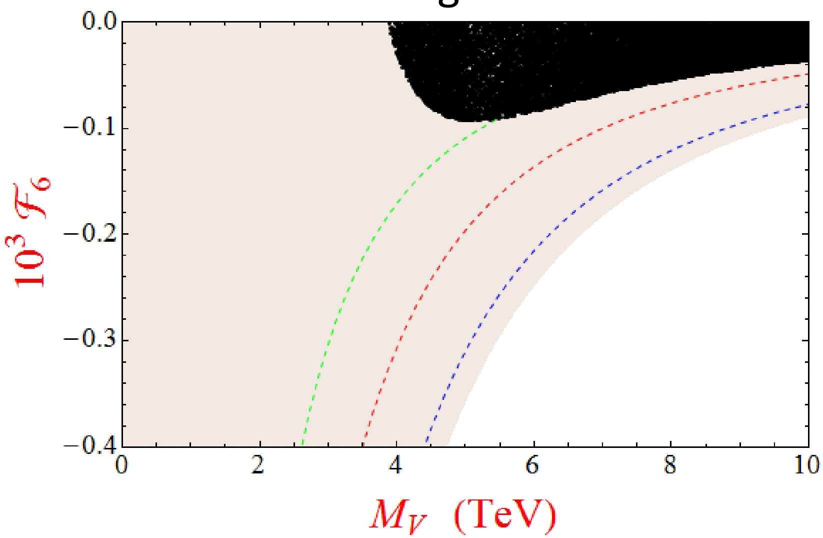
• $w^a w^b \rightarrow w^c\, w^d$ scattering



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



• $w^a w^b \rightarrow hh$ scattering

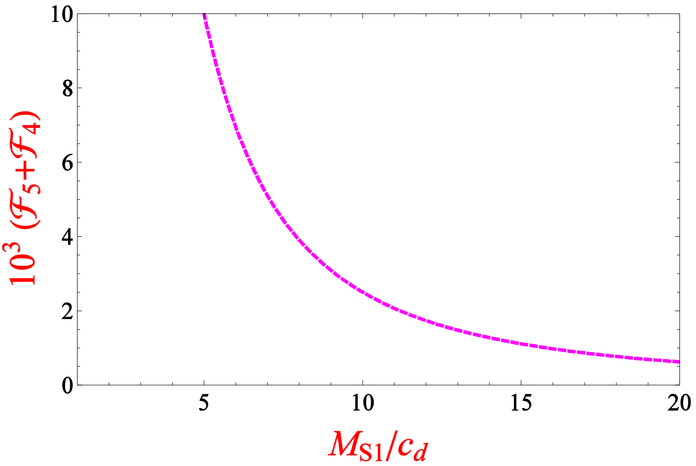


• $hh \rightarrow hh$ scattering $\rightarrow 0$

* Pich,Rosell,Santos,SC, [arXiv:1510.03114 [hep-ph]]

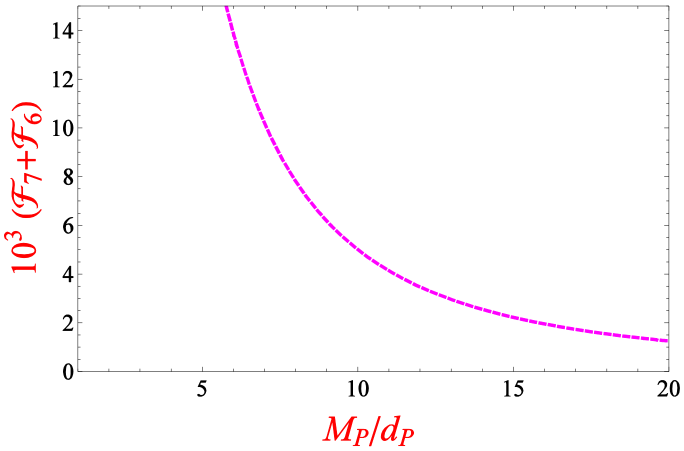
Scattering couplings
(NOT affected by S+T + 2WSRs bounds)

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



Contribution from $\mathbf{S_1}$ resonances
(e.g., $c_d \sim v$, $0 < M_{S1} < 5$ TeV)

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



Contribution from **P** resonances
(e.g., $c_d \sim v$, $0 < M_P < 5$ TeV)

* Pich,Rosell,Santos,SC, [arXiv:1510.03114 [hep-ph]]

Conclusions

1) **Build a custodial-invariant Lagrangian with R + light dof ($\chi + \psi$)**

2) Low-energy expansion and matching: **R** contributions to the EFT @ O(p^4)

→ **NLO eff. couplings in terms of R parameters**

3) High-energy constraints on **R** theory → strong low-energy predictions

✓ **Diferent Resonances**

✓ **Different patterns for EFT couplings**

✓ **Different importance for low-energy observables**

Low-energy physics tells about the high-energy resonance structure

BACKUP

PREDICTIONS:
ONE-LOOP results + UV-constraint

Higgsless
C & P-even

$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

LO

$$S = \boxed{4\pi v^2\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)} + \frac{1}{12\pi}\left[\left(\log\frac{M_V^2}{m_H^2}-\frac{11}{6}\right) - \kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2}-\frac{11}{6}-\frac{M_A^2}{M_V^2}\log\frac{M_A^2}{M_V^2}\right)\right]$$

[terms $O(m_S^2/M^2_{V,A})$ neglected]

(k_W=a)

✓ 1st and 2nd WSRs at LO and NLO + ππ-VFF:

→ 2nd WSR: $0 < a = M_V^2/M_A^2 < 1$

* Pich,Rosell, SC, PRL 110 (2013) 181801; JHEP 01 (2014) 157

PREDICTIONS:
TREE-LEVEL results + UV-constraint

Higgsless part CP conserving
Only P-even interactions

- Higgsless R Lagrangian with only bosons

*(general custodial R Lagrangian in *)*

$$\chi_V^{\mu\nu} = \frac{F_V}{2\sqrt{2}} f_+^{\mu\nu} + \frac{iG_V}{2\sqrt{2}}[u^\mu, u^\nu] + \cancel{\frac{\widetilde{F}_V}{2\sqrt{2}}} f_-^{\mu\nu}$$

$$\chi_A^{\mu\nu} = \frac{F_A}{2\sqrt{2}} f_-^{\mu\nu} + \cancel{\frac{\widetilde{F}_A}{2\sqrt{2}} f_+^{\mu\nu}} + \cancel{\frac{i\widetilde{G}_A}{2\sqrt{2}}[u^\mu, u^\nu]},$$

$$\chi_{S_1} = \frac{c_d}{\sqrt{2}} \langle u_\mu u^\mu \rangle$$

- Integrate out V and A:

$$\gamma^* \to \omega^+\omega^- \ \mathbf{EM-FF:} \qquad \mathbf{F_V G_V = v^2}$$

$$\mathbf{1 + 2\, WSR\, on\, \Pi_{W_3B}:} \qquad \mathbf{F_V^2 - F_A^2 = v^2,\ F_V^2 M_V^2 - F_A^2 M_A^2 = 0}$$

$$a_1 = -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2},$$
$$(a_2 - a_3) = -\frac{F_V G_V}{2M_V^2},$$
$$a_4 = \frac{G_V^2}{4M_V^2},$$
$$a_5 = \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2},$$

$$\boxed{\begin{aligned} a_1 &= -\frac{v^2}{4}\left(\frac{1}{M_V^2} + \frac{1}{M_A^2}\right), \\ (a_2 - a_3) &= -\frac{v^2}{2M_V^2}, \\ a_4 &= \frac{v^2}{4}\left(\frac{1}{M_V^2} - \frac{1}{M_A^2}\right), \\ a_5 &= -\frac{v^2}{4}\left(\frac{1}{M_V^2} - \frac{1}{M_A^2}\right) + \frac{c_d^2}{4M_{S_1}^2}, \end{aligned}}$$

(x) Longhitano '80, '81

* Ecker et al. '89
* Pich,Rosell,Santos,SC,[1501.07249]; forthcoming FTUAM-15-20

RESONANCE LAGRANGIAN

- Introduce light dof **+ Resonances** *,**

- Lightest SU(2) triplets V, A, S, P and singlets V_1, A_1, S_1, P_1 **

*(antisymetric-tensor formalism $R_{\mu\nu}$ for spin-1 Resonances *)*

- To extract their contribution to $\mathcal{L}_{p4}$

(NOTICE that this avoids contributions to $\mathcal{L}_{p2}$, avoiding large low-energy corrections to SM)

➔ We need only **R operators O(p²)**

$$
\begin{aligned}
\mathcal{L}_R &= \frac{1}{2}\langle \nabla^\mu R\,\nabla_\mu R - M_R^2 R^2\rangle + \langle R\chi_R\rangle \qquad (R=S,\,P)\,,\\
\mathcal{L}_R &= -\frac{1}{2}\langle \nabla^\lambda R_{\lambda\mu}\,\nabla_\sigma R^{\sigma\mu} - \frac{1}{2}M_R^2 R_{\mu\nu}R^{\mu\nu}\rangle + \langle R_{\mu\nu}\chi_R^{\mu\nu}\rangle \qquad (R=V,\,A)\,,\\
\mathcal{L}_{R_1} &= \frac{1}{2}\left(\partial^\mu R_1\,\partial_\mu R_1 - M_{R_1}^2 R_1^2\right) + R_1\chi_{R_1} \qquad (R_1=S_1,\,P_1)\,,\\
\mathcal{L}_{R_1} &= -\frac{1}{2}\left(\partial^\lambda R_{1\,\lambda\mu}\,\partial_\sigma R_1^{\sigma\mu} - \frac{1}{2}M_{R_1}^2 R_{1\,\mu\nu}R_1^{\mu\nu}\right) + R_{1\,\mu\nu}\chi_{R_1}^{\mu\nu} \qquad (R_1=V_1,\,A_1)\,,
\end{aligned}
$$

* Ecker et al. '89
** Cirigliano et al., NPB753 (2006) 139
** Pich,Rosell,SC '12, '13
** Pich,Rosell,Santos,SC, [1501.07249]; forthcoming FTUAM-15-20

BOSONIC SECTOR : χ

- Building blocks with bosons χ (x):

EW Goldstones (ω^a) →

$$D_\mu U = \partial_\mu U - i\hat{W}_\mu U + iU\hat{B}_\mu\,,$$
$$u^\mu = iu_R^\dagger(\partial_\mu - i\hat{B}_\mu)u_R - iu_L^\dagger(\partial_\mu - i\hat{W}_\mu)u_L = iu(D^\mu U)^\dagger u\,,$$

EW gauge bosons (B, W^a) →

$$\hat{W}_{\mu\nu} = \partial_\mu\hat{W}_\nu - \partial_\nu\hat{W}_\mu - i[\hat{W}_\mu,\hat{W}_\nu]\,, \qquad \hat{B}_{\mu\nu} = \partial_\mu\hat{B}_\nu - \partial_\nu\hat{B}_\mu - i[\hat{B}_\mu,\hat{B}_\nu]\,,$$
$$f_\pm^{\mu\nu} = u_L^\dagger\hat{W}^{\mu\nu}u_L \pm u_R^\dagger\hat{B}^{\mu\nu}u_R\,.$$

Higgs (singlet h) → **h** via polynomials **$\mathcal{F}$(h/v)** & derivatives

soft-scale!!!

- "Chiral" counting*,**:

$$\partial_\mu\,,\quad m_W\,,\quad m_Z\,,\quad m_h \quad\sim\quad \mathcal{O}(p)$$
$$D_\mu U\,,\quad V_\mu\,,\quad g'v\mathcal{T}\,,\quad \hat{W}_\mu\,,\quad \hat{B}_\mu \quad\sim\quad \mathcal{O}(p)\,,$$
$$\hat{W}_{\mu\nu}\,,\quad \hat{B}_{\mu\nu} \quad\sim\quad \mathcal{O}(p^2)\,.$$

(x) Apelquist,Bernard '80
(x) Longhitano '80, '81
(x) Herrero,Morales '95
(x) Pich,Rosell,SC '12 '13
(x) Alonso et al., PLB722 (2013) 330
...etc

* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

** Urech '95

‘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 FTUAM-15-20

‘CHIRAL’ expansion in ECLh

- EFT Lagrangian at LO and NLO in chiral exp. *

$$\mathcal{L}_{ECLh} = \mathcal{L}_{p^2} + \mathcal{L}_{p^4} + \ldots$$

SM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Examples of BSM terms:

$$\mathcal{L}_{p^2}^{\rm BSM} = \frac{(a-1)\,h}{2v} \mathrm{Tr}\{D_\mu U^\dagger D^\mu U\} + \ldots$$

$$\mathcal{L}_{p^4}^{\rm BSM} = \frac{i}{2}(a_2 - a_3)\,\mathrm{Tr}\{f_+^{\mu\nu}[u_\mu, u_\nu]\} + \mathcal{F}_{X\psi\psi}\,\mathrm{Tr}\{f_{+\,\mu\nu} d^\mu J_V^\nu\} + \ldots$$

which leads to a chiral exp. in the sctatering

$$T(2\to 2) = \frac{p^2}{v^2} + \underbrace{\frac{a_{(4)} p^4}{v^4}}_{tree-NLO} + \underbrace{\frac{p^4}{16\pi^2 v^4}}_{1\ell oop-NLO} + \ldots$$

* Weinberg ‘79
* Manohar,Georgi, NPB234 (1984) 189
* Urech ’95
* Georgi,Manohar NPB234 (1984) 189
* Buchalla,Catà,Krause ‘13
* Hirn,Stern ‘05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149
* Pich,Rosell,Santos,SC, forthcoming

Integrating out the RESONANCES

$$e^{iS[\chi,\psi]_{\rm EFT}} \;=\; \int [dR]\; e^{iS[\chi,\psi,R]}$$

- **At the practical level, ***

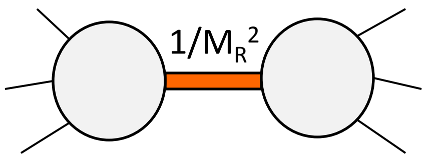
1.) Compute the Resonance EoM for p<<M_R:

$$R_{c\ell} \;=\; \frac{1}{M_R^2}\left(\chi_R - \frac{1}{N}\langle\chi_R\rangle\right) \;+\; \ldots \qquad (R=S,\,P)\,,$$

$$R^{\mu\nu}_{c\ell} \;=\; -\frac{2}{M_R^2}\left(\chi^{\mu\nu}_R - \frac{1}{N}\langle\chi^{\mu\nu}_R\rangle\right) \;+\; \ldots \qquad (R=V,\,A)\,,$$

$$R_{1\;c\ell} \;=\; \frac{1}{M_{R_1}^2}\chi_{R_1} \;+\; \ldots \qquad (R_1=S_1,\,P_1)\,,$$

$$R^{\mu\nu}_{1\;c\ell} \;=\; -\frac{2}{M_{R_1}^2}\chi^{\mu\nu}_{R_1} \;+\; \ldots \qquad (R=V,\,A)\,,$$



2.) Tree-level contribution to the O(p^4) ECLh for p<<M_R:

$$\boxed{S[\chi,\psi]_{\rm EFT} \;=\; S[\chi,\psi,R_{c\ell}]}$$

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

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

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

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

* Ecker et al. '89

$SU(2)_L \otimes SU(2)_R \,/\, SU(2)_{L+R}$ Resonance Theory (P-even)

$$\mathcal{L} = \mathcal{L}_{\rm EW}^{(2)} + \mathcal{L}_{\rm GF} + \mathcal{L}_V + \mathcal{L}_A + \mathcal{L}_{VV}^{\rm kin} + \mathcal{L}_{AA}^{\rm kin} + \ldots$$

w/ field content: $SU(2)_L \otimes SU(2)_R/SU(2)_{L+R}$ EW Goldstones + SM gauge bosons

+ one $SU(2)_L \otimes SU(2)_R$ singlet Higgs-like scalar S_1 with m_{S1}=126 GeV ***

+ lightest V and A resonances -triplets- *(antisym. tensor formalism)* (x)

•Relevant resonance Lagrangian (x), **

$$\begin{aligned}
\mathcal{L} \;=\;& \frac{v^2}{4}\langle u_\mu u^\mu\rangle \left(1+\frac{2\,a}{v}\,h\right) && \longleftarrow \text{h + } \omega \text{ sector}\\
&+ \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{i\,G_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu,u^\nu]\rangle && \longleftarrow \text{V + } \omega \text{ sector}\\
&+ \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle + \sqrt{2}\,\lambda_1^{hA}\,\partial_\mu h\,\langle A^{\mu\nu} u_\nu\rangle && \longleftarrow \text{A+h+} \omega \text{ sector}
\end{aligned}$$

NOTATIONS:

$\omega = \mathbf{a} = \kappa_{\mathbf{W}} = \kappa_{\mathbf{Z}}$

We will have 7 resonance parameters:

F_V, G_V, F_{AW}, κ_W, λ_1^{SA}, M_V and M_A

High-energy constraints will be crucial

(x) SD constraints: Ecker et al. '89
(x) EoM simplifications: Xiao, SC '07
(x) EoM simplifications: Georgi '91
(x) EoM simplification: Pich,Rosell,SC '13

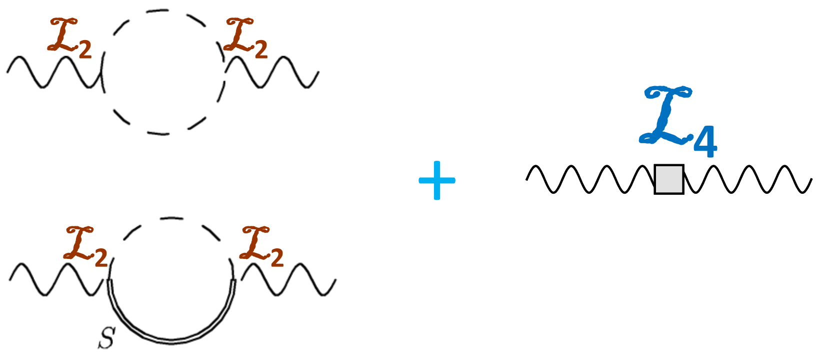
** Appelquist, Bernard '80
** Longhitano '80 '81
** Dobado,Espriu,Herrero '91
** Dobado et al. '99
** Espriu,Matias '95 …

*** Alonso et al. '13
*** Manohar et al. '13
*** Elias-Miro et al. '13…

	P	C	CP	h.c.
S	S	S^T	S^T	S
P	$-P$	P^T	$-P^T$	P
$V^{\mu\nu}$	$V_{\mu\nu}$	$-V^{\mu\nu\, T}$	$-V^T_{\mu\nu}$	$V^{\mu\nu}$
$A^{\mu\nu}$	$-A_{\mu\nu}$	$A^{\mu\nu\, T}$	$-A^T_{\mu\nu}$	$A^{\mu\nu}$

	P	C	CP	h.c.
U	$U^\dagger$	U^t	U^*	$U^\dagger$
u	$u^\dagger$	u^t	u^*	$u^\dagger$
u^μ	$-u_\mu$	$u^{\mu\ t}$	$-u^t_\mu$	u^μ
$(d^\mu X)$	$(d_\mu X')$	$(d^\mu X)'$	$(d_\mu X)'$	$(d^\mu X^\dagger)$
$f_\pm^{\mu\nu}$	$\pm f_{\pm\,\mu\nu}$	$\mp f_\pm^{\mu\nu\ t}$	$-f^t_{\pm\,\mu\nu}$	$f_\pm^{\mu\nu}$
$\partial^\mu h$	$\partial_\mu h$	$\partial^\mu h$	$\partial_\mu h$	$\partial^\mu h$

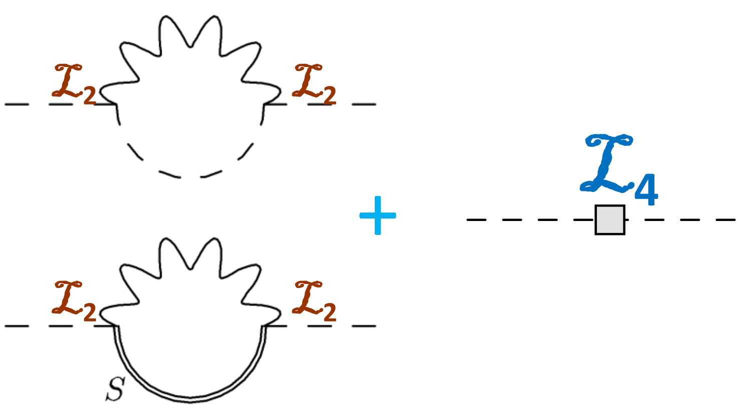
➔ W^3B correlator*



$$S \;=\; -\,16\pi\, \mathbf{a_1^r}(\mu) \;+\; \frac{(1-a^2)}{12\pi}\left(\frac{5}{6}+\ln\frac{\mu^2}{m_h^2}\right)$$

3 eff. couplings →

➔ NGB self-energy *



$$T \;=\; \frac{8\pi}{c_W^2}\, \mathbf{a_0^r}(\mu) \;-\; \frac{3\,(1-a^2)}{16\pi c_W^2}\left(\frac{5}{6}+\ln\frac{\mu^2}{m_h^2}\right)$$

* Dobado et al. '99
* Pich, Rosell, SC '12, '13
* Delgado,Dobado,Herrero,SC [in prep]

→Similar in linear models:
Masso,Sanz,PRD87 (2013) 3, 033001
Chen,Dawson,Zhang,PRD89 (2014) 015016

also notice the subtlety*,** $g^{(')} \sim m_{W,Z}/v \sim p/v$ *[notice $e \sim p/v$ too]*

* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

** Urech '95

(x) Apelquist,Bernard '80
(x) Longhitano '80, '81
(x) Herrero,Morales '95
(x) Pich,Rosell,Sc '12 '13
(x) Brivio et al. '13
(x) Gavela,Kanshin,Machado,Saa '14, etc.

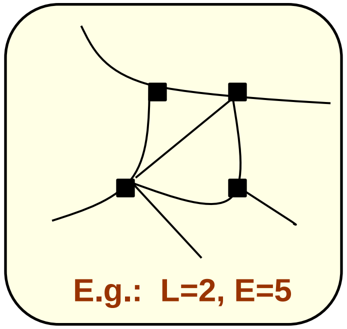
Counting, loops & renormalization

•In general, the O(p^d) Lagrangian has the symbolic form (χ=W,B,π,h),

$$\mathcal{L}_d \;=\; \sum_k f_k^{(d)}\, p^d \left(\frac{\chi}{v}\right)^k$$

$$f_k^{(2)} \sim v^2$$
$$f_k^{(4)} \sim a_i$$
...

leading to a general scaling* of a diagram with
- L loops
- E external legs
- N_d vertices of $\mathcal{L}_d$



$$\mathcal{M} \sim \left(\frac{p^2}{v^{E-2}}\right)\left(\frac{p^2}{16\pi^2 v^2}\right)^L \prod_d \left(\frac{f_k^{(d)} p^{(d-2)}}{v^2}\right)^{N_d}$$

[scaling of individual diagrams; cancellations & higher suppressions for the total amplitude]

• O(p^d) loop divergence + O(p^d) chiral coupling = UV-finite

E.g. W_LW_L-scat:**

LO O(p^2)➔ $\frac{p^2}{v^2}$ (tree)

NLO O(p^4)➔ $a_i\,\frac{p^4}{v^4}$ (tree) + $\frac{p^4}{16\pi^2 v^4}\left(\frac{1}{\epsilon}+\log\right)$ (1-loop)

* Weinberg '79
* Urech '95
* Georgi,Manohar NPB234 (1984) 189
* Buchalla,Catà,Krause '13
* Hirn,Stern '05
* Delgado,Dobado,Herrero,SC,JHEP1407 (2014) 149

** Espriu,Mescia,Yencho '13
** Delgado,Dobado '13

S-parameter sum-rule *

✓ In this work, dispersive representation introduced by Peskin and Takeuchi*.

$$S = \frac{16}{g^2 \tan\theta_W} \int_0^\infty \frac{\mathrm{dt}}{t} \left(\mathrm{Im}\widetilde{\Pi}_{30}(t) - \mathrm{Im}\widetilde{\Pi}_{30}(t)^{\mathrm{SM}} \right)$$

$$= \int_0^\infty \frac{\mathrm{dt}}{t} \left(\frac{16}{g^2 \tan\theta_W} \mathrm{Im}\widetilde{\Pi}_{30}(t) - \frac{1}{12\pi} \left[1 - \left(1 - \frac{m_{H,ref}^2}{t} \right)^3 \theta(t - m_{H,ref}^2) \right] \right)$$

→ The convergence of the integral requires $\rho_{\mathbf{S}}(\mathbf{t}) \equiv \frac{\mathbf{1}}{\pi} \mathrm{Im}\widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{t}) \quad \stackrel{\mathbf{t}\to\infty}{\longrightarrow} \quad \mathbf{0}$

→ S-parameter defined for an arbitrary reference value $m_{H,ref}$

→ Higher threshold cuts in $\mathrm{Im}\Pi_{30}$ will be suppressed in the dispersive integral

→ At tree-level: $S_{\mathrm{LO}} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right)$

* Peskin and Takeuchi '92.

High-energy constraints

- ✓ We will have 7 resonance parameters: F_V, G_V, F_A, κ_W, λ_1^{SA}, M_V and M_A.
- ✓ The number of unknown couplings can be reduced by using short-distance information.
- ✓ In contrast with the QCD case, we ignore the underlying dynamical theory.

0) <u>Once-subtracted dispersion* relation for</u> $\Pi_{30}(s) = \frac{g^2 \tan\theta_W}{4}\, s\, [\Pi_{VV}(s) - \Pi_{AA}(s)]$

- ✓ Once-subtract. dispersive relation from tree+1-loop spectral function**

  $\pi\pi$, $h\pi$ … (higher cuts suppressed) $\Pi_{30}(s) = \Pi_{30}(0) + \frac{s}{\pi}\int_0^\infty \frac{\mathrm{d}t}{t\,(t-s)}\mathrm{Im}\Pi_{30}(t)$

- ✓ F_R^r and M_R^r are *renormalized* couplings which define the resonance poles at the one-loop level.

$$\Pi_{30}(s)|_{\mathrm{NLO}} = \frac{g^2\tan\theta_W}{4}\, s\, \left(\frac{v^2}{s} + \frac{F_V^{r\,2}}{M_V^{r\,2}-s} - \frac{F_A^{r\,2}}{M_A^{r\,2}-s} + \overline{\Pi}(s)\right)$$

* Peskin,Takeuchi ‘90, ‘91

** Pich, Rosell, SC ‘08

i) Weinberg Sum Rules (WSR)*

$$\Pi_{30}(s) = \frac{g^2 \tan\theta_W\, s}{4}\,[\,\mathbf{\Pi_{VV}(s) - \Pi_{AA}(s)}\,]$$
$$= \frac{g^2 v^2 \tan\theta_W}{4} + s\,\widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{s})$$

1ST WSR:

$$\left|\mathbf{s} \times \mathbf{\Pi_{V-A}(s)}\right| \stackrel{\mathbf{s}\to\infty}{\longrightarrow} \mathbf{0} \Longrightarrow \int_0^\infty \mathbf{dt}\ \rho_{\mathbf{S}}(\mathbf{t}) = \frac{\mathbf{g^2 v^2}\tan\theta_{\mathbf{W}}}{\mathbf{4}}$$

2ND WSR:

$$\left|\mathbf{s^2} \times \mathbf{\Pi_{V-A}(s)}\right| \stackrel{\mathbf{s}\to\infty}{\longrightarrow} \mathbf{0} \Longrightarrow \int_0^\infty \mathbf{dt}\ \mathbf{t}\ \rho_{\mathbf{S}}(\mathbf{t}) = \mathbf{0}$$

* Weinberg'67
* Bernard et al.'75.

$$\rho_{\mathbf{S}}(\mathbf{s}) = \frac{\mathbf{1}}{\pi}\mathrm{Im}\widetilde{\mathbf{\Pi}}_{\mathbf{30}}(\mathbf{s})$$

i.i) LO

$$F_V^2 - F_A^2 = v^2$$
$$F_V^2\, M_V^2 - F_A^2\, M_A^2 = 0$$

(1 / 2 constraints)

i.ii) Imaginary NLO

$$\mathrm{Im}\Pi_{V-A}(s) \sim \mathcal{O}\left(\frac{1}{s^{\Delta/2}}\right)$$

(1 / 2 constraints)

i.iii) Real NLO: fixing of $F_{V,A}^r$ or lower bounds**

$$F_V^{r\,2} - F_A^{r\,2} = v^2\,(1 + \delta^{(1)}_{\rm NLO})$$
$$F_V^{r\,2}\, M_V^{r\,2} - F_A^{r\,2} M_A^{r\,2} = v^2 M_V^{r\,2} \delta^{(2)}_{\rm NLO}$$

(constraints on $F_{V,A}^r$)

F_R^r and M_R^r are *renormalized* couplings which define the resonance poles at the one-loop level**

$$\Pi_{30}(s) = \Pi_{30}(0) + \frac{s}{\pi}\int_0^\infty \frac{\mathrm{d}t}{t\,(t-s)}\mathrm{Im}\Pi_{30}(t)$$

$$\Pi_{30}(s)|_{\rm NLO} = \frac{g^2\tan\theta_W}{4}\; s\;\left(\frac{v^2}{s} + \frac{F_V^{r\,2}}{M_V^{r\,2}-s} - \frac{F_A^{r\,2}}{M_A^{r\,2}-s} + \overline{\Pi}(s)\right)$$

* Weinberg'67
* Bernard et al.'75.
** Pich, Rosell, SC '08

LO results***

i.i) 1st and 2nd WSRs **

$$S_{\rm LO} = \frac{4\pi v^2}{M_V^2}\left(1+\frac{M_V^2}{M_A^2}\right)$$

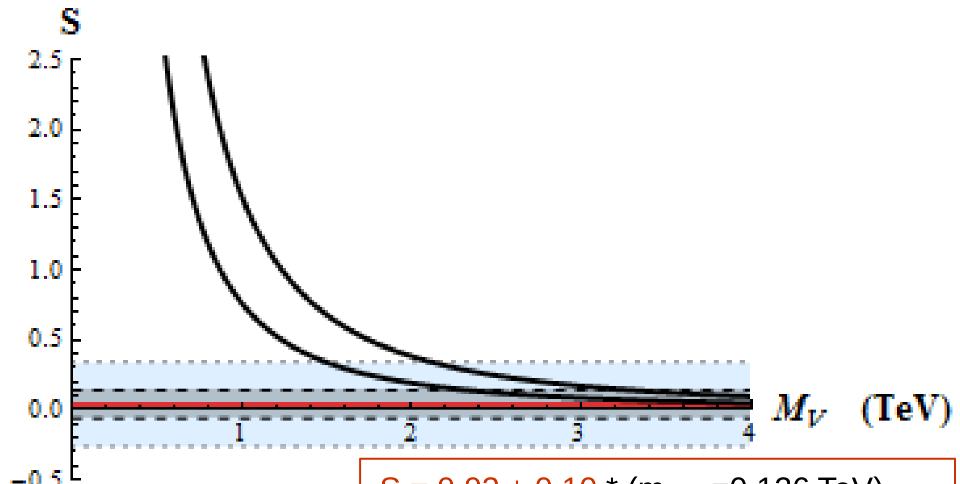
$$\boxed{\frac{4\pi v^2}{M_V^2} < S_{\rm LO} < \frac{8\pi v^2}{M_V^2}}$$

$$S_{\rm LO} = 4\pi\left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2}\right), \qquad T_{\rm LO} = 0$$

i.ii) Only 1st WSR *** (lower bound for $M_A > M_V$)

$$S_{\rm LO} = 4\pi\left\{\frac{v^2}{M_V^2} + F_A^2\left(\frac{1}{M_V^2} - \frac{1}{M_A^2}\right)\right\}$$

$$\boxed{S_{\rm LO} > \frac{4\pi v^2}{M_V^2}}$$



S = 0.03 ± 0.10 * ($m_{H,ref}$=0.126 TeV)

At LO M_V > 2.4 TeV at 68% CL

(M_V > 3.6 TeV if T_{LO}=0 also considered)

* Gfitter
* LEP EWWG
* Zfitter

** Peskin and Takeuchi '92.

*** Pich, Rosell, SC '12

*NLO results:** 1st and 2nd WSRs in Π_{30}

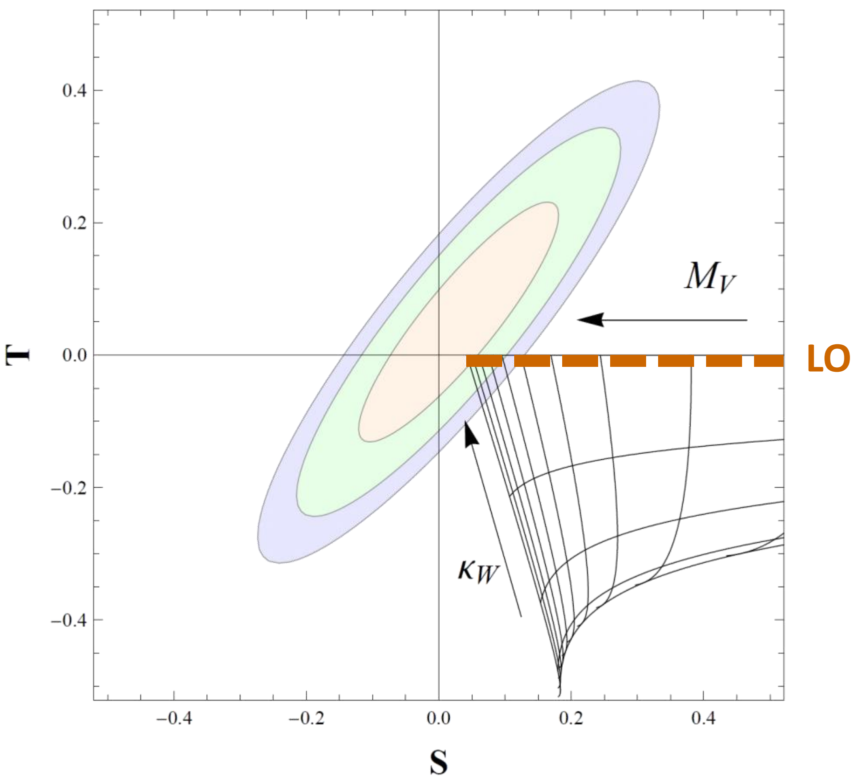
$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

LO

$$S = \boxed{4\pi v^2\left(\frac{1}{M_V^2}+\frac{1}{M_A^2}\right)} + \frac{1}{12\pi}\left[\left(\log\frac{M_V^2}{m_H^2}-\frac{11}{6}\right) - \kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2}-\frac{11}{6}-\frac{M_A^2}{M_V^2}\log\frac{M_A^2}{M_V^2}\right)\right]$$

[terms $O(m_S^2/M^2_{V,A})$ neglected]

(*asymptotically-free theories*)



✓ 1st and 2nd WSRs at LO and NLO + ππ-VFF:

→ 2nd WSR: $0 < \kappa_W = M_V^2/M_A^2 < 1$

At NLO with the 1st and 2nd WSRs

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

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

* Pich,Rosell,SC '12, '13

*NLO Results:** Only 1st WSRs in Π_{30}

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

$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2}-\kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

$$S > \underbrace{\boxed{\frac{4\pi v^2}{M_V^2}}}_{\text{LO}} + \frac{1}{12\pi}\left[\left(\ln\frac{M_V^2}{m_H^2}-\frac{11}{6}\right)-\kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2}-\frac{17}{6}+\frac{M_A^2}{M_V^2}\right)\right]$$

[terms $O(m_S^2/M^2_{V,A})$ neglected]

- ✓ **Assumption** **$M_A > M_V$** for the S lower-bound
- ✓ Only 1st WSR at LO and NLO + $\pi\pi$-VFF:

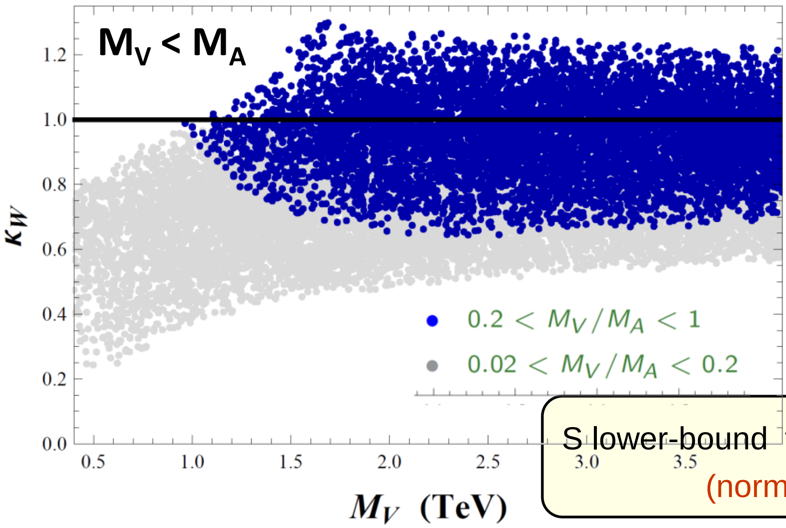
→ Free parameters: M_V, M_A and κ_W

* Pich,Rosell,SC '12, '13

** Orgogozo,Rychkov '11

*NLO Results:** Only 1st WSRs in Π_{30}

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



$$T = \frac{3}{16\pi\cos^2\theta_W}\left[1+\log\frac{m_H^2}{M_V^2} - \kappa_W^2\left(1+\log\frac{m_{S_1}^2}{M_A^2}\right)\right]$$

LO

$$S > \boxed{\frac{4\pi v^2}{M_V^2}} + \frac{1}{12\pi}\left[\left(\ln\frac{M_V^2}{m_H^2} - \frac{11}{6}\right) - \kappa_W^2\left(\log\frac{M_A^2}{m_{S_1}^2} - \frac{17}{6} + \frac{M_A^2}{M_V^2}\right)\right]$$

S lower-bound for $M_A > M_V$ (normal hierarchy)

At NLO with only 1st WSRs

$M_V > 1$ TeV, $\kappa_W \in (0.6\,,\,1.3)$ at 68% CL

for moderate splitting $0.2 < M_V/M_A < 1$

$\kappa_W = g_{HWW}/g_{HWW}^{SM}$

very different from the SM

if one requires large (unnatural) splittings

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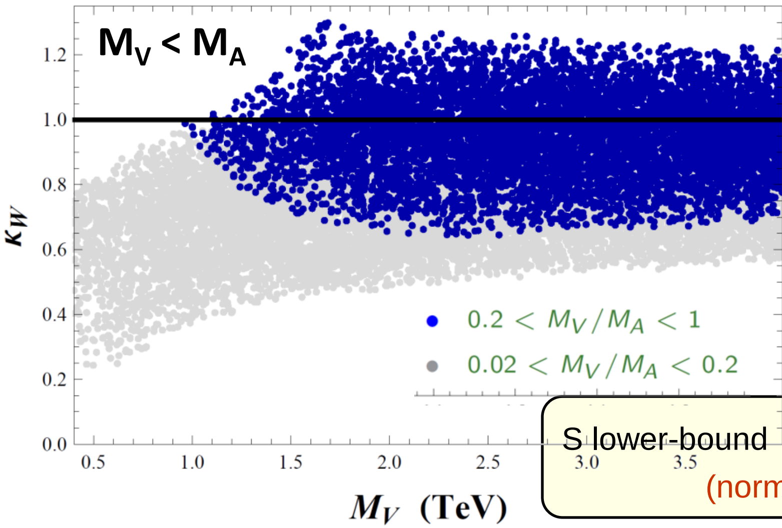

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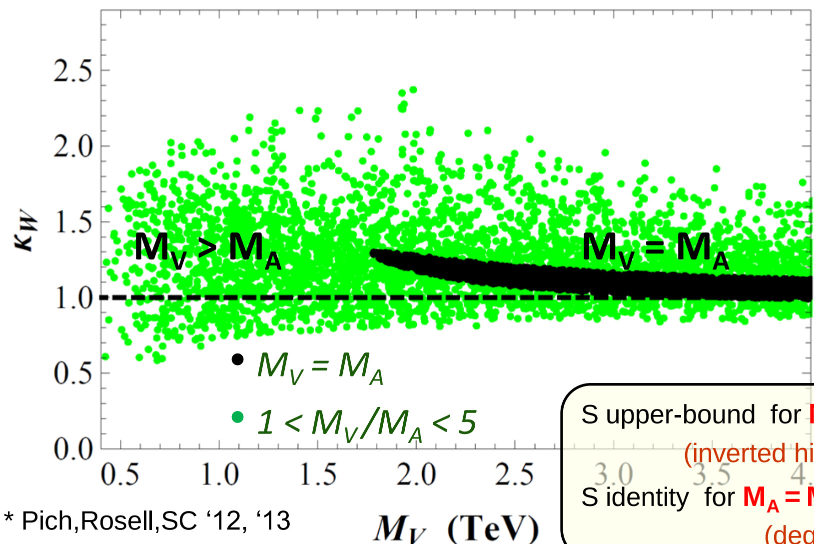

S upper-bound for $M_A < M_V$
(inverted hierarchy)

S identity for $M_A = M_V$
(degenerate)

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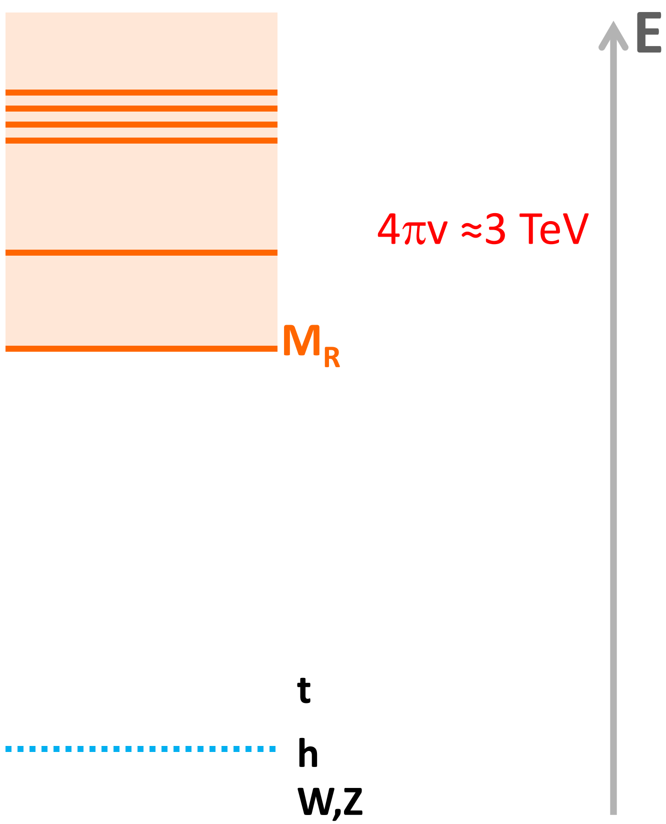
Energy scales in a strong-int. Higgs theory?



Naïve rescaling
from QCD to EW scale

QCD → **EW**

$F_\pi = 0.090$ GeV → $v = 0.246$ TeV

$\Lambda_{\chi PT} = 4\pi F_\pi \approx 1.2$ GeV → $\Lambda_{EW} = 4\pi v \approx 3.1$ TeV

$M_\rho = 0.770$ GeV → $M_{V1} = 2.1$ TeV

$M_{a1} = 1.260$ GeV → $M_{A1} = 3.4$ TeV

EFT general considerations

1. "SM" content: - Bosons χ: Higgs h + EW Golsdtones $\omega^{\pm}$,z + gauge bosons A^a_μ,B_μ,

   - Fermions ψ: (t,b)-type doublets

2. Applicability: $E \ll \Lambda_{EChL} \sim \min\{4\pi v,\ M_R\}$ ($4\pi v \sim 3$ TeV)

3. EW would-be Goldston bosons ➔ Non-linear realization $U(\omega^a)$

4. **Custodial symmetry:** $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ pattern

5. Gauge symmetry: $SU(2)_L \otimes U(1)_Y$

Additionally it is appropriate to work with

6. Renormalizable R_ξ gauge: Landau gauge convenient ($m_{\omega\pm,z} = 0$)